CARBON STOCK ESTIMATES FOR RED SPRUCE (*Picea rubens*) FOREST IN CENTRAL NOVA SCOTIA

By

Anthony Robert Taylor

A Thesis Submitted in Partial
Fulfillment of the Requirements for the
Degree of Master of Science in Forestry

Faculty of Forestry and the Forest Environment
Lakehead University
April, 2005

Library and
Archives Canada

Published Heritage
Branch

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque et
Archives Canada

Direction du
Patrimoine de l'édition

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence
ISBN: 0-494-10673-5
Our file Notre référence
ISBN: 0-494-10673-5

NOTICE:
The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:
L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

ABSTRACT

Taylor, A.R. 2005. Carbon stock estimates for red spruce (*Picea rubens*) forest in central Nova Scotia.

Key Words: Red spruce, biomass, carbon sequestration, carbon storage, dead organic matter, silviculture, forest management, Nova Scotia, Kyoto Protocol, greenhouse gas.

Carbon storage was measured in natural red spruce dominated stands in the Eastern Eco-region of central Nova Scotia (NS). Twenty-four plots over a 140-year chronosequence were established. Within each plot, major carbon pools including above-and-belowground tree biomass, dead organic matter (DOM) and upper (0-0.1 m) mineral soil were measured. Carbon storage measurements were compared with simulation results for NS predicted by the beta-version of the CBM-CFS 3 in order to observe any significant differences and make potential calibrations. The calibrated beta-model was then used to simulate and compare several forest management scenarios currently being used in NS to manage red spruce forests and to examine their potential to enhance carbon sequestration. Overall carbon storage increased throughout stand development peaking in the 81-100 year age class at 247 Mg C ha^{-1}. Significant differences between the observed carbon storage and the CBM-CFS 3 (beta) predicted values were recognized. These differences were attributed to over estimation of belowground DOM pools by the model and the design of the sampling regime of the observed data. A traditional clear-cut scheme (100% removal of aboveground tree biomass) used to manage red spruce in NS, and a partial-cut scheme (50% removal of aboveground tree biomass) were then simulated with the calibrated model. The partial-cut stand displayed maximum carbon storage of 232.38 Mg C ha^{-1}, while the clear-cut stand showed 197.75 Mg C ha^{-1}. On average the partial-cut stand stored 202 Mg C ha^{-1} between years 80 and 240 of the simulation, while the clear-cut stand stored 123 Mg C ha^{-1}, thus indicating a higher carbon sequestration potential for partial-cutting.

CONTENTS

TABLES

FIGURES

ACKNOWLEGMENTS

I would like to give my sincere appreciation to my supervisor Dr. Jian Wang for his help, support and guidance throughout the development of my thesis. I would also like to thank my committee members Dr. Qinglai Dang, Dr. Ken Brown and my external reviewer Dr. Werner Kurz. For assistance with working with the CBM-CFS 3 (beta version) I would like to thank Greg Rampley and Stephen Kull. For assistance in the field I would like to thank my brother Seth Taylor, Gordon Mailman and Taylor Lumber Company Ltd.

Finally I would like to thank my parents Robert and Eva Taylor for their love and support and pushing me to accomplish my goals in life.

CHAPTER ONE

GENERAL INTRODUCTION

1.1 INTRODUCTION

Climate change is considered to be one of the largest threats to the sustainability of the Earth's environment. It is widely accepted among the scientific communities that the build-up of greenhouse gases in the atmosphere, primarily carbon dioxide (CO_2), is responsible for this change. Over the past two centuries, since the beginning of the industrial revolution, the CO_2 concentration in the atmosphere has increased from close to 280 ppm to 367 ppm in 1999 (IPCC 2001). This is mostly due to increased burning of fossil fuels for energy production and transportation (IPCC 2001). The global consumption of fossil fuels is estimated to release into the atmosphere every year more than 22 billion tones of CO_2 (Government of Canada 2002a). If this trend continues, by the end of the century, the concentration of CO_2 in our atmosphere will be at least double what it was prior to the industrial revolution. Projections of future climate change based on climate models indicate a warming of 1.5-4.5 °C upon doubling of atmospheric CO_2 emissions (Rizzo and Wiken 1992). Scientists predict that Northern nations will be more strongly affected by climate change than those closer to the equator, therefore making countries such as Canada particularly vulnerable (Government of Canada 2002b).

In December 2002, the Canadian federal government committed itself by ratifying the Kyoto Protocol. Under this legally binding protocol, Canada must reduce its collective emissions of greenhouse gases by 6% below 1990 levels by the period 2008-2012 (Government of Canada 2002a).

Canada's approach to reducing its CO_2 emission commitment of 240 megatons (MT) from the projected "business-as-usual" emission level in 2010 involves reductions from several of Canada's industrial sectors including a 20 MT reduction of emissions from forest management activities (Government of Canada 2002b). Canada, however, would like to increase the potential of this forest carbon sink. Investments in plantations, policy changes to reduce deforestation and changes in forest management practices, including intensive forest management and improvement to forest conservation, could significantly add to this sink (Government of Canada 2002b). One part of the solution to this challenge is to quantify the carbon sequestration capacity of Canadian forests.

According to Kurz et al. (2002), Canada's carbon budget can be significantly affected by forest management activities implemented at the operational scale. Forest ecosystems store more carbon than any other terrestrial ecosystem and afforestation, reforestation, and other forest management measures to increase forest productivity beyond the business-as-usual approach could sequester significant quantities of atmospheric CO_2 (Dixon et al. 1994). Silvicultural practices may be able to affect how much carbon a forest stand absorbs, how long it is stored, and how much of it is emitted back into the atmosphere. Papadopol (2002) suggests that sustainable forest management practices may be able to increase stored carbon in the forest, for example by reducing soil disturbances and by enhancing regeneration and re-growth after harvest or other disturbances. With growing national and international awareness that land-use change and forestry can contribute to increasing carbon sources and sinks, forest managers will need to assess how their management plans and actions will affect terrestrial carbon stocks (Kurz et al. 2002).

Due to increased demand for forest product in Nova Scotia, the Department of Natural Resources has implemented new forest sustainability regulations. These regulations have led to increases in silviculture activity in the province (NSDNR 2003a). Whether increased silviculture activity in Nova Scotia is leading to a net carbon sink is currently unclear.

To more clearly understand how forest management activities affect carbon storage in red spruce (*Picea rubens*) forest in Nova Scotia, a better understanding of the carbon dynamics in natural unmanaged red spruce forest must be achieved. Currently there are few estimates of carbon storage in red spruce forests in Nova Scotia, which are of major economic importance to the forest industry.

To properly asses carbon dynamics in terrestrial ecosystems ground inventories, flux measurements and bottom up modelling approaches are required (Nilsson et al. 2003). Chronosequence approaches are often used to study carbon dynamics throughout forest succession (Wang et al. 2003, Davis et al. 2003). Boone et al. (1998), and Grigal and Ohmann (1992) showed the importance of stand development stages on carbon storage in forest ecosystems. Therefore, Chapter Two of this thesis uses a chronosequence approach to examine changes in carbon storage throughout stand development in red spruce forest in central Nova Scotia.

In order to quantify and predict changes and carbon stocks in Canadian forest ecosystems, scientists at the Canadian Forest Service are developing the third version of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS 3). This model provides a working framework to predict and monitor carbon dynamics in Canadian forests at the landscape and stand level. The model is compliant with evolving international carbon accounting rules (Kurz et al. 2002). In order for this model to be scientifically credible it must be tested and calibrated to some extent against actual field measurements. Chapter Three of this thesis focuses on comparing carbon storage predictions for red spruce forest in Nova Scotia by the CBM-CFS 3 with measured field data from Chapter Two.

Chapter Four focuses on examining the effect of two different forest harvesting systems on carbon storage in red spruce forest in Nova Scotia. Some studies have suggested that forest management activities may enhance the sequestration and storage capacity of carbon in forests (Schroeder 1991, Dixon et al. 1994, and Griss 2002). Harmon and Marks (2002) and Lee et al. (2002) showed that partial-cut harvesting systems demonstrated a higher potential to store carbon then clear-cut harvesting. Using the calibrated CBM-CFS 3 from Chapter Three, two different forest harvesting simulations were created and run in order to explore the potential influences that partial-cut and clear-cut harvesting systems may have on the carbon pools within red spruce stands in Nova Scotia.

1.2 LITERATURE REVIEW

Increases in the concentration of atmospheric greenhouse gasses (GHG) since the beginning of the industrial revolution have given rise to concerns about the impacts of climate change (IPCC 2001). Implementation of the Kyoto Protocol (UNFCCC 1997) has increased demand for information on the potential of forest ecosystems to mitigate increases in atmospheric carbon dioxide concentrations. According to the Marrakesh Accords (UNFCCC 2002), countries such as Canada, which have ratified the Kyoto Protocol, may use forest management (FM) activities to counter GHG emissions and meet reduction targets. The decision as to whether or not to use FM activities must be made by August 2006.

This literature review briefly examines Canada's commitment to the Kyoto Protocol. It focuses on how Canada may be able to use FM activities to offset GHG emissions levels; the types of FM activities that may qualify and some of the initiatives underway in Canada to monitor and report offsets produced from FM activities. Particular focus is on Nova Scotia forestry, where recent increases in intensive forest management may provide an example of how FM activities could be used to combat climate change.

1.2.1 THE KYOTO PROTOCOL AND CANADA

Kyoto Protocol Overview

With increasing global awareness of potential climate change due to the negative effects of anthropogenic activities on the Earth's natural environment, certain initiatives have been undertaken by the United Nations in order to mitigate these negative affects. In Rio de Janeiro, Brazil, 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was adopted with the objective of reducing atmospheric concentrations of GHG to a level that would prevent dangerous interference with the Earth's climate systems (Nelson and Vertinsky 2003). Initially, the UNFCCC was primarily concerned with acquiring a commitment from industrialized countries that would reduce their GHG emissions to 1990 levels by 2000. This first step came into effect in March, 1994; this was a voluntary commitment, and was soon recognized as non-achievable as such. Nonetheless, the UNFCCC acted as a launching pad for potential further action. It established a general framework of principals, institutions, and a process by which governments could meet regularly to discuss potential solutions to global climate change.

Since then, a number of United Nations conferences have been held, including the one in Kyoto, Japan, in 1997. The outcome of this particular conference was a Protocol to the UNFCCC, which is formally known today as the Kyoto Protocol (Government of Canada 2002a). The Kyoto Protocol defines a more specific framework of principles and agreements where by industrialized countries which ratify the Protocol will be legally bound to reduce their collective GHG emission levels within a set time frame.

The main objectives of the Kyoto Protocol are to lower GHG emissions, and to insure greater energy efficiency, sustainable industrial growth, innovative technologies and cleaner air. The Protocol addresses six main greenhouse gases where CO_2 is by far the most important gas, accounting for over four fifths of total greenhouse gas emissions from developed countries in 1995 (UNFCCC 2004).

In order to achieve its objectives, the Kyoto Protocol requires that those countries which ratify the agreement to reduce their collective GHG emission levels to 5% below their 1990 levels by the first commitment period of 2008-12 (Nelson and Vertinsky 2003). During this period, each country's emission levels will be calculated as an average of the 5 years from 2008-12. For parties who fail to reach their target GHG levels, details concerning non-compliance measures have not yet been worked out (UNFCCC 2004). Specific details and rules of how GHG emissions are to be measured and how credit can be attained for reductions in GHG emissions can be found in the Marrakesh Accords, which spell out the specific framework of how the Protocol will be governed.

The Kyoto Protocol entered into force February 16th 2005, the ninetieth day after the date on which not less than 55 countries, including countries accounting for at least 55% of industrialized country emissions, ratified the Protocol. The current government of the United States has said it will not ratify the Protocol and the Australian government has expressed its intent not to ratify in the near future (Nelson and Vertinsky 2003).

Canada's Role

On December 17, 2002, the Kyoto Protocol was ratified in Canada. Under the Protocol, Canada has agreed to lower its greenhouse gas emissions by 6% below 1990 levels during the first commitment period (2008-2012) (Government of Canada 2002b). This means that Canada is responsible for reducing its annual GHG emissions level by 240 megatonnes (MT) from the projected "business-as-usual" emissions level in 2010.

In order to meet Canada's emissions target, the Canadian Government has developed a national "Climate Change Plan". This is a three step approach which reduces emissions over time in five main areas. These include: 1) actions (such as in transportation and buildings) taken by Canadians and the various levels of Government, 2) large industrial emitters, 3) other industrial emissions (technology, infrastructure and efficiency gains), 4) agriculture, forestry and landfills (sinks and offsets), and 5) international emissions reductions.

The first step involves reductions in these areas that are currently being carried out in partnership with the provinces, the territories and the private sector. This initial step accounts for an approximate 80 MT reduction towards Canada's 240 MT target. The second step involves potential new actions towards emission reductions in the five main areas that could potentially reduce Canada's emission levels by a further 100 MT. The third step generally examines what reductions in emission levels need to be accomplished. It outlines current and potential actions and further research and development which could be used to address the remaining 60 MT reduction (Government of Canada 2002b).

1.2.2 IMPORTANCE OF FORESTRY

Forest as Carbon Sinks

Terrestrial vegetation plays a pivotal role in the global carbon cycle (Schroeder 1991). Large amounts of CO_2 are stored in terrestrial vegetation. On average, it is estimated that the entire CO_2 content of the atmosphere passes through the terrestrial vegetation every seven years, with about 70% of the entire exchange occurring through forest ecosystems (Schroeder 1991). This signifies the importance of the forests as a buffer for controlling atmospheric CO_2 concentrations and suggests their potential use to the storage of carbon to slow or offset increases in atmospheric CO_2 concentrations.

Canada has over 400 million ha of forests, nearly 10% of the global forests area (NRCAN 1999). Forests, therefore, are considered to be one of Canada's most important instruments in the fight against climate change. The use of forest carbon management could be used to help reduce Canada's net CO_2 emission levels. Net reductions in GHG emissions can be achieved under the Kyoto Protocol either by reducing emission sources or, as stipulated in Articles 3.3 and 3.4 of the Protocol, by enhancing sinks through absorption in terrestrial ecosystems through land-use change and forestry practices (UNFCCC 1997). Forest ecosystems can act as carbon sinks by storing carbon as biomass through the process of photosynthesis, and can also act as carbon sources emitting carbon back into the atmosphere through the processes of respiration, decomposition and fire emissions (Government of Canada 2002b).

Implications for Forestry in Canada

Part of Canada's action plan to reduce national GHG emission levels includes a potential offset from the forestry sector. Current projections indicate that the existing forestry practices in Canada (business-as-usual) will result in a carbon sink of approximately 20 MT (Government of Canada 2002b).

Under the Kyoto Protocol, the Marrakesh Accords establish the overall framework for policy and climate change mitigation actions in Canada's forests, setting the rules for forest carbon accounting in Canada. The framework pertains to the first commitment period only. According to the Kyoto Protocol, it is mandatory for industrialized countries, such as Canada, that ratify the Protocol, to account for carbon stock changes during the commitment period on areas affected by land-use changes.

Land-Use Changes and Land-Use

The Protocol separates the accounting of carbon stock changes resulting from "land-use changes" from "land uses" such as forestry. Land-use changes which relate to forestry activities include afforestation (A), reforestation I, and deforestation (D) activities (ARD). Since 1990, A and R activities result in increases in carbon stocks, where afforestation refers to the establishment of forest on land that has not held forest for at least 50 years, and reforestation refers to land that did not have forest at the end of 1989 and was subject to non-forest land-use. Activities resulting in deforestation, the conversion of forests to a non-forest (harvesting followed by regeneration is not considered deforestation) leads to decreases in carbon stocks. When total ARD activities result in a net carbon sink, the credits can be used to offset emissions from other sectors in that country. When these activities result in a net source, the debits will be added to the country's emissions balance (Kurz et al. 2002).

In some industrialized countries such as Canada, business-as-usual ARD activities will almost certainly result in a net source of CO_2 since the emissions from D will exceed the emission reductions from A and R. According to Nelson and Vertinsky (2003), the creation of new forests through A and R is projected to result in a sink of roughly 1 Mt/yr CO_2, while D is projected to be a source of 16 Mt/yr CO_2. This yields a net source of CO_2 which adds to the nation's emissions balance; however, industrialized countries have the option to include "land uses" such as forest management (FM) activities since 1990 in their accounting schemes. If FM activities create carbon sinks, this can be put towards carbon credits which a country can use to first offset a possible net source from ARD activities and to offset emissions from other sectors. There are, however, country-specific caps upon which a maximum amount of credit can be used in order to offset ARD activities and the offsets for emissions from other sectors (Kurz et al. 2002).

The Potential of Forest Management

According to the Kyoto Protocol, FM is defined as a system of practises for the stewardship and use of forests including the harvest-regeneration cycle. Under the Marrakesh Accords (UNFCCC 2002), FM activities can be used as a sink to offset any net source resulting from ARD activities up to a cap of 33 Mt/yr CO_2 in 2008-12. Additional FM sink capacity can be used to offset other sectors in Canada, up to a national specific cap of 44 Mt/yr CO_2 in 2008-12. In order for ARD or FM to qualify as part of Canada's accounting, the land must be identified to be "forest" as defined by the Marrakesh Accords. Accounting for changes in carbon stocks on these lands also means that the lands must be formally identified as forests shown to have been subject to ARD or FM practices since 1990 and spatially delineated (Nelson and Vertinsky 2003). Identifying what forested land will qualify for managed forest is one of the major barriers facing Canada (Griss 2002).

In countries which choose to use FM as part of their accounting scheme, an important matter to consider is the distinction between the total forest area and the managed forest area. This point is critical to Canada, where the total forest area is estimated at 400 million ha and the actual managed forest is only a percentage of this. According to Lowe et al. (1996), Canada's total estimated managed forest area (the area which is accessible by road and has forest suitable for timber extraction) is 134 million ha. Nelson and Vertinsky (2003) state that this area is made up of regions effected by natural disturbances and harvesting acting as sources of CO_2, also, regions of regeneration, representing areas of sinks of CO_2. In total, it is estimated that Canada's FM areas amount to a net sink of 35 Mt/yr CO_2 in 2008-12 based on "business-as-usual" activity. Taking into consideration that ARD activities in Canada are projected as a net source of 15 Mt/yr CO_2 in 2008-12, total forest activities are estimated to result in a net sink of 20 Mt/yr CO_2.

Increasing Carbon Sequestration through Forest Management

Canada would like to increase the potential of its forests carbon sink. Investments in plantations, policy changes to reduce deforestation, and changes in forest management practices, including intensive forest management and improvement to forest conservation, could significantly add to this sink (Government of Canada 2002b). Several studies have been done in Canada which examine potential FM options which could possibly increase carbon sequestration and reduce emissions. Parker et al. (2000) suggest that intensive forest management can increase productivity and, therefore, carbon storage capabilities. For example, activities including assisted regeneration and tree planting, vegetation management, and fertilization can help to increase the ability of a forest to sequester and to store carbon through increases in productivity. There are a number of suggested potential mitigation methods to manipulate the carbon cycle through silvicultural means, therefore, increasing sequestration of C in tree biomass and forest soils (Papadopol 2002 and Griss 2002). Some of these include:

Reforesting immediately after harvest

Reforesting immediately after harvest helps to maintain an active and almost continued C sequestration function (Papadopol 2002). Particularly in areas not successfully regenerated after harvest, where the species composition is undesirable, or of low-productivity. Restoring forest cover after harvest helps to avoid areas left bare of vegetation or areas occupied with undesirable low-productivity species. By reforesting an area after harvest by either planting or through vegetation control management (herbicides, manual weeding etc.), it insures that a productive forest of desirable species will be established and, therefore, produces a higher sequestration efficiency (Schroeder 1991 and Timmer 2003). Restoring forest cover as soon as possible also avoids long intervals with the forest soil exposed, which can lead to higher decomposition rates of soil organic matter and therefore a source of CO_2 (Covington 1981, Federer 1984, Johnson 1992, and Johnson 1995). Covington (1981) described differences in organic matter storage in forest floors of northern hardwood forest that had been harvested at different dates. The study found that forest floor mass declined sharply, by as much as 40-50% within 20-years following harvest. This loss was mainly attributed to increased decomposition rates and decreases in litter inputs. Reviews of studies completed since Covington (1981), however, argue that this loss of 40-50% is too large and not fully supported (Johnson 1992 and Yanai et al. 2003).

Density control

Forest management activities such as cleaning, pre-commercial thinning and commercial thinning are used to increase the amount of quality timber from a forest stand by helping to reduce competition between trees, thus increasing incremental growth of dominant crop trees due to the reduction in inter-tree competition (Nyland 1996). These activities may also be useful in increasing C sequestration. Firstly, increasing the mean annual growth of dominant crop trees by eliminating less desirable species and suppressed trees, the crop trees are increasing their C storing capacity. Schroeder (1991) reviewed studies of the effect of thinning on C storage in Douglas-fir (*Pseudotsuga menziesii*) and loblolly pine (*Pinus taeda*) stands. He states that thinning may increase carbon storage in very dense young stands where early thinning increases productivity by leaving well-spaced stems on the best micro-sites. Griss (2002) states that on productive forest land thinning allows remaining crop trees to grow faster, resulting in a shortened rotation period, allowing a greater amount of forest products to be produced from a smaller land base. Secondly, increased commercial and pre-commercial thinning may allow more timber to be extracted from an area, thereby reducing the area that needs to be harvested to achieve a harvest volume target. By reducing the area needed to be harvested, there is a reduction in carbon that would be lost due to harvesting a larger area. For example, thirty-year old red spruce stands cleaned at various intensities in Nova Scotia displayed increases in merchantable volume when compared with non-treated stands (NSDNR1988). Observation of pre-commercially thinned spruce-fir stands in Nova Scotia indicates that thinning reduced the merchantable rotation age by as much as 13 years on average (NSDNR 1992). Increases in the yield of merchantable timber per ha from these activities means less area would need to be harvested in order to acquire the same volume of wood from untreated forests.

Harvesting

The harvesting system adapted in FM can influence the carbon balance in the forest. For example, clear-cutting systems remove the most tree biomass per unit area at a given time and therefore, remove the most carbon. Partial-cutting techniques, such as selection harvesting or shelterwood methods, remove less carbon at once, but remove it more frequently leaving a continuous amount of growing biomass in the forest (Papadopol 2002). Harmon and Marks (2002) examined the effects of clear-cut and partial-cut harvesting on Douglas-fir and western hemlock (*Tsuga heterophylla*) using the forest carbon model STANDCARB. They found that partial-cut harvesting may provide as much forest product as a traditional clear-cut system while increasing carbon stores. Three factors which they determined most important in developing an optimum carbon sequestration harvesting system are 1) rotation length, 2) amount of live trees harvested, and 3) amount of detritus removed by slash burning fires; where longer rotation lengths, low-tree utilization, and low-slash burning levels, provides the largest gains in forest ecosystem carbon. Lee et al. (2002) also found that partial-cut harvesting maximized ecosystem carbon assimilation. Studying boreal mixedwood stands in northern Ontario, Lee et al. (2002) attributed the higher carbon sequestration in the partial-cut area mainly to the growth of the vigorous residual trees remaining as opposed to the absence of trees on the clear-cut site. In contrast to other studies (Federer 1984 and Covington 1981), Lee et al. (2002) found that forest floor decomposition rates were generally lower in the clear-cut stand then the partial-cut stand, possibly due to the rapid re-vegetation of pioneer species creating new canopy cover.

1.2.3 QUANTIFYING FOREST CARBON

Due to the increased awareness of carbon storage and fluxes (inputs and outputs of carbon) in forest ecosystems, carbon budgets, which study and estimate carbon storage and fluxes, have become the focus of much research in recent years (Davis et al. 2003). Forest carbon is now an economic commodity in which there is keen interest worldwide to quantify and report storage and fluxes of forest carbon in a standard and verifiable manner (Prisley and Mortimer 2004). Nations which have ratified the Kyoto Protocol and are intending on reporting FM activities are now faced with critical economic and policy decisions with regard to estimating and projecting forest carbon stocks and fluxes (Prisley and Mortimer 2004).

To properly assess CO_2 fluxes of the terrestrial biosphere, ground-based inventories, flux measurements, and bottom-up modeling approaches are used (Nilsson et al. 2003). Due to the potential cost involved, estimations of forest carbon are rarely done from observational data alone (Prisley and Mortimer 2004). More often models are being developed. Numerous studies involving forest carbon accounting modeling have been completed over the past decade. Some recent examples of prominent forest carbon accounting modeling work include: Kurz and Apps (1999), Homann et al. (2000), Richards (2001), Jiang et al. (2002), Seely et al. (2002), Fukuda et al. (2003), Masera et al. (2003) and Paul et al. (2003).

Carbon Budgets in Canadian Forest

Measurement tools and inventories are required to verify carbon sequestration in order to receive credit. In Canada an effort is being made to develop tools which model carbon stocks, and fluxes caused by natural processes and anthropogenic influences in forest ecosystems. Some examples of recent modelling efforts which study carbon storage and fluxes in Canadian forest include: Kurz and Apps (1999), Banfield et al. (2002), Seely et al. (2002), Tremblay et al. (2002), and Peng et al. (2003).

Several research initiatives in Canada are currently studying carbon storage and fluxes in forest ecosystems to better understand how Canadian forests will play a role in its GHG reduction commitments. Such initiatives include: The BIOCAP Canada Foundation, Greenhouse Gas Management Canada and Fluxnet Canada. Major contributions are being made by Canadian Forest Service (CFS) researchers across Canada, with lead research taking place at the Pacific Forestry Centre in British Columbia and the Northern Forestry Centre in Edmonton. The National Forest Carbon Accounting Program is developing the framework for a national forest carbon monitoring accounting and reporting system. The system will be built upon decades of science and current research from within the CFS, other federal departments, the provinces and territories, the forest industry, universities and other communities (Fowler et al. 2002). The framework will incorporate existing forest information, such as forest inventories, temporary and permanent sample plots, and systems quantifying forest growth and yield developed by the forest community over the last several decades.

A major contributor to this program is the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS). Since the late 1980s, CFS researchers have been developing a computer-simulation model that describes the carbon dynamics of Canada's forest ecosystems. The Carbon Budget Model of the Canadian Forest Sector is a general accounting framework that tracks carbon stocks and fluxes in forest ecosystems. It incorporates collected forest inventory data and modeled processes to simulate the carbon cycle of the forest (NRCAN 2001).

Over the past decade, Dr. Werner Kurz, a research scientist at the Pacific Forestry Centre, Dr. Mike Apps, a Northern Forestry Centre research scientist, and other researchers have been developing the CBM-CFS (Kurz et al. 1992). The model has been useful in exploring possible scenarios concerning natural disturbance, forest management, and growth and decomposition rates. As an example, Kurz and Apps (1999) estimated, using the CBM-CFS 2, net ecosystem carbon fluxes for Canada's 404 million ha forest areas for the period 1920-1989. They found changes in disturbance regimes have affected the forest age-class structure and increased the average forest age. Taking this information into consideration, they found increases in forest disturbances over the past decade, primarily fire and insect damage, which resulted in a reduction of forest ecosystem carbon storage. Other studies which have used the CBM-CFS to explore carbon dynamics in Canadian forests include: Peng et al. (2000), Banfield et al. (2002), Liu et al. (2002) and Li et al. (2003b).

Currently, Dr. Kurz and the CFS accounting team are working with the Model Forest Network to develop an operational-scale carbon accounting tool (CBM-CFS 3) and supporting data bases with regional parameter values (Kurz et al. 2002). When this model is developed, it will be available to anyone interested in using it to estimate landscape-level and stand-level forest carbon storage and dynamics. In particular, the model may be useful to forest managers having to make important management decisions taking into consideration forest ecosystem carbon storage.

In order for models such as the CBM-CFS 3 to accurately simulate carbon stocks and fluxes, detailed forest inventories, growth and yield information, and data describing natural disturbances required for forest management are needed. Much of this information is already gathered by forest managers; however, data concerning uncommonly measured carbon pools such as understory vegetation and dead organic matter, including coarse woody debris, forest floor litter and soil organic carbon, is not usually available. Such carbon pools are important and are required in order to produce scientifically-credible information regarding carbon stocks and stock changes in forest ecosystems (Kurz et al. 2002). For modeling tools such as the CBM-CFS 3 to be scientifically credible, not only must they be based upon the best available scientific data, but they also must be validated and calibrated to some extent against actual carbon budget field data, where the carbon pools in a particular forest area have been physically measured and analysed.

1.2.4 NOVA SCOTIA FORESTRY

The Nova Scotia Forest Industry is unique compared with the rest of Canada in that roughly 70% of the forest resource ownership is private, the rest being government owned (NSDNR 2003). The province of Nova Scotia has a forested area of approximately 4.2 million ha, with roughly 2.3 million ha of softwood forests, 1.0 million ha of mixed-wood forests, and the rest hardwood and other forest types (NSDNR 2003). These forests provide vital services to Nova Scotia, including wildlife habitat, recreation, hunting and fishing grounds, and forest products.

Current Forestry Situation

One of the major issues facing Nova Scotia's forests today is whether the recent increase in timber demand will lead to wood supply sustainability problems in the future. Over the past decade, forest product demand has increased significantly, which has led to significant increases in timber harvesting. The 1999 Wood Supply Forecast for Nova Scotia (1996-2070) confirmed that existing harvest levels on small private woodlots were not sustainable with the then current levels of silviculture on those lands (NSDNR 2000a). Considering that privately owned land in Nova Scotia accounts for 70% of the productive forestland base, this was a major issue for the Nova Scotia forestry industry. Because of the increase in forest product demand and the end of federal government assistance for private land silviculture, the Nova Scotia Department of Natural Resources (NSDNR) developed regulations (Nova Scotia Forest Sustainability Regulations) that became effective in the spring of 2000 which required registered buyers of wood products, utilizing greater than 5000 cubic meters of wood from private lands annually, to prepare and submit to NSDNR a "Wood Acquisition Plan". This Wood Acquisition Plan system acts as a mechanism for getting registered buyers to administer silviculture programs on private lands.

The goal of the increasing silviculture activity on private lands in Nova Scotia is to aid in sustaining the forest resources. Each registered buyer is responsible for keeping track of the volume of wood they utilize annually and must submit this information to NSDNR. For each cubic meter of wood that is utilized, the buyer accumulates a debt of credit. Currently in Nova Scotia, each cubic meter of softwood is worth $3.00 in credit and each cubic meter of hardwood is worth $0.60 in credit. Annually, the buyer is responsible to insure that an equivalent of silviculture activity credit is completed on private land to balance the debt accumulated from that year's wood utiliziation. The NSDNR has created a list of silviculture activities, each of which are equal to so many credits per ha of area completed, and have certain technical standards that must be satisfied. The credited silviculture activities include: plantation establishment, manual-weeding, pre-commercial thinning, commercial thinning, shelterwood harvesting, and seed tree harvesting. (see Appendix I for complete list of silviculture activities and credit value).

Increased Carbon Sequestration from Silviculture

Due to Nova Scotia's new forest sustainability regulations, there is now a significant increase in the amount of silviculture activity being carried out by forest companies. Currently 15% of harvested land in Nova Scotia (private and Crown) is reforested through planting, with approximately 7034.7 ha of regenerating forest being pre-commercially thinned annually (NSDNR 2003). Some of the desired consequences of this practice are increases in the productivity of forestlands, shorter rotation periods, and a sustainable wood supply.

Increased intensive forest management in Nova Scotia due to the now required silviculture activity will hopefully lead to an increased future wood supply. According to Parker et al. (2000), increased forest management may lead to increased carbon sequestration and storage. Whether the increased silviculture activities being carried out in the province are leading to a net carbon sink is currently unclear: If so, this would contribute positively towards Canada's FM carbon budget and aid in achieving the GHG emissions reduction target from FM activities.

Significance of Red Spruce Stands

According to NSDNR (2003), Nova Scotia's 4.25 million ha of forest land is 54% softwood cover type. Spruce species make up roughly 30% of the merchantable volume of softwood. Red spruce is Nova Scotia's provincial tree and is also the province's most valuable lumber and pulp wood species. After balsam fir, red spruce is the most common softwood species in Nova Scotia (Saunders 1970).

Red spruce is a predominant species except in the Cape Breton uplands, and the western part of the province. The cool moist climate of Nova Scotia is ideal for this tree as it occurs both in extensive pure stands and mixed with various hardwoods and softwoods (Saunders 1970). In low land swampy areas, red spruce usually forms associations with black spruce, tamarack and red maple. On well drained soils and upland areas, red spruce does the best, when commonly found with yellow birch, sugar maple and beech. Red spruce is shade tolerant, but shows the best growth in full sunlight. Under ideal conditions this species reaches dimensional lumber log size in 60 years and commonly lives up to 200-years (Saunders 1970).

Given the commercial value and the abundance of red spruce in Nova Scotia, understanding the carbon dynamics of red spruce stands and its associated stands is critical in order to estimate carbon budgets of areas which have been influenced through FM activities. Before a net carbon balance can be calculated from FM activities, which may or may not enhance carbon sequestration and storage in red spruce forests, a clear understanding of the carbon dynamics in natural red spruce stands that have not received silvicultural treatment, must be obtained.

CHAPTER TWO

CARBON STORAGE IN NOVA SCOTIA RED SPRUCE FOREST

2.1 INTRODUCTION

Carbon storage and fluxes in forests have been the focus of much research in recent years due to the role of CO_2 in global climate change (Davis et al. 2003). According to Papadopol (2002), afforestation and forest management measures may have the potential to increase carbon sequestered from the atmosphere in forest ecosystems, which may act as an important tool in the fight against climate change, considering these ecosystems store more carbon than other terrestrial ecosystems (Dixon et al. 1994).

Canada has over 400 million ha of forest, nearly 10% of the global forest area (NRCAN 1999). Under the Kyoto Protocol, net reductions in GHG emissions can be achieved by enhancing carbon sinks through land-use change and land uses such as forest management (FM). Papadopol (2002) and Parker et al. (2000) suggest that FM activities such as reforestation, plantation establishment, early competition control, thinning and selection harvesting may enhance a forest's ability to sequester carbon.

Part of Canada's action plan to reduce national GHG emission levels includes a potential offset from the forestry sector. Enhanced carbon sinks through FM activities can be put towards carbon credits which Canada can use to counter balance possible net sources of GHG from land-use changes and emissions from other sectors. Canada would like to increase the potential of its forest carbon sinks; however, part of the challenge in utilizing FM activities in order to receive GHG credits is to quantify Canadian forests as potential carbon sinks. Measurement tools and inventories will be required to verify potential carbon sequestration in order to receive credit.

Currently in Canada, research is underway to develop tools and methods to model and monitor carbon stocks and fluxes. Computer models, such as the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS 3), are presently being developed in order that scientists and forest managers will be able to predict and measure changes in carbon stocks (at the stand and landscape level due to natural processes and forest management activities (Kurz et al. 2002)). In order for models, such as the CBM-CFS 3, to accurately predict carbon stocks and fluxes and to be scientifically credible they must not only be based upon the best available forest inventory and scientific data, but they must also be validated and calibrated to some extent against actual field data.

Over the past four years, silviculture activity has increased significantly in Nova Scotia due to more intensive forest management on privately owned lands. Currently, roughly 70% of the forest land base is privately owned in Nova Scotia (NSDNR 2003). The 1999 Wood Supply Forecast for Nova Scotia (1996-2070) confirmed that existing harvest levels on small private woodlots were not sustainable with the then current levels of silviculture practised on these lands (NSDNR 2003). The Nova Scotia Department of Natural Resources therefore developed a new Forest Sustainability Regulations program which uses a system of silviculture credits. According to these regulations, Registered Buyers of wood products annually utilizing greater than 5000 cubic meters of wood from private lands must annually complete a certain level of silviculture activity based on the wood that they have utilized. Due to the implementation of these new regulations, there has been a significant increase in silviculture activity taking place in the province.

Papadopol (2002) suggests increased silviculture activity may lead to increased productivity in forest ecosystems and, thus, enhanced carbon sequestration.

In the present day forestry practices in Nova Scotia, the forest managers' objective is not to store carbon *per se*, but it is usually to maximize the financial value of stands. Activities undertaken toward those ends may or may not increase carbon storage even if they are successful (Schroeder 1991). To better understand the effects of silviculture activities on forest ecosystems, a sound understanding of the natural dynamics of carbon storage in those forests is required.

About 54% of Nova Scotia's forest cover consists of softwood forest type (NSDNR 2003). Red spruce is the province's most valuable lumber and pulpwood species and is the most common softwood after balsam fir (Saunders 1970); thus, red spruce forest form a major carbon pool among Nova Scotia forest ecosystems. There are few estimates of carbon storage in these forest, especially at the different stages of development.

Given the commercial importance and abundance of red spruce in Nova Scotia, understanding the carbon dynamics of red spruce stands and their associated stands is critical to estimate the carbon budgets of the areas which have been influenced through FM activities. Before a net carbon balance can be calculated from FM activities, which may or may not enhance carbon sequestration and storage in red spruce forests, a clear understanding of the carbon dynamics in natural red spruce stands with no silvicultural treatment must be obtained.

Little research has been done in Nova Scotia studying the effects of stand developmental stages on carbon pools in red spruce (*Picea rubens*) stands. Therefore, Chapter two will primarily focus on determining how carbon storage varies during the different stand developmental stages in natural red spruce dominated forests in central Nova Scotia.

To accomplish this, carbon stocks will be measured over a chronosequence of naturally regenerated even-aged red spruce stands in central Nova Scotia. Many studies have shown the importance of stand age on the size of carbon pools in the forest biomass and floor of forest ecosystems (Boone et al. 1998; Covington 1981, Wang et al. 2003 and Rothstein et al. 2004). Within this chronosequence, measurements of biomass, necromass, forest floor and mineral soil will be undertaken in order to determine the carbon stocks in each red spruce stand to be examined. This information will be used to determine potential changes in carbon stocks throughout the chronosequence. Recognizable patterns in carbon stocks will be fitted to mathematical growth functions in order to predict the changes in carbon pool sizes as the stand ages.

2.2 MATERIALS AND METHODS

2.2.1 STUDY AREA

The Eastern Eco-region (NSDNR 2003b) of the Atlantic Maritime ecozone (ESWG 1996) in lower central Nova Scotia (LCNS) (see Appendix I) is the main study area of this project. Nova Scotia lays halfway between the equator and the North Pole giving it a temperate climate, which is influenced heavily by the Atlantic Ocean. This results in high humidity and frequently fluctuating weather conditions. The predominant winds have, however, come from the west in Nova Scotia and, therefore, continental climate conditions also strongly influence Nova Scotia's overall climate (Anonymous 1992).

The Eastern Eco-region is the eastern extension of the Appalachian peneplain which slopes towards the Atlantic Ocean. It is boarded by the Atlantic Coastal Eco-region in the south and to the north by the St. Mary's Fault. The Eastern Eco-region is subdivided into five separate Eco-districts, each of which displays its own geophysical features.

Generally the highest points of elevation found in the Eastern Eco-region are 220m above sea level. The total area of this Eco-region is 6350 km^2 or 11.5% of the province. It is characterized by warmer summers and cooler winters with a mean winter temperature of -5.0 C. Average monthly temperatures in this area range from 22°C to 23°C in July and between -8°C to -12°C in January. The average annual number of frost free days ranges from 80 days in the interior to 160 days along the Atlantic coastal region (Environment Canada 1990). Total average annual precipitation in LCNS ranges from 1200 mm in the interior to 1400 mm along the Atlantic coastal region (Environment Canada 1990). Only about 15% of this precipitation on average accumulates as snow. The dominant natural disturbances in this area affecting forests are wildfires and hurricanes (NSDNR 2003b).

Within the Eastern Eco-region temporary sample plots were located in two out of the five Eco-districts that make up this region. These Eco-districts are the Rawdon\Wittenburg Hills Eco-district, and the Eastern Granite Uplands Eco-district. These two Eco-districts are generally located at the centre of the eastern mainland of Nova Scotia.

Rawdon\Wittenburg Hills Eco-district

The Rawdon\Wittenburg Hills Eco-district of the Eastern Eco-region is comprised of a total area of 576 km^2 or 9% of the Eastern Eco-region. This Eco-district is mainly characterized by two slate ridges which rise notably above the surrounding valleys of the Stewiacke, Musquodoboit and Shubenacadie rivers in central Nova Scotia. The sample plots in this Eco-district were primarily focused in the Wittenburg Hills area, which runs parallel with the Musquodoboit and Stewiacke river valleys. This ridge runs northeast and is comprised of folded Meguma Group slate (NSDNR 2003b). Sandy clay loams and clay loams occur on the sides of this ridge, while well drained soils of sandy loams and loams derived from shales and slates can be found on top of the ridge (NSDNR 2003b). Most areas examined along this ridge consisted of shallow poorly decomposed organic soils. Underlying this was found to be a shallow mineral soil layer strongly characterized by eluviations and a high concentration of coarse fragments which grades with depth into the underlying slate bedrock.

Along the Wittenburg Hills ridge red spruce (*Picea rubens* Sarg.) forests are very common. In this area, red spruce, black spruce (*Picea mariana* Mill.), balsam fir (*Abies balsamea* (L.) Mill.), red maple (*Acer rubrum* L.), eastern hemlock (*Tsuga canadensis* (L.) Carr.) and eastern white pine (*Pinus strobus* L.) form predominant associations. Sugar maple (*Acer saccharum* Marsh.), beech (*Fagus grandifolia* Ehrh.) and yellow birch (*Betula papyrifera* Marsh.) are also abundant. White spruce (*Picea glauca* (Moench) Voss), red spruce and balsam fir form mixedwoods with these hardwood species on upland flats, lower slopes and valleys (Loucks 1962).

Lesser woody vegetation and shrubs in these areas growing mostly in places of poor drainage and repeated disturbances include rhodora (*Rhododendron canadense* (L.) Torr.), speckled alder (*Alnus rugosa* Spreng.), mountain maple (*Acer spicatum* Lam.), wintergreen (*Gaultheria procumbens* L.) and mountain-holly (*Nemopanthus mucronata* Raf.). Some common herbs and mosses in this eco-region include gold-thread (*Coptis groenlandica* Fern.), naked miterwort (*Mitella nuda* L.), bunch berry (*Cornus canadensis* L.), bristly clubmoss (*Lycopodium annotinum* L.), sphagnum moss (*Sphagnum* Dill. (Spp.)), and wood fern (*Dryopterus spinulosa* (O.F. Muell.) Watt.).

Eastern Granite Uplands Eco-district

The Eastern Granite Uplands Eco-district of the Eastern Eco-region is comprised of a total area of 602 km^2 or 9.5% of the Eco-region. This Eco-district is a narrow stretching ridge (80 km long by 8-10 km wide) running from Waverly to Sheet Harbor and north of the coastal Eastern Shore Eco-district (NSDNR 2003b). This Eco-district can be described as rough and rugged, characterized by steep cliffs of granite, dissecting narrow river gorges, such as the Musquodoboit, and an abundance of lakes (approximately 11.1% coverage). Also of notice are the long narrow lakes that dissect the Eco-district, such as Lake Charlotte, and Porters Lake (NSDNR 2003b).

The Eastern Granite Uplands Eco-district, as the name suggest, is underlined by granite with bare exposed granite outcrops being very common, as much as 15% of the total area. Also common are large house-size boulders of granite dotting the landscape. Due to its erosion resistant granite bedrock most of the soils in this area are coarse textured and shallow. In many of the sites studied in this area the soil is best described as a thin organic layer lying over granite bedrock or a very shallow (0.20 m) mineral soil.

As commonly found in the Rawdon\Wittenburg Hills Eco-district the mineral soils examined in the Eastern Granite Uplands Eco-district were characterized by an eluviated A horizon.

Softwood stands predominate in this area with red spruce stands on the better drained soils. Both red spruce and black spruce seem to thrive on these shallow soils with black spruce dominating in lower lying poor drained areas. Other softwood species present include eastern white pine, and red pine (*Pinus resinosa* Ait.) and stands of hemlock on steep side slopes of hills and hummocks next to rivers and streams (NSDNR 2003b). Tolerant hardwood species are less common, found on the few scattered drumlins in the area. However, it can be noted that after clear-cut harvesting pioneer species such as white birch and red maple are commonly found, usually proceeding an underlying blanket of regenerating spruce seedlings.

2.2.2 SAMPLING DESIGN

This study used a factorial sample regime, where even-aged red spruce dominated softwood stands (roughly 50% red spruce or greater) were sampled from seven different chronological stages of development. These developmental stages were based on the age-class structure used by the Nova Scotia Forest Inventory Report (NSDNR 2000b). Stands were sampled from two different Eco-districts within the Eastern Eco-region (NSDNR 2003b) (see Table 2.1). Although two separate Eco-districts were sampled, data collected from stands within each Eco-district were merged in order to represent the larger Eastern Eco-region of Nova Scotia.

In each age class, a red spruce dominated stand, which had been naturally regenerated, was measured for carbon storage. To the degree possible, site quality was controlled in the site selection process to ensure selected stands were as characteristically similar as possible. At least two replicate stands were selected to represent each age class in both Eco-districts. In some cases more than two stands were located and analyzed, while in others less than two sample stands were located. Table 2.1 shows the number of stands and plots established for each Eco-district and age class.

In each selected sample stand, one or two 20 m x 20 m replicate sample plots were established depending on the size and the within-stand variability of the sample stand. Each sample plot location was chosen based on an area, which most closely represented the overall condition of that particular sample stand.

Table 2.1 The number of stands and plots established for each Eco-district and age class of the Eastern Eco-region.

Eco-district	Age Class	Number of stands sampled	Number of plots established
Rawdon/Wittenburg Hills	1-20 years	4	4
	21-40 years	2	2
	41-60 years	3	3
	61-80 years	2	2
	81-100 years	1	2
	101-120 years	1	2
	121-140 years	0	0
Eastern Granite Uplands	1-20 years	4	4
	21-40 years	1	1
	41-60 years	1	1
	61-80 years	1	1
	81-100 years	0	0
	101-120 years	1	1
	121-140 years	1	1

2.2.3 COMPARISON BETWEEN DEVELOPMENTAL STAGES

This study attempted to compare even-aged red spruce dominated softwood stands that had been naturally regenerated after harvest from seven separate age classes of stand development. As much control as possible was undertaken to select softwood stands of red spruce that have been naturally regenerated with a history of no silviculture activity. When selecting sample stands to compare between developmental stages, site quality, pre-harvest forest type, site index, stand age and other biogeophysical factors were taken into consideration and controlled to the degree possible to ensure that sites being compared were as similar as possible with respect to these variables.

In stands less than 75 years old, the harvest history was mostly known, with most being the result of clear-cut harvesting. However, for a few of these stands and the majority of the older stands, greater than 75 years old (especially the 100+ year old stands) the harvest history is unclear. Most of these older stands are likely the result of stand replacing natural disturbances common to this eco-region, most likely windthrow.

2.2.4 FIELD MEASURMENTS AND DATA COLLECTION

To account fully for the impact of forest practices on carbon storage in a forest ecosystem, it is necessary to assess all relevant carbon pools. These carbon pools include the total above and belowground vegetation biomass, and aboveground and soil dead organic matter. In each sample stand, a 20 m x 20 m plot was established to measure these carbon pools.

In a forest ecosystem, the major carbon pools are in vegetation and soils. Most of the carbon (excluding soil organic carbon) in forest ecosystems is contained in tree stems, branches and foliage, and in surface detritus, with smaller carbon pools in understory shrubs and herbs. To estimate the total carbon storage in each sample stand, the following features were measured and examined in each plot:

1) Above and below ground tree biomass
2) Seedlings and saplings
3) Above ground biomass of shrubs and herbs
4) Standing dead trees and snags
5) Downed woody debris
6) Forest floor and mineral soil

Above and Below Ground Tree Biomass

In each 20 m x 20 m sample plot, the DBH (diameter at 1.3 m height) of all stems > 2.0 cm was measured to the nearest tenth of a centimeter using a DBH measuring tape. The heights of at least three red spruce trees (dominant and co-dominant) present in the sample plot were measured in meters using a Suunto clinometer. The DBH measurements were than used to calculate the fresh and oven-dried total aboveground biomass of these trees along with the biomass of their bole, branches and foliage components. This was accomplished using allometric tree biomass equations developed by Ker (1984) for major Maritime tree species. Tree carbon content was calculated assuming a carbon concentration of 50% of oven-dry biomass (Kurz et al. 1992).

Belowground tree biomass was estimated for those trees with a DBH > 2.0 cm. It was estimated using regression equations used to extrapolate aboveground biomass to whole-tree biomass from Li et al. (2003a). Two separate regression equations were used which estimated the belowground biomass of all softwood species (see Equation 2.1) and the belowground biomass of all hardwood species (see Equation 2.2).

$$RB_S = 0.222AB_S \tag{2.1}$$

$$RB_H = 1.576AB_H^{0.615} \tag{2.2}$$

where: RB = Root biomass of softwood (S) and hardwood (H)
AB = Aboveground biomass

Seedling and Sapling Biomass

The biomass of tree seedlings (height <1.3 m) and saplings (DBH <2.0 cm) was estimated in five randomly located 1 m^2 sub-plots. Seedlings and saplings were identified and counted in each sub-plot. Each seedling and sapling was then excavated from the soil in each sub-plot to gather all roots possible. The samples for each plot were first weighed fresh, than a smaller sub-sample was collected from each plot sample for weighing and then oven-drying. The sub-samples were than cut up for oven-drying and dried at 70 °C for 48 hours to determine oven-dried biomass. The oven-dry biomass for the total seedlings and saplings for each plot was then calculated by scaling-up using the appropriate expansion factor from the oven-dried sub-sample measurements.

Aboveground Biomass of Shrubs and Herbs

In each of the five randomly located 1 m^2 sub-plots all shrubs and herbs present were identified and their percent cover was estimated. The above ground biomass of all the shrubs and herbs was clipped from each of the five randomly located 1 m^2 sub-plots. The shrubs were separated from the herbs and each group was weighed fresh. Larger samples had sub-samples collected from them, while smaller samples were not sub-sampled. These samples and sub-samples were then oven-dried at 70 °C for 48 hours to determine oven-dried biomass. These samples were then scaled up using the appropriate expansion factor in order to estimate the oven-dry biomass of shrubs and herbs for the entire 20 m x 20 m plot. Carbon content was assumed to be 50% of the oven-dried biomass of shrubs and herbs.

Standing Dead Trees and Snags

All trees in each 20 m x 20 m plot (DBH >2.0 cm at 1.3 m height), which had recently died and appeared to still retain most of their branches (>75%) but no foliage were identified and measured for DBH and height. DBH values were then used to estimate the total oven-dry biomass of the tree minus the foliage and 12.5% of the branch biomass component. These calculations were based on the tree biomass equations for major Maritime tree species by Ker (1984). Trees that had died and appeared to have lost more than 75% of their branches, but not less than 50% were identified and measured for DBH and height. DBH values were used to estimate the total oven-dry biomass of the tree minus the foliage and 37.5% of the branches.

For this project snags were identified as dead trees missing their tops and that were leaned over no more than 45° degrees. All snags contained in the plot were measured for base diameter and height. They were also divided into three separate decay class groups. Base diameter and height measurements were used in order to calculate bole volume using a paraboloid function described by Husch et al. (2003) (see Equation 2.3). Smalian's formula was considered in order to estimate snag volume, however, a top end diameter would have been needed, which was not measured.

$$V = \frac{1}{2}(A \times H) \qquad (2.3)$$

where: V = volume

A = base diameter
H = height

Several snags representing three different wood decomposition classes were selected to be felled and had a disk cut from them. Decaying wood was stratified into one of three decay classes based on Davis et al. (2003): (I) wood hard but not stained, visible rings, bark intact; (II) wood hard but stained, rings indistinguishable bark sloughed off; (III) advanced wood decay with loss of original form, wood friable. The volume and mass of each disk was calculated after they had been oven-dried (70 °C for 48 hours). Volume was calculated using water displacement. Volume and mass measurements were used to calculate an average wood density value for each decay class. These density values were then used to calculate the oven-dried biomass of each snag from the determined bole volume.

Downed Woody Debris

Downed woody debris (DWD) was defined as all dead pieces of wood lying on the forest floor with a large end diameter greater than or equal to two centimeters. It also included those snags leaned more than 45° degrees. DWD was measured using Line Intersect Sampling as described by Husch et al. (2003). This method involved extending a line (20 m long line was used) across the plot, than traversing the line, maintaining the initial direction and recording the diameters (cm) of every piece of DWD that intersected the line. Diameters were measured at the point where the line crossed the piece. Each piece that was measured was stratified into one of the three established decay classes. The total number of diameter measurements for each decay class was recorded and Equation 2.4 from Husch et al. (2003) was used to calculate the total volume of DWD for each decay class per hectare. The total volume of each decay class was than converted into dry weight from the specific weight of the decay classes.

$$\hat{T}/ha = \frac{1.2337}{L}\sum_{i=1}^{n} d_i^2 \qquad (2.4)$$

where: $\hat{T}/ha$ = cubic meters of DWD per hectare
d_i = diameter of ith element (cm)
L = transect length (m)

Forest Floor and Mineral Soil

Soil samples were collected from 3-5 randomly selected points in each 20 m x 20 m plot, depending on the homogeneity of the forest floor. At each point, a soil pit 25 cm x 25 cm was dug to sample the forest floor litter layer (L-layer), moss layer (M-layer), fermentation and humus horizons (F and H layers).

Each layer of forest floor sampled in each soil plot was separated and collected into plastic bags. These layers were then weighed fresh. All the layer samples collected were oven-dried at 70 °C for 48 hours. L and M-layer carbon mass was assumed to be 50% of dry weight (Davis et al. 2003). FH-layer samples were ground with a mortar and Pestle than sieved through a 2 mm sieve to remove rocks and coarse roots. Small sub-samples of the ground and sieved FH-layer samples were then analysed by a LECO analyser (Lakehead University Lab) in order to determine carbon content.

The carbon content for each layer in each plot was summed together. The carbon values attained for each 25 x 25 cm plot were then summed together for each 20 x 20 m plot and scaled up in order to estimate the total forest floor litter and organic soil carbon mass per ha.

In the majority of the sites sampled in both Eco-districts the mineral soil layer was shallow and contained a high percentage of coarse fragments. Therefore only the upper 10 cm of the mineral soil layer were sampled. Mineral soil samples were only sampled and measured from four of the 20 m x 20 m sample plots, which ranged across the age classes sampled. Mineral soil samples were collected at the same randomly selected points in each 20 m x 20 m plot as the forest floor and organic soil layers, depending on the homogeneity of the forest floor. At each point, the organic layers were removed first and then the top 10 cm of mineral soil were excavated.

The mineral soil samples were first weighed fresh, and then had a sub-sample removed. This sub-sample was weighed fresh than oven dried at 70 °C for 48 hours. The bulk density was then calculated. These samples were then ground with a mortar and pestle then sieved through a 6 mm sieve to remove rocks and coarse roots. These samples were then sieved through a 2 mm sieve in order to be analyzed for carbon content by a LECO analyser (Lakehead University Lab). Carbon mass was then estimated for the volume and total weight of mineral soil layer sampled using a calculated average bulk density value of 0.8 g/cm^3 and average carbon content of 6.43 %. Carbon mass was then scaled up in order to determine the average mineral soil carbon mass per ha. This average value (51.44 Mg C ha^{-1}) was used to describe the top 10 cm of mineral soil carbon in all the stands sampled.

2.2.5 DATA ANALYSIS

The calculated carbon masses determined for each carbon pool in each stand were converted to megagrams (Mg) per ha. In order to recognize any changes in the carbon mass of each carbon pool during the different developmental stages, the mean carbon mass was calculated for each developmental stage for each carbon pool measured. The mean carbon mass for total site carbon was also calculated for each developmental stage.

These data were also plotted for each carbon pool separately against the age of the sample stand. This made it possible to visually observe any trends in carbon mass over time. Potential trends recognized in the data were attempted to be modeled using regression analysis.

Only the tree, seedling and sapling, shrub and herb, and standing dead tree and snag carbon pools showed noticeable trends and were modeled using non-linear regression. All non-linear model fitting was carried out using SYSTAT software (SYSTAT Version 10). The following is a description of the models chosen to represent each carbon pool:

1) Tree data were modeled using the Chapman-Richards function (see Equation 2.5). The Chapman-Richards model has been shown to be very flexible and has been used extensively in growth and yield studies in forestry describing height-age, diameter-age, basal area-age and volume-age relationships (Wang and Kimmins 2002).

$$C = a[1-\exp(-bT)]^c \tag{2.5}$$

where C is carbon mass, T the age of the stand, and a, b and c are the parameters.

2) Seedling and sapling, and shrub and herb carbon pool data were fitted to a four-parameter model having a single minimum, a single inflection point, and an asymptote:

$$C = (a+bT)c^T + d*T \tag{2.6}$$

where C is carbon mass, T the age of the stand and a, b, c, and d are constant coefficients; however, the function $d*T$ was added to a standard growth model (Ratkowsky 1990) to create a better fit to the data.

3) Standing dead tree and snag carbon pool data were fitted to an extended version of the Freundlich model (Ratkowsky 1990), namely:

$$C = aT^{bT^{-c}} \tag{2.7}$$

where C is carbon mass, T the age of the stand and a, b, and c are the constant coefficients.

In order to estimate the total site carbon per hectare the calculated carbon masses estimated for each carbon pool were summed together for each sample stand. These estimates were plotted against stand age in order to create an observed total stand carbon mass per hectare over a chronosequence of red spruce dominated stands. A non-linear regression model was fitted to total site carbon. A logistic model was choosen that best fit the sigmoidel response of total site carbon mass over time. This simple logistic model was extended to four-parameters using a model from Ratkowsky (1990) to allow for a nonzero asymptote as shown below:

$$C = a + \frac{b}{\left(1 + \exp\left(c - dT\right)\right)} \tag{2.8}$$

where C is carbon mass, T the age of the stand and a, b, c, and d are the parameters.

2.3 RESULTS

Carbon Storage Over Stand Age

Some of the carbon pools showed noticeable trends over time, such as the tree, seedling and sapling, shrub and herb, and standing dead tree and snag carbon pools. Others, however, such as the forest floor and mineral soil, and downed woody debris carbon pools did not (Figure 2.1). A single outliner was identified from the measured carbon pool data (108-year old stand). This outliner is particularly apparent from Figures 2.1a and e. This site had an unusually high concentration of herbs, namely ferns, and the lowest site index value observed from the stands sampled. It was therefore decided it would be omitted from the non-linear regression analysis for the tree carbon, shrub and herb carbon pools and total site carbon.

In Figure 2.1a, tree carbon mass increases with time following a general sigmoidel response. Carbon begins to accumulate rapidly from less then 20 years of age until roughly around 50-70 years of age. After this point, tree carbon mass begins to level off. Due to this sigmoidal response the Chapman-Richards function (Equation 2.5) was used to fit an average carbon mass curve to the measured tree carbon data (Figure 2.2a). Results for the final fit of the tree carbon mass curve can be found in Table 2.2. Asymptotic standard error, 95% confidence interval, and R^2 values are presented.

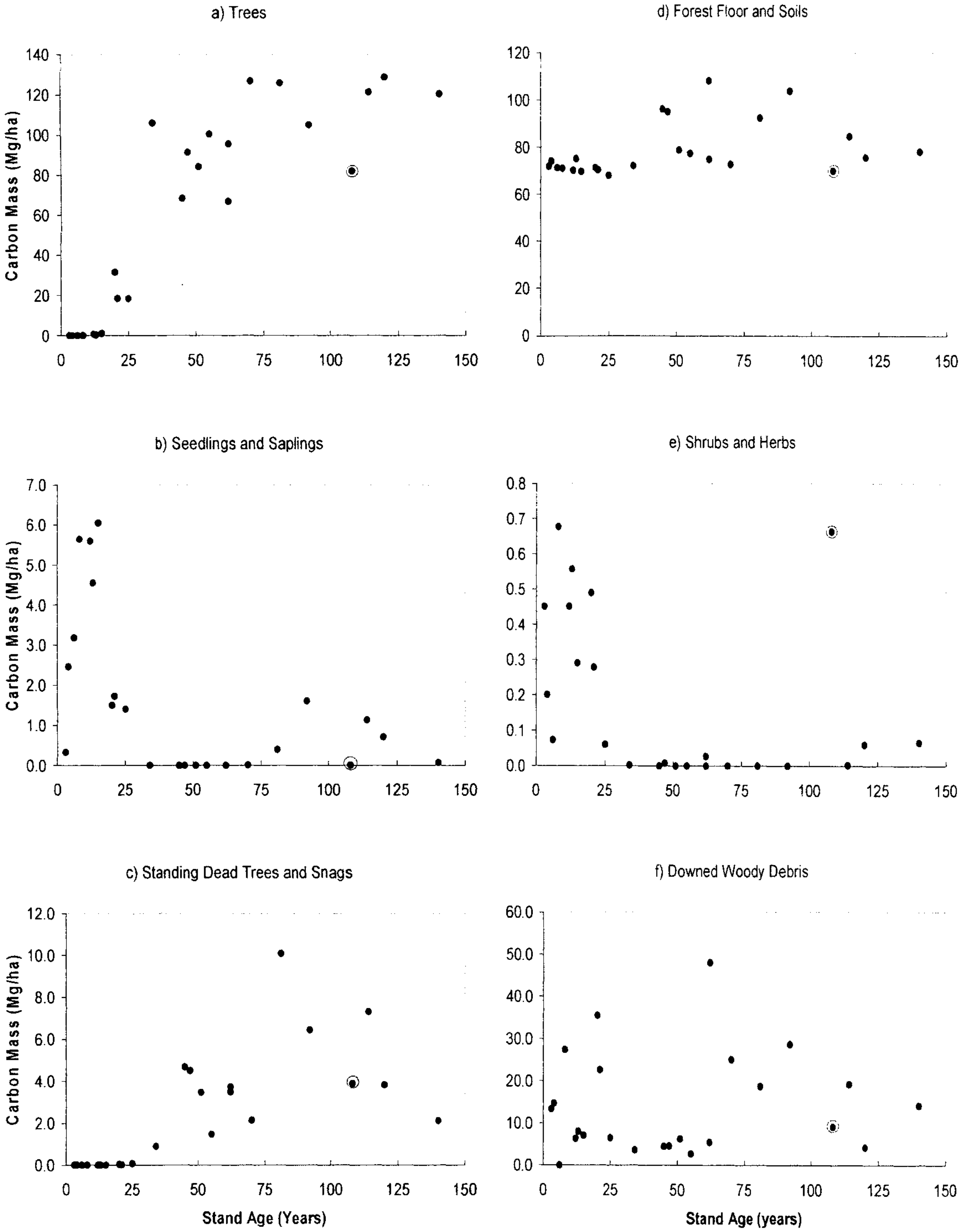


Figure 2.1 The mass of each carbon pool over a chronosequence of red spruce dominated stands. The outliner value identified from the 108-year old stand is highlighted by a red circle.

Both the seedling and sapling, and shrub and herb carbon pools display a similar trend in carbon mass over time (Figure 2.1b and e). In both pools carbon mass reaches a maximum value within the first 25 years of stand age. There is then a rapid decrease in carbon mass which reaches a minimum in both pools between 25 and 50 years of stand age. From this point in time until the oldest stages of stand development carbon mass appears to slightly increase. As a result of these trends a non-linear four-parameter model having a single minimum, a single inflection point, and an asymptote (Equation 2.6) was fitted to these data to best describe the observed relationship between carbon mass and stand age (Figure 2.2b and e).

A general trend in carbon mass can be observed in standing dead tree and snag carbon mass (Figure 2.1c). Carbon mass appears to increase significantly around 25 years of age until it peaks between the ages of 75 and 100 years. After this peak, carbon mass begins to decrease. In order to facilitate this relationship a non-linear regression model known as an extended version of the Freundlich model (Equation 2.7) was chosen to be fitted to this data (Figure 2.2d).

Forest floor and soil carbon (Figure 2.1d) (that included the average mineral soil carbon value of 51.44 Mg C ha^{-1}), was found to be roughly constant over time, while no trend in downed wood debris carbon (Figure 2.1f) could be recognized from visual inspection. Therefore these carbon pools were not fitted to any model.

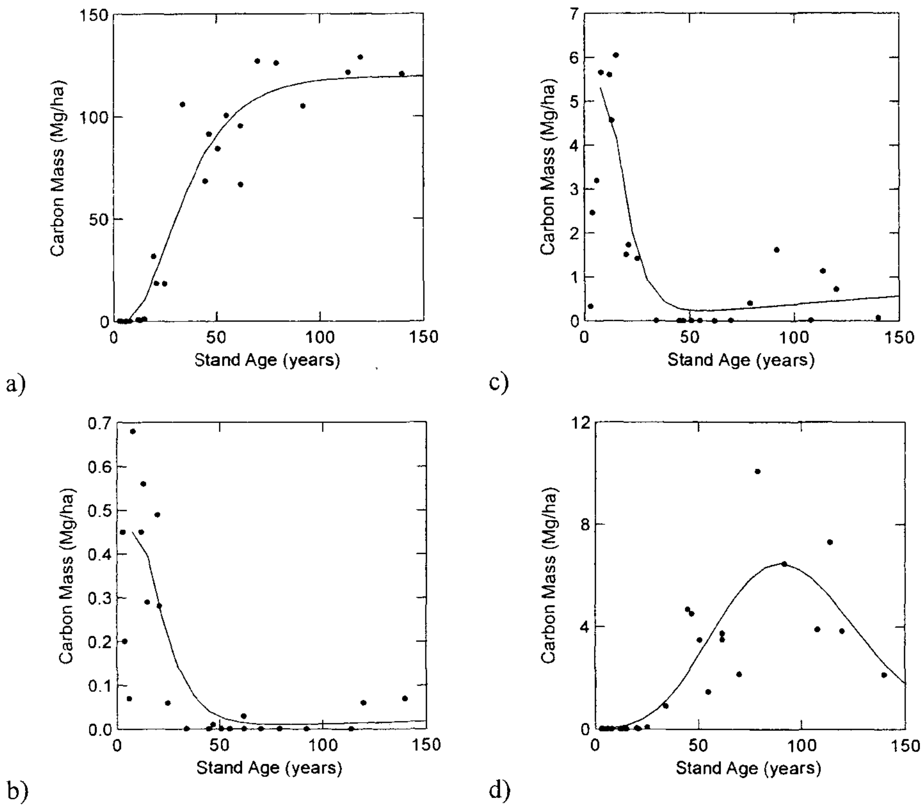


Figure 2.2 Carbon mass versus age and the fitted curves for a) Trees, b) Shrubs and Herbs, c) Seedlings and Saplings, and d) Standing dead trees and snags.

Table 2.2 Fitting statistics for each of the modeled carbon pools (A) Above and below ground tree carbon, (B) Seedling and sapling carbon, (C) Shrub and herb carbon, (D) Standing dead trees and snag carbon, and (E) Total site carbon.

Carbon Pool[a]	Parameter	Estimate	ASE[b]	Lower[c]	Upper	Raw R^2	Mean corrected R^2
A	a	119.757	8.395	102.244	137.270	0.964	0.912
	b	0.054	0.016	0.021	0.087		
	c	4.092	2.031	-0.146	8.329		
B	a	-11.803	3.212	-18.503	-5.103	0.926	0.882
	b	3.977	0.835	2.234	5.719		
	c	0.849	0.013	0.822	0.876		
	d	0.004	0.002	-0.001	0.009		
C	a	-0.132	358.155	-877.328	621.926	0.801	0.687
	b	0.163	92.600	-31.604	356.024		
	c	0.889	0.027	0.833	0.945		
	d	0.000	0.466	-0.858	1.092		
D	a	1.531	0.215	1.085	1.977	0.840	0.713
	b	-0.077	0.026	-0.131	-0.024		
	c	-0.006	0.013	-0.033	0.021		
E	a	63.017	31.873	-3.695	129.728	0.989	0.911
	b	167.534	36.858	90.390	244.678		
	c	2.254	1.239	-0.341	4.848		
	d	0.068	0.025	0.016	0.120		

[a] The sample sizes (n) for A, B, C, D, and E are 23, 24, 24, 24, and 23.
[b] Asymptotic standard error.
[c] 95% confidence interval

There is a sigmoidel relationship between total site carbon mass data and stand age (Figure 2.3). Site carbon is the lowest in the youngest aged stands, and then begins to increase rapidly until between the ages of 76–100 years old. The rate of carbon accumulation then begins to slow down. A four-parameter logistic growth model (Equation 2.8) was fitted to the data to describe carbon accumulation (Figure 2.3). The R^2 value for this curve is 0.989, indicating good agreement between the stand age and carbon mass. Results for the final fit of this curve can be found in Table 2.2.

In order to detect model inadequacies residual analyses based on the preliminary non-linear least-squares fit were performed. Figure 2.4a shows the plot of the residuals against stand age. The plot demonstrates a homogenous band centered on zero, indicating the total site carbon model was appropriately identified and fitted. Figure 2.4b shows how the estimated total site carbon values compare with the measured total site carbon values. The 1:1 ratio line in Figure 2.4b represents a perfect fit.

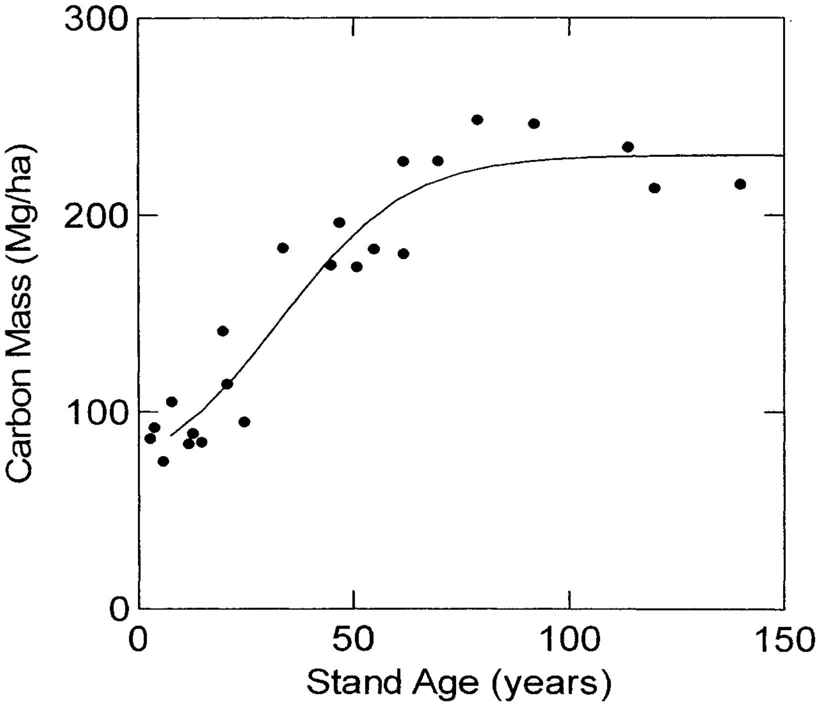


Figure 2.3 Total site carbon data and the best fitted curve versus stand age.

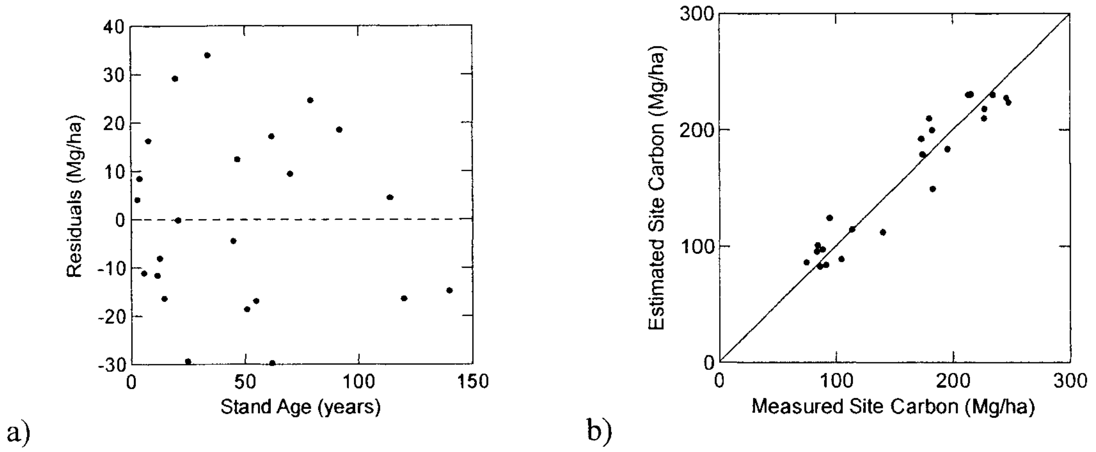


Figure 2.4 a) A plot of the residuals against stand age, and b) the relationship between estimated carbon mass and measured carbon mass for each of the sample plots.

Carbon Storage Along Stand Developmental Age Classes

In the previous section carbon pool field data results are plotted over actual stand age for each sampled plot. In practise however, Nova Scotia Forest inventory data are grouped into 20-year age classes. In order to better compare this data with NS forestry inventory data the raw field data were grouped into age classes to create mean 20-year age class values for each of the carbon pools.

Figure 2.5a demonstrates a general increase in above and belowground tree carbon mass over time. It increases from a minimum of 4.25 Mg C ha^{-1} in the youngest age class to a maximum of 120.58 Mg C ha^{-1} in the 121-140 year age class.

Seedling and sapling carbon mass peaks in the 1-20 year age class at 3.67 Mg C ha^{-1} (Figure 2.5b). It then drops to zero carbon mass in the 41-60, and 61-80 years age classes. Seedling and sapling carbon mass begins to accumulate again in the 81-100, and 100+ year age classes.

Standing dead tree and snag carbon mass begins to accumulate during the 21-40 year age class (Figure 2.5c). Carbon mass then increases to a maximum of 8.27 Mg C ha^{-1} in the 81-100 year old age class. It then begins to decrease during the last two age classes.

No noticeable trend in forest floor litter and mineral soil carbon mass over time is apparent from visual inspection of Figure 2.5d. Carbon mass is the lowest in the 21-40 year age class at 71.97 Mg C ha^{-1}, and highest in the 81-100 year age class at 98.44 Mg C ha^{-1} .

Shrub and Herb carbon mass is the smallest carbon pool component showing a maximum carbon mass at 0.40 Mg C ha^{-1} within the 1-20 year age class (Figure 2.5e). After this it falls to zero carbon mass in the 41-60 year age class then increases to 0.24 Mg C ha^{-1} in the 101-120 year age class. Carbon mass then falls slightly in the oldest age class.

The downed woody debris carbon pool (Figure 2.5f) begins with 14.08 Mg C ha^{-1} in the first age class. It then decreased until the 41-60 year age class. Then a significant increase in downed woody debris carbon mass is observed in the 61-80 year age class with a maximum carbon mass of 26.23 Mg C ha^{-1}. Carbon mass then begins to decrease.

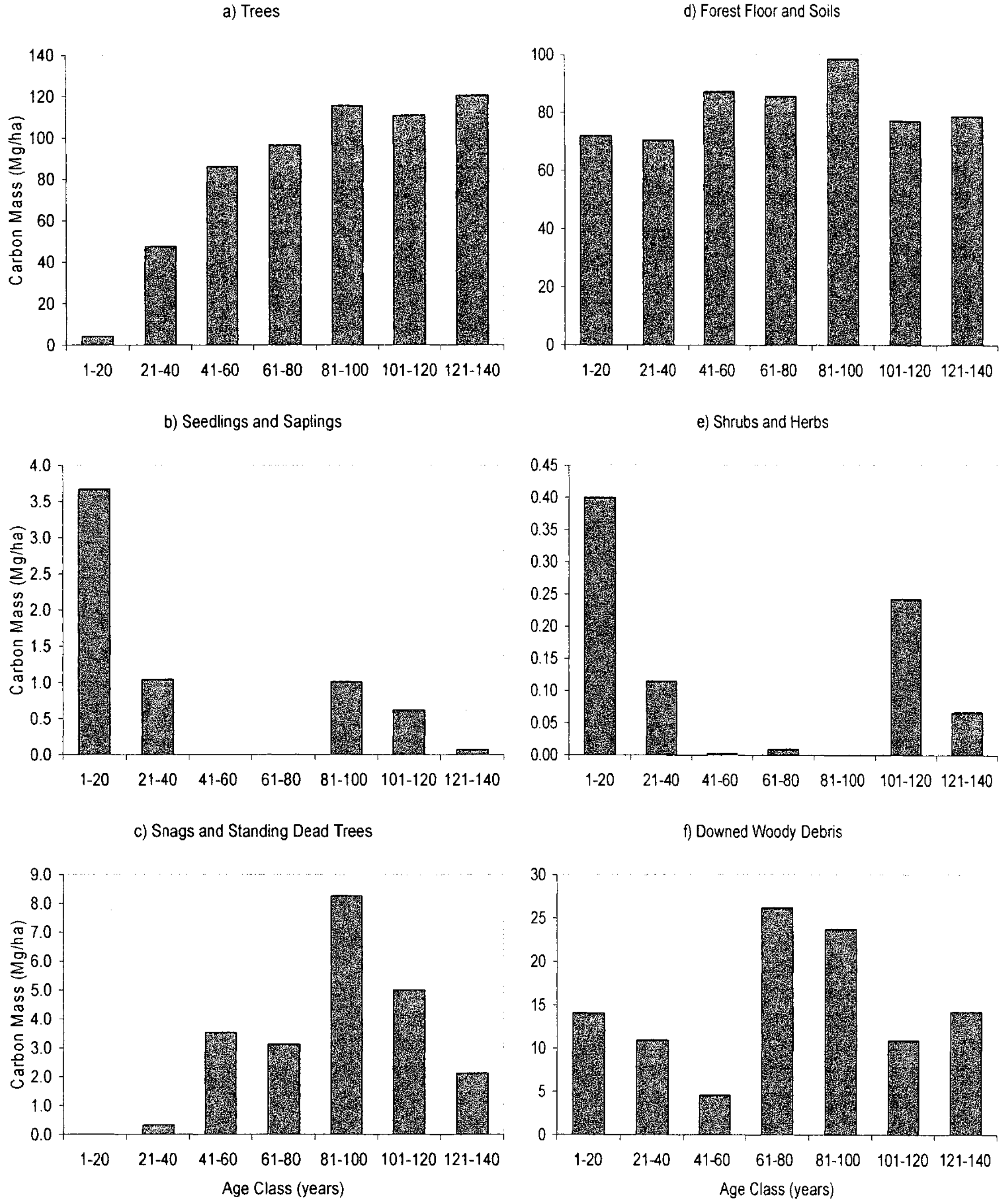


Figure 2.5 Influence of stand age class on carbon storage for each carbon pool.

An increase in total site carbon mass from 94.37 Mg C ha^{-1} in the youngest age class to 247.04 Mg C ha^{-1} in the 81-100 year age class can be observed in Figure 2.6. It then decreases to 215.60 Mg C ha^{-1} in the 121-140 year age class.

In the 1-20 year age class (Figure 2.6) forest floor and mineral soil carbon makes up the largest portion of total site carbon mass, followed by downed woody debris, tree, and seedling and sapling carbon, respectively. For the 21-40 year age class, forest floor and mineral soil carbon again makes up the largest proportion of carbon mass, followed by tree, and downed woody debris carbon. For the remaining age classes tree carbon makes up the largest proportion of site carbon, then forest floor and mineral soil, and downed woody debris carbon.

The smallest and least significant carbon pool in terms of its influence on total site carbon mass is the shrub and herb layer. Due to its small size within each age class (less than 0.5 Mg C ha^{-1}) it is not readily visible by visual inspection of Figure 2.6.

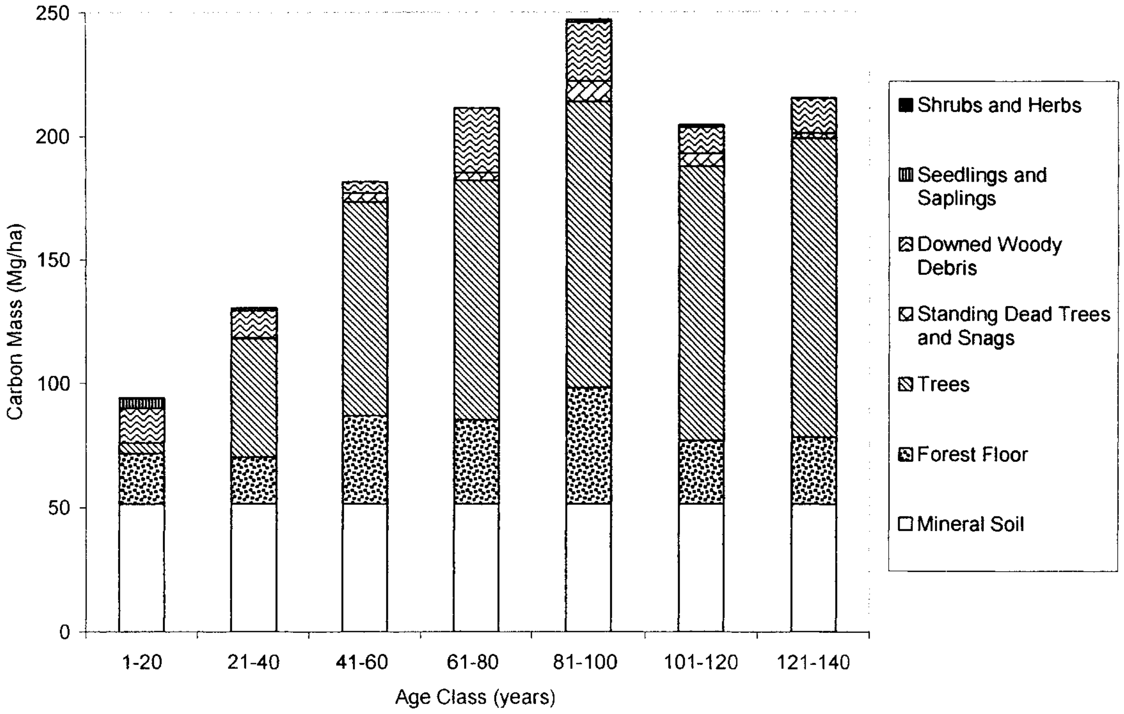


Figure 2.6 Total site carbon storage for each age class and the proportion of each carbon pool.

2.4 DISCUSSION

This chapter focused on examining the storage and changes in carbon storage along a chronosequence of red spruce dominated forest stands in the Eastern Eco-region of Nova Scotia. The results indicate that overall carbon storage increases as stands develop, demonstrating a sigmoidal growth pattern. Some of the individual carbon pools within the observed stands also displayed recognizable patterns in carbon accumulation.

Above and Below Ground Tree Carbon Mass

Results from the measurements of total above and belowground tree carbon mass indicate a general increase in carbon mass as stand age increases. This is illustrated in Figures 2.1a and 2.5a. Above and belowground tree carbon mass is at its minimum within the 1-20 year age class at 4.25 Mg C ha^{-1} and at its maximum within the 121-140 year age class at 120.58 Mg C ha^{-1}. The aboveground tree biomass values of red spruce stands from this study are within agreement with biomass values obtained by Freedman et al. (1982) who measured aboveground biomass in red spruce dominated stands in central Nova Scotia.

The observed trend in Figures 2.1a and 2.5a can be described as sigmoidal in nature and is commonly found in plant growth studies (Hunt 1982). In an asymptotic function, the form of its progression is controlled by one main characteristic feature: the value of the dependent variant gradually ascends (or descends) to a plateau which it never quite meets. This is seen within the range of the observed data. This classic sigmoidal pattern was also observed in live vegetation carbon pools over a chronosequence of jack pine stands in Michigan (Rothstein et al. 2004). Mund et al. (2002) also found a similar trend in tree carbon storage over a chronosequence of spruce forest in central Europe. Wang et al. (2003) found similar growth trends in tree biomass in studies done on post fire succession in black spruce stands in the boreal forest of central Canada.

To facilitate this growth form, a model derived by Richards (1959) based on von Bertalanffy's quantitative laws about organisms, which is commonly known as the Chapman-Richards function in forestry, was chosen. Figure 2.2a shows the plotted above and belowground tree carbon data versus stand age with the fitted model. Only one outliner data point was recognised and removed in order to achieve a better model fit. This outliner was a 108 year old stand within the Rawdon/Wittenburg Hills Eco-district. This site displayed the lowest site index of all the stands sampled and therefore was omitted from the tree carbon data.

The model of tree carbon mass shows a sigmoidal increase in carbon mass as stand age increases. This shape is related to the productivity of the forest stand over time. According to Ryan et al. 1997, Fujimori (2001), and Binkley (2004), it is a general pattern for a young forest to display a rapid increase in net production until a certain age, then gradually decrease in productivity. Net primary productivity (NPP) usually peaks within the stem exclusion stage of stand development then begins to decrease as the stand reaches maturity (Ryan et al. 1997 and Smith et al. 1997). Several studies on black spruce in Canada have shown that tree NPP peaks around a stand age of 40 years (Chen et al. 2003, and Lamberty et al. 2004). Binkley (2004) found that Douglas-fir stands in the Coastal Range of Oregon displayed a peak rate in stem increment near age 25-30 years followed by a rapid decline. This complies with Figure 2.1a and 2.5a where the greatest change in carbon accumulation is found within the 21-40 and 41-60 year age classes.

After this stage carbon accumulation begins to slow. Chen et al. 2002 attributes this slowing to decreases in biomass growth in woody components (i.e. stems, branches, and coarse roots). Binkley (2004) suggest that changes in stand growth arise from a host of interacting processes, including: "the supply and use of resources (light, water and nitrogen), competition for resources, and differences in the efficiency of trees using resources to grow". Binkley (2004) proposes that decline in stand-level wood growth that commonly occurs after canopy closure is influenced strongly by increasing dominance of larger trees leading to declining efficiency of resource use by smaller trees.

Seedling and Sapling Carbon Mass

Seedling and sapling carbon mass is described in Figures 2.1b and 2.5b. It is rated highest within the first age class of stand development at 3.67 Mg C ha^{-1} after clear-cut harvesting. It then decreases significantly to 1.05 Mg C ha^{-1} in the 21-40 age class and then to zero in the 41-60 age class. In the 81-100 year age class, carbon mass increases to 1.01 Mg C ha^{-1}. This trend in seedling and sapling carbon mass over stand age agrees with carbon stock measurements by Davis et al. (2003) in *Nothofagus* stands in New Zealand. It also closely coincides with the stages of stand development described by Oliver (1981). The first 0-20 year age class represents the initial stage of stand development and is often referred to as the stand initiation stage (Smith et al. 1997). During this stage of stand development, a disturbance, such as clear-cutting in this study, has created a unit of vacant growing space where fast growing seedlings and saplings can become established or can allow pre-existing smaller trees to expand into it. During this stage there is also little competition for light and nutrients from larger trees and, thus, young tree seedlings and saplings flourish creating an area of high stem density. At some point, the above and belowground growing space is filled. Tree crowns become closed and intense competition between individuals begins. This leads into the stand exclusion stage (Smith et al. 1997), where competition for growing space causes the smaller less tolerant trees to die, this being represented by the 21-40 age class.

In the 81-100 year age class, the seedling and sapling carbon increases from zero to 1.01 Mg C ha^{-1}. This increase in the carbon pool might represent the understory re-initiation stage of stand development (Smith et al. 1997). This increase in seedling and sapling growth may be caused by openings within the stand crown created by trees lost due to natural disturbances such as pest or wind damage. These gaps allow for the establishment of new seedlings beneath the old stand. This finding agrees with Stewart et al. (2003) who examined stand structure in old growth forest in Nova Scotia. They state that generally forests between 100-150 years old are in a transition phase where the original overstory begins to slowly break up, promoting understory development and recruitment of new cohorts to the overstory.

It is also important to note that the seedling and sapling carbon pool measured those trees which had a DBH less then 2 cm, and/or were less then 1.5 m tall; therefore, in the first age class, much of the regenerating trees fit within these size limits. In the 21-40 year age class, many of the seedlings and saplings from the first age class had grown out of this size limit and would not be included within the seedling and sapling carbon pool; thus, this carbon pool would be smaller then in the 0-20 year age class.

To represent the changes in seedling and sapling carbon mass over stand age through modeling, the non-linear regression model described by Equation 2.6 was fitted to the field data. The curves produced by the model resemble the description of the seedling and sapling carbon pool over time as described by Figure 2.1b, with the larger carbon value appearing in the initial stand stages, then sharply dropping off. The model was fitted to the primary carbon data collected from each sample plot and, therefore, shows slight differences from the mean data values that were calculated for each age class in Figure 2.5b. In spite of this, the model appears to be biologically reasonable. The mean corrected-R^2 value is 0.882, however, the model is only suggested by this study to describe the relationship of seedling and sapling carbon mass over the development of red spruce stands. It was not examined in this study for further statistical significance.

Shrub and Herb Carbon Mass

The shrub and herb carbon pool followed a similar trend as the seedling and sapling carbon pool. Figures 2.1e and 2.5e show that carbon mass is the highest within the 1-20 year age class at 0.40 Mg C ha^{-1}. It then falls sharply to 0.11 Mg C ha^{-1} in the next age class. Shrub and herb carbon does not increase again until the 101-120 year age class. This pattern of shrub and herb carbon mass over time parallels with the preceding pattern of seedling and sapling development. The only exception was the data collected from the 108-year old stand in the Rawdon/Wittenburg Hill Eco-district. This site contained an above average concentration of fern vegetation that was not observed at all in any of the other sites over 20-years old. Therefore, this data value was omitted from the non-linear regression analysis for this carbon pool.

In the beginning of stand development, after the clear-cut disturbance, the abundance of light, nutrients and lack of competition from larger trees allows for the establishment of some pioneer shrubs and herbs, particularly species such as wild raspberry (*Rubus strigosus*), blackberry (*Rubus hispidus*) and blue berry (*Vaccinium* *angustifolium*). Once the seedlings and saplings begin to grow and to occupy more space in the disturbed area, increased competition for light makes survival hard for the shrubs and herbs of the understory. Undergrowth becomes scarce because illumination on the forest floor is very low. This trend has been observed by other forest chronosequence studies as well, such as Rothstein et al. (2004), where it was found that in jack pine stands disturbed by wildfire, herbaceous plants and shrubs dominated vegetation early in the chronosequence, but overstory trees began to account for more than 90% of live vegetation from year 14 onward. This situation was also reported by Ford and Newbould (1977) in oak forest in England. They found that ground vegetation biomass peaked two years following clear-cutting, then decreased with time as trees become re-established and cover increased.

In order to model this trend in shrub and herb carbon mass over stand age, the model used for the seedling and sapling carbon pool was applied (Equation 2.6). The trend line describes the relationship of carbon mass versus stand age; however, the increase in carbon mass that can be found in the 101-120 year age class that is observed in Figure 2.5e is not as dramatic within the model. The model shows a rapid decrease in shrub and herb carbon mass within the first 50 years of stand development. It then begins to gradually increase slightly over stand age within the observed range of data. The model seems to be biologically reasonable with regards to the changes in carbon mass over time. This model is merely suggested in this study as a potential model to describe the relationship between shrub and herb carbon mass in red spruce stands over the course of stand development.

Standing dead tree and Snag Carbon Mass

The standing dead tree and snag carbon pool included all standing dead organic matter that was leaning over no more than 45°. Included were all trees which appeared to have recently died and lost most of their foliage and branches. The change in carbon mass in this pool is shown in Figures 2.1c and 2.5c. In the first age class, there is relatively little carbon in this pool. It then begins to accumulate in the 21-40 year age class. Except for a small decrease in the 61-80 year age class, carbon mass increases until a maximum mean value of 8.27 Mg C ha^{-1} in the 81-100 year age class. Mean age class values then begin to steadily decrease within the range of observed data.

This trend in standing dead tree and snag carbon mass may be partially explained by natural thinning and stem exclusion. In the sites examined in this study, at beginning of stand development after the clear-cut, all standing dead trees and snags had been removed from the stand. This pool did not begin to increase in mass until the 21-40 and 41-60 year age classes. These age classes represent the stem exclusion stage of stand development. This increase in carbon mass is likely due to an increase in dead trees from natural thinning. During this stage, trees begin to vigorously compete with each other for growing space causing the weaker suppressed trees to die. This mechanism of survival was directly observed in this study. In stands approximately 20 to 60 years old, the canopy was closed and stem density was very high (as high as 7050 stems/ha with an average DBH of 9 cm in a 34 year old stand). In these stands the presence of dead trees due to suppression was quite apparent.

Standing dead tree and snag carbon mass was highest in the 81-100 year age class. This was due to a combination of dead tree carbon mass still retained within the stand from the stem exclusion stage and by the natural mortality of some of the trees which had previously survived the stem exclusion phase. At this point in the stand's development, some of the shorter-lived species such as balsam fir, which was a common tree species in the red spruce stands examined in this study, would begin to die. In Nova Scotia, balsam fir matures within 60-70 years (Saunders 1970). It is also important to note that trees that die within this age class are much larger than trees that would have died during the earlier stem exclusion stage. This effect would mean greater inputs of dead trees into this carbon pool.

For the last two age classes, snag and standing dead tree carbon mass decreases. This may be the result of increased decomposition of some of the dead tree mass present within the stand due to increased light from openings in the crown as the stand ages and from the fact that some of the snags will merely fall over and be added to the downed woody debris pool. There may also be less input into this carbon pool since the stem exclusion stage of stand development has past.

Equation 2.7 was used to model the change in snag and standing dead tree carbon mass over time. The fitted model describes changes in carbon mass similar to that described by the mean carbon mass values for each age class in Figure 2.5c. The mean corrected-R^2 value is 0.713 indicating agreement between the data and fitted values (Table 2.2). This model, like the models suggested for the seedling and sapling and shrub and herb carbon pools, was not further examined in this study as to its statistical significance. It is only suggested here as a possible model to describe the relationship of snag and standing dead tree carbon mass over stand age.

Downed Woody Debris Carbon Mass

From visual inspection of Figures 2.1f and 2.5f, a possible pattern in downed woody debris (DWD) carbon mass can be detected. In age class 0-20, mean carbon mass is 14.08 Mg C ha^{-1}. It then decreases to a minimum mean value of 4.59 Mg C ha^{-1} in the 41-60 year age class. DWD then increases substantially to a maximum mean value of 26.23 Mg C ha^{-1}. It then decreases again in the following age classes. This see-saw pattern seems to be indicative of a large input of DWD following clear-cutting, then another large input of DWD within the 61-80 year age class. In both instances, DWD carbon mass begins to decrease following these inputs. Rothstein et al. (2004) found a similar pattern in dead wood (which included both downed dead wood and standing dead wood) in jack pine stands following wildfire succession. In their study, dead wood initially declined from a peak value of 31 Mg C ha^{-1} at year 1 to a minimum of 0.05 Mg C ha^{-1} at year 27. It then increased slightly in the mature stands. Rothstein's initial dead wood value is somewhat higher than is observed in this study; however, they also included standing dead trees in their dead wood carbon pool. Following a fire disturbance, much of the carbon in this pool came from the dead trees that were left standing. Where in this study, the stand replacing disturbance was clear-cut harvesting, which removed much of this source of carbon.

The first input of DWD carbon mass is mainly caused by the abundance of slash and other coarse woody debris left over from the harvesting disturbance. In all the young sites examined in this study, tree-length and cut-to-length harvesting methods were employed using a single-grip harvester or by manual cutting with a chain saw. Slash was left on site. This would create a large DWD carbon pool within the first age class.

Without additional inputs of DWD of such magnitude, carbon mass in those pools would likely begin to decrease as decomposition rates exceeded the rate of input.

Dead woody debris carbon increases in the 61-80 year age class. This increase may be in part due to fallen dead trees and snags that have died in the previous stem exclusion stage of stand development. Trees, which have died from natural suppression, would represent a significant input of DWD. During this age class, there might also be an additional input of dead trees from damage caused by windthrow or pest damage. Mature stands of taller trees are more susceptible to wind damage then shorter immature stands (Ruel 1995). Particularly on shallow soils such as encountered in this study. MacLean (1980) concluded that mortality from spruce budworm was consistently higher in mature balsam fir and spruce stands then in immature stands. Mortality from naturally shorter lived and/or pioneer species such as tamarack and balsam fir within the red spruce stands would also act as inputs of DWD carbon mass during this age class.

Forest Floor and Mineral Soil Carbon Mass

Forest floor and mineral soil carbon mass did not seem to show any recognizable trends throughout stand development; therefore, no attempt was made to model any potential patterns over stand age. Carbon mass was highest in the 81-100 year age class with a mean value of 98.44 Mg C ha^{-1} and lowest in the 21-40 year age class with a mean value of 70.38 Mg C ha^{-1}. Since a constant mean value of 51.44 Mg C ha^{-1} was used to represent the mineral soil carbon concentration in all sample plots, changes in forest floor and mineral soil carbon mass measurements were due to changes in forest floor measurements alone.

Contrary to the results of this project, past studies examining patterns in forest floor organic matter over time have shown changes in forest floor mass during succession following harvesting. One such study worth noting is that of Covington (1981) who studied forest floors in northern hardwood stands in New Hampshire. This study examined a series of different aged stands in order to distinguish patterns in the forest floor mass and organic matter content throughout stand development after logging. Covington's findings substantiated a model curve that predicted a loss of 50% of forest floor organic matter in the first 20 years following logging. It then predicted a steady increase in organic matter in the forest floor until a steady state was achieved in the oldest stands where organic matter content was essentially unchanged. Covington defined the cause of this sudden drop in organic matter within the first 20 years of stand development to be increased decomposition rates and reduced inputs of litter. This pattern was tested by Federer (1984) within the same region. Federer found that the forest floors did not show the same dramatic drop in organic matter within the first 20 years following logging, but, did show that the oldest stands had the most organic matter in forest floors and those stands between 10 and 30 years old had the least.

Yanai et al. (2000) re-examined the findings by Covington (1981) within the same northern hardwood sites in New Hampshire as Frederer (1984). Yanai found that organic matter content of the forest floor did not change according to the pattern predicted by Covington (1981). In fact, stands sampled by Yanai, that were in the age range in which declines were predicted, had more organic mass in the forest floor than they had 15 years earlier. Changes in organic mass of the forest floors studied were not significantly related to stand age either in a linear or polynomial regression. Rather, Yanai et al. (2000) found that the actual year, in which the stand had been harvested and the harvesting technique implemented, explained more of the variation in forest floor. Grigal and Ohmann (1992), who examined carbon storage in the forest floors of different upland forest types in the Lake States of the United States, noted that increases in forest floor carbon storage were weakly associated with age and scantly conform to findings by Covington (1981). Grigal and Ohmann (1992) found that forest floor carbon mass was more strongly influenced by soil (surface clay) and climatic variables than stand age. Yanai, also, noted that attempting to detect small rates of change in forest floor organic matter using reasonable sampling techniques was difficult due to the high spatial variation in forest floor organic matter.

These findings may help to explain why no apparent pattern in the change of forest floor carbon mass was detected in the red spruce stands examined in central Nova Scotia for this study. A chronosequence approach to detecting the governing dynamics of carbon within the forest floor may be prone to much error. For example, Freedman and Wallace (1986) found, from a study of 23 hardwood stands in Nova Scotia, that inter and intra-stand variation in forest floors to be greater than that related to stand age. Perhaps this variation accounts for the lack of pattern of forest floor carbon mass in this study.

Forest floor and mineral soils examined for this study were mostly shallow soils over bed rock. In all sites the litter layer, moss layer and organic soil layers were sampled. Mineral soil layers were sampled from four sample plots and to a depth of 10 cm; therefore, some error might be expected with soil carbon estimates due to the lack of mineral soil sampling intensity, which might have accounted for any spatial variation across the landscape in mineral soil characteristics such as soil depth, bulk density and rock content. Results from other soil carbon studies (Davis et al. 2003, Grigal and Ohmann 1992) have, however, shown that changes in carbon storage over time following a disturbance appear to be more noticeable in the forest floor than in the mineral soil. Johnson (1992) reviewed 11 studies which found no significant changes in soil carbon after harvest regardless of forest age. The lack of sampling intensity of mineral soils in this study may, therefore, have little effect on noticeable changes in soil carbon that may have occurred due to stand developmental stage.

Forest floor and mineral soil carbon mass were low in this study in comparison with other work done by Freedman and Morash (1985) in red spruce dominated stands in central Nova Scotia. They found that forest floor and soil layers in pole and mature red spruce stands to contain a mean value of 213,730 kg/ha and 264,150 kg/ha of organic matter respectively. Assuming an organic carbon content of 50 %, this works out to be 132.01 Mg C ha^{-1} and 106.81 Mg C ha^{-1}. These values are higher than the mean forest floor and soil carbon values measured in this study. Freedman and Morash (1985) measured mineral soils to lower root-exploitable depth. Mean mineral soil sample depth was 21.0 cm in pole aged stand and 26.3 cm in the mature aged stand.

Tremblay et al. (2002) estimated organic carbon in forest soils in Quebec. They developed two models, based on a range of simple field measurements, to estimate mean forest floor and mineral soil carbon under different upland forest types in Quebec. They found upland spruce stands to contain on average 118 ± 43 Mg C ha^{-1} within the total forest floor and mineral soil layers. The range in total soil carbon (forest floor and mineral soil) for spruce sites was 25-314 Mg C ha^{-1}, where n=1466. This is higher than any of the mean soil carbon values calculated for each age class in this study; however, these values do fit within the range of data obtained by Tremblay et al. (2002). Tremblay also noted that mineral soil depth and bulk density varied considerably over the wide geographical distribution of sites they sampled.

Total Site Carbon

The change in total site carbon over time for each developmental stage is described in Figure 2.6. This figure shows that total site carbon mass increases from the 1-20 year age class until the 81-100 year age class. Figure 2.6 also illustrates the influence of each carbon pool on total site carbon. Except for the first age class, above and belowground tree carbon and forest floor and soil carbon are the largest two carbon pools. In the 1-20 year age class, tree carbon is exceeded by the DWD carbon pool. A similar trend was also observed by Davis et al. (2003). From the number of carbon pools measured, above and belowground tree carbon explained the most variation in total site carbon mass over time.

The total site carbon model (Equation 2.8) provides carbon mass predictions for natural red spruce dominated forest in the Eastern Eco-region of lower central Nova Scotia. The model represents the sum of all of the carbon pool components measured in these forest ecosystems. The statistics in Table 2.2 indicate that the model fits well to the collected data. Residual analyses based on the preliminary non-linear least squares fit were performed to detect any possible model inadequacies. The plot of residuals against stand age displays a homogenous band centered on zero, indicating the total site carbon mass prediction model was appropriately identified and fitted. Simple regression between the estimated and measured total site carbon mass showed that the total site carbon mass model provides a reasonable fit for the actual measured field data.

The model was chosen based on the mathematical properties of the sigmoidal-based function. The shape of the curve and its parameters have ecological significance, demonstrating reasonable patterns in the accumulation of carbon in a forest ecosystem within the range of observed data and, therefore, the model should not be extrapolated out of the data range.

The four-parameter logistic function (Equation 2.8) is an extension of the three-parameter simple logistic model also known as the autocatalytic function (Ratkowsky 1990). The three-parameter model has been used extensively in animal ecology studies for the modelling of change in numbers of individuals within a population and in plant growth studies (Hunt 1982). It is one of the most versatile models for fitting sigmoidal responses having a lower asymptote of zero and a finite upper asymptote (Ratkowsky 1990). To allow for a non-zero lower asymptote, (such as needed in this case) the parameter a is added to the function. Parameter a represents the lower asymptote or the minimum site carbon mass. Parameter a is added because site carbon mass is always greater then zero. Parameters $a + b$, in the equation, represent the upper asymptote or the maximum total site carbon mass, where b represents the range. Parameter c represents the choice of the zero of time and d is the rate constant (which relates to spread of curve along the X axis) (Richards, 1959).

According to the model, at age three (the youngest stand sampled), after the clear-cut disturbance, there is an estimated 82.12 Mg C ha^{-1} of total site carbon. At age 140 years, which was the oldest red spruce stand sampled, the estimated total site carbon mass is 230.43 Mg C ha^{-1}. This range of total site carbon values generally agrees with other total site carbon storage measurements throughout the scientific literature (Davis et al.

(2003), Grigal and Ohmann (1992)). Direct comparison of carbon stocks in this study with those of other studies can be, however, somewhat arbitrary. This is due to the lack of standard sampling methods employed. Many studies use different sampling methods or measure different carbon pools when measuring total site carbon. Not to mention, that spatial heterogeneity within the landscape with regard to forest ecosystem type can create high variability among total site carbon measurements.

Davis et al. (2003) used similar sampling methods that were employed in this study for measuring total site carbon. They found site carbon storage in indigenous forest in New Zealand to peak at 219 Mg C ha^{-1} in 125 year old stands. Grigal and Ohmann (1992) measured carbon storage in upland forests of Lake States in the United States. Their data ranged from 139 Mg C ha^{-1} in mature jack pine stands to 234 Mg C ha^{-1} in mature northern hardwood type stands, which is consistent with data from this study. Rothstien et al. (2004) found total site carbon values to range from a minimum of 59 Mg C ha^{-1} to a maximum of 112 Mg C ha^{-1} at 72 years in a chronosequence of jack pine stands in Michigan. Results from other studies, however, were significantly different than those results reported here. For example, Wang et al. (2003) found total site carbon along a chronosequence of black spruce stands in northern Manitoba following fire disturbance to range from 458 Mg C ha^{-1} in the youngest stand sampled (3 years since disturbance) to 470.4 Mg C ha^{-1} in the oldest stand (151 years since disturbance). This difference is basically attributed to the large mineral soil carbon pool.

Generally, in forest ecosystems peak growth rate or net ecosystem productivity (NEP) occur within the earlier stages of stand development (Smith et al. 1997). Such is the case in this study. For total site carbon, the inflection point is found at a stand age of

33 years. At this point, the red spruce stand is accumulating carbon fastest at 2.8 Mg C ha^{-1} yr^{-1}.

NEP is a measure of the carbon balance of an ecosystem (Barnes et al. 1998). It tracks the difference between net primary productivity (NPP) and heterotrophic respiration (Rh). After NEP reaches its maximum capacity in the earlier stages of stand development, it then begins to decline. This is illustrated in Figures 2.3 and 2.5 where carbon mass accumulation begins to slow down in the later stages of stand development. This is often referred to as 'culmination of current annual increment' in forestry terms. Smith and Long (2001) indicate that changes in stand NEP are a direct consequence of stand development. Stand development is associated with fundamental changes in structure and function, including canopy reorganization, size class differentiation and self thinning. The onset of age-related decline in production is a direct consequence of the structural changes and shifts in carbon allocation associated with canopy closure and maximum foliage. In the early stages of stand development prior to a stand replacing disturbance there is often a negative NEP. This is not detected in this study, however, it is caused mainly by low NPP, and increased rates of Rh due to increased light reaching the forest floor and the decomposition of slash residues left over after disturbance (Barnes et al. 1998). Before canopy closure, understory vegetation, and seedlings and saplings are the dominant contributor to site NEP. In young trees within the stand, increases in NPP are proportional to increasing foliage. After canopy closure, foliage no longer accumulates at the stand level and may begin to decline. As the stand ages, canopy closure begins to shade out younger trees and understory vegetation. With decline in foliage and stand density, NPP begins to culminate. Ryan et al. (1997), explains that declining productivity, as a forest ages, may be the result of other physiological factors as well, including a) increased hydraulic resistance within trees as they grow taller; b) decreased nutrient supply in the soil as nutrients accumulate in biomass; c) reduced leaf area caused by crown abrasion; d) increased mortality of older trees; and e) increased reproductive effort, where the increased carbon cost of reproduction can be up to 15% of annual wood growth.

2.5 CONCLUSION

The results indicate that total site carbon increases over time in a sigmoidal fashion within the observed range of stand age. This pattern of growth is common to plant studies and agrees with many past carbon budget and forest ecosystem studies. Above and belowground tree carbon and forest floor and soil carbon represented the two largest carbon pools in the red spruce forest ecosystem. The above and belowground tree carbon pool displayed the highest magnitude of variation over time from 4.25 Mg C ha^{-1} in the youngest age class to a maximum of 120.58 Mg C ha^{-1} in the 121-140 year age class. It also had the most influence on changes in total site carbon. Other carbon pools which showed significant trends in carbon mass over time included the seedling and sapling, shrub and herb and standing dead tree and snag carbon pools. Each displayed recognizable patterns of forest ecosystem dynamics. To represent these patterns non-linear growth models were suggested and fitted to these data.

In order to model the sigmoidal growth pattern observed in total site carbon a four- parameter logistic function was chosen. This model was tested by residual analysis and proved to be statistically and biologically sound. Within the range of data observed in this study, the total site carbon model estimates the changes in total site carbon mass over stand age for natural red spruce dominated stands in the Eastern Eco-region of Nova Scotia. It predicts at age three (the youngest stand sampled), there is an estimated 82.12 Mg C ha^{-1} of total site carbon. At age 140 years, which was the oldest red spruce stand sampled, the estimated total site carbon mass is 230.43 Mg C ha^{-1}. Estimated net ecosystem productivity is highest at age 33 years accumulating carbon at 2.8 Mg C ha^{-1} yr^{-1}.

Overall, the study found that total ecosystem carbon storage following clear-cutting increased over time, indicating a net sink of carbon within the sampled chronosequence. The information from this study will be useful to better understand carbon storage and dynamics in natural red spruce forest in Nova Scotia. It will provide a benchmark by which to compare and evaluate carbon budget models which may be used in the future to examine and predict carbon stocks in Nova Scotia forest and the potential effects of various forest management scenarios on carbon stocks.

CHAPTER THREE

CBM CFS III CALIBRATION

3.1 INTRODUCTION

Forest ecosystems are a crucial component in the global carbon cycle. Through such processes as photosynthesis, respiration, decomposition and oxidation (forest fires), carbon is continually being exchanged between the forest and atmosphere. Globally, the terrestrial biosphere is thought to be a net sink of carbon, accumulating 2.3 Gt carbon per year in the 1990s (Watson et al. 2000). When forests go through periods of massive biomass loss caused by either natural disturbances or by anthropogenic influences, they may, however, act as net sources of carbon to the atmosphere.

With increasing concern about the possible adverse consequences of global climate change and the impact of increasing atmospheric CO_2, the ability of forests to sequester carbon has become a vital issue. Mitigation of atmospheric CO_2 levels through the use of forest ecosystems as potential carbon sinks will require, among other things, accurate estimation of carbon fluxes and storage within these systems.

Models of carbon budgets, which assess the dynamics of carbon fluxes and storage in forests caused by natural processes and anthropogenic influences such as land-use changes and forest management measures, are now needed to provide the information required to implement the Kyoto Protocol. Due to provisions in the Kyoto Protocol, carbon crediting schemes such as Joint Implementation and Clean Development Mechanisms have created the potential for forest carbon to become an economic commodity that may be traded in markets such as the Chicago Climate Exchange (Prisley and Mortimer 2004). Given such circumstances, the ability to quantify and report forest carbon stocks and stock changes (known as forest carbon accounting) is of particular importance to scientists and policy makers who are considering forest land-use changes and forest management practice in order to meet their greenhouse gas reduction targets under the Kyoto Protocol.

In Canada, effort is being made to develop tools that model carbon stocks in forest ecosystems. Currently the Canadian Forest Service Carbon Accounting Team is leading the way by developing the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS). By working with Canada's Model Forest Network, universities and industry, the carbon accounting team is in the process of developing the CBM-CFS 3 (beta). This new version of the model, when fully developed, will be an operational scale model capable of estimating carbon fluxes and stocks in Canadian forests at the landscape and stand levels. It will provide scientists and forest managers with a scientific tool for measuring the impacts of planned activities on forest carbon stocks. The objective is to build a model that is not only a research tool as were its earlier versions, but is also a user-friendly decision support tool (Kurz et al. 2002).

Carbon accounting tools must be scientifically credible. They must be based upon the best available scientific data and they must be validated and calibrated (to some extent) against actual field data.

The CBM-CFS 3 is an aspatial model. Essentially, records describing stands or groups of stands with similar attributes are loaded into the model as input information. The input takes into consideration special information pertaining to each of the records. This information includes inventory data, growth and yield curves, transition rules, and disturbance information. These data are used by the model to construct a scenario for each stand or group of similar stands, which allows it to simulate how the stand will grow and change over time due to natural disturbances and management regimes. While importing this input data, the user must go through a process whereby he or she affiliate (map) data with specific predefined categories and parameters built into the model which describe geographic location, climatic variables, decomposition rates, etc. Once the importing process is complete, the model has the information it needs to schedule and run a simulation defined by the user. Of course, the preceding description is quite general. Much more detail is involved in preparing import information and simulation criteria, however; the above outlines some of the major steps involved.

Presently, the CBM-CFS 3 is a beta-version model that needs to be tested and compared with actual field data. As previously mentioned, the model has built-in parameters and assumptions describing such things as climatic variables, ecosystem characteristics and decomposition rates for certain geographical areas in Canada that are selected by the user when importing and simulating data. These parameters are, however, general in nature, pertaining to large geographical and ecological boundaries. For forest managers interested in considering carbon balances in the management decision criteria of smaller management units, some fine tuning or calibration of the models' parameters may be required.

The previous chapter described carbon pools along a chronosequnce of red spruce dominated stands in the Eastern Eco-region of Nova Scotia. In order to estimate carbon fluxes and stocks in the forests of this region in Nova Scotia using the CBM-CFS 3, an individual would need to select the specific tree species, spatial units and ecological boundaries associated with this area available in the model. In this case, it would consist of the Nova Scotia Administration Boundary and Atlantic Maritime Eco-boundary. A set of parameters have been predefined within the model to describe the various ecosystem processes which take place in forest ecosystems within this area, depending upon the forest inventory and disturbance regimes imported into the model. These parameters, however, pertain to a wide geographical area which contains much spatial heterogeneity with regard to such factors as climate and forest ecosystem type.

The objective of this chapter is to answer the following question: How do carbon stocks predicted by the CBM-CFS 3 model for red spruce stands in Nova Scotia compare with actual field measurements of carbon stocks?

The specific objectives are as follows:

- To simulate stand-level carbon stocks for natural grown red spruce stands following a clear-cut disturbance in Nova Scotia using the CBM-CFS 3.
- To compare these model results with actual field data of carbon stocks collected from natural grown red spruce dominated stands in the Eastern Eco-region of Nova Scotia.
- To calibrate the CBM-CFS 3 in order to more accurately estimate stand-level carbon stocks of red spruce stands for the Eastern Eco-region of Nova Scotia.

3.2 MATERIALS AND METHODS

To run a simulation of the CBM-CFS 3 for users who do not use the Woodstock or SFMM timber supply models or are not modelling afforestation-related projects, the first step is to construct an import file in either Microsoft ® Excel, Access, or as a text file. This file contains specific data that describe the forest area to be simulated by the program (see Appendix III). The data are divided into the following fields: Age Classes, Disturbance Types, Classifiers and Values, Inventory, Growth and Yield, Transition Rules, and Disturbance Events. These fields describe the age-class structure, forest growth and disturbances which affect the forest inventory.

In order to accurately simulate a natural red spruce dominated stand in Nova Scotia an import file describing the type of natural red spruce stands studied in Chapter Two was created. To incorporate the appropriate growth and yield data that best describes these red spruce stands, the "Revised Normal Yield Tables For Nova Scotia" (NSDNR 1990) were used. Based on the average site index of the stands examined in Chapter Two, a Land Capability Class four volume growth and yield curve was chosen. Merchantable volume was selected in order to meet the format requirements of the CBM-CFS 3. Because the Nova Scotia growth curves only describe stand growth up to 110 years of age, 11 age classes 10 years in size were created to describe stand development.

The inventory data consisted of a single one hectare red spruce stand at age one following a clear-cut disturbance. Altogether two disturbance types were imported. They consisted of clear-cut harvesting and wild fire. To end the simulation after 110 years of growth, the stand was clear-cut harvested at year 111. The transition rules imported describe that the stand will revert back to a one year old red spruce stand following the clear-cut disturbance using the same growth curve.

To run a red spruce stand simulation using the CBM-CFS 3 the import file was imported into the model using the CBM-CFS Standard Import Tool. This tool allows the user to bring information describing their forest stand or stands into the model for processing and to match up specific information contained in the import file with certain sets of categories and parameters provided with the database for the model. For example, some of the classifiers within the import file, which describe each record in the forest inventory of the import file such as leading tree species, are matched up with a standardized species list within the model. Leading species is one key to selecting volume to biomass conversion parameters. Disturbance types listed within the import file are matched up with specific disturbance matrices provided with the database of the model that describe the effects of that disturbance on forest carbon pools. Also, spatial units, which describe the administrative and ecological boundary properties, are selected during the import process. In this study, the Nova Scotia Administrative Boundary and the Atlantic Maritime Ecological Boundary were selected. Once the import process is complete the model is ready to run a simulation.

The first objective of this chapter was to produce stand-level carbon stock estimates for naturally grown red spruce stands following a clear-cut disturbance in Nova Scotia using the CBM-CFS 3. For this exercise no calibration of the model was attempted. The simulation was run using the imported data file, which described the red spruce stand, and the predefined generic settings already programmed into the model that were defined and selected during the import process. This was done to create a simulation that any user of the model would use for this type of forest in this area, based solely on the options available to the user during the import process. The only option that was adjusted outside the import process was that the last disturbance type during the initial simulation process was changed to a clear-cut disturbance from the historic default wildfire disturbance. This was done to simulate a stand which originated from a clear-cut disturbance.

Results from this first simulation were observed for total site carbon, biomass carbon and dead organic matter carbon (DOM). Total site carbon from the simulation was visually compared with the observed total site carbon data from Chapter Two. They were both plotted graphically against one another to distinguish noticeable differences in the quantity of carbon per ha, and the change in carbon accumulation over stand development. Biomass and DOM carbon pools simulated by the model were compared with similar pools from the observed field data from Chapter Two in order to distinguish any differences in carbon mass or accumulation.

Significant differences between the CBM-CFS 3 simulation results and the measured data from Chapter Two were detected, therefore calibration of the CBM-CFS 3 model was considered in order to minimize these differences. The difference between total site carbon results was due largely to over estimation of the DOM pool by the CBM-CFS 3, more specifically, the slow DOM pools. Therefore an attempt was made through sensitivity analysis to understand which variables and parameters within the CBM-CFS 3 model would be most appropriately adjusted to lower the slow DOM pools without causing significant changes to other carbon pools or the pattern of net ecosystem productivity over stand development.

An attempt was made to incorporate as much specific information pertaining to conditions which best describe the specific area in Nova Scotia (Eastern Eco-region) for which the simulation was being carried out. More general parameters used by the CBM-CFS 3 relevant to the Nova Scotia Administrative Boundary and the Atlantic Maritime Ecological Boundary were adjusted based on information from the literature specific to the Eastern Eco-region of Nova Scotia. Such adjustments included changes to the mean annual temperature within the climate data assumptions and changes in some of the DOM turnover parameters.

After performing sensitivity analysis of various model parameters and settings including adjustments to the clear-cut harvesting disturbance matrix, climate data, DOM turnover parameters (average stand age, average soil DOM, decay multiplier), and DOM parameter decay rates, it was decided that direct adjustment of the slow above and below ground DOM pool decay rates had the most significant effect on lowering these pools.

Kurz and Apps (1999) state that the CBM-CFS II estimates of DOM carbon pool sizes and their dynamics are associated with the largest uncertainties within that model. They suggest that the source of this uncertainty is related to the parameters which define the decomposition rates. The methodology behind defining these decomposition rates in the CBM-CFS II is still very similar to the way in which these rates are defined in the CBM-CFS 3. Therefore, by using the reparametization approach used by Kurz and Apps (1999) to bring DOM carbon content values into close agreement with alternate data sets, a similar approach was adopted here in order to lower the simulated DOM carbon pool content. The lowered DOM pool content in turn lowered the overall total site carbon content, bringing it in closer agreement with the measured field data results.

To achieve close agreement between the CBM-CFS 3 simulated total site carbon results and the observed data, slow DOM decay rates were adjusted until the simulated results were statistically close enough to the observed data. In order to measure any improvements in the models predictions due to reparameterization, a number of methods outlined by Mayer and Butler (1993) used in statistical validation of simulation models were employed. These methods included visual comparisons, measures of deviance between the simulated and observed data, and statistical test.

Visual comparisons consisted of graphical displays of both the simulated data and observed data against stand age, and plots displaying the observed data versus the predicted data directly. Measures of deviance between the simulated and observed data were mean absolute error (MAE) and mean absolute percent error (MA%E) (Mayer and Butler 1993), which are defined as follows:

$$MAE = \left(\frac{\sum |yi - \hat{y}i|}{n} \right)$$

$$MA\%E = \frac{100\left[\sum \left(\frac{|yi - \hat{y}i|}{|yi|} \right) \right]}{n}$$

where y_i represents observed values, $\hat{y}_i$ predicted values, and *n* the number of data pairs.

Statistical tests applied to the data included regression analysis of the observed versus the predicted data. The fitted constants provided from the regression were used to indicate any observed biases in the models predictions against the perfect fit line of $y = \hat{y}$. In order to directly measure how far removed the model's predictions are from the observed data with regard to the perfect fit, modelling efficiency (EF) was tested. EF is defined as:

$$EF = \frac{1-\sum(y_i-\hat{y}_i)^2}{\sum(y_i-\bar{y})^2}$$

Using these evaluation methods the reparameterization which displayed the most improvement in agreement with the observed data was selected as the calibrated model.

3.3 RESULTS

Noticeable differences can be observed between the predicted data and the observed data (Figure 3.1). Overall the simulated curve yields higher carbon content values throughout stand development then the observed data and Equation 2.8.

Differences between the shapes of the simulated curve versus the observed data and Equation 2.8 are noticeable throughout stand development. In the earlier stages of development, following the clear-cut disturbance, the simulated curve displays significantly larger carbon content. At year zero carbon content is 211.34 Mg C ha^{-1}. This mass then quickly begins to dissipate to a low of 144.43 Mg C ha^{-1} at age 18. After which carbon mass begins to steadily increase. The observed data and the curve produced by Equation 2.8 do not show this initial high carbon content following the clear-cut disturbance, but rather, display significantly lower carbon mass. For example, Equation 2.8 predicts 82.12 Mg C ha^{-1} in year three (within the range of observed data).

Also of notice is the difference between the shape of the simulation curve and the observed data during the later stages of the stands development. The simulated curve maintains a higher rate of increase in carbon mass as the stand ages, while the observed data begin to level off as summarized by Equation 2.8.

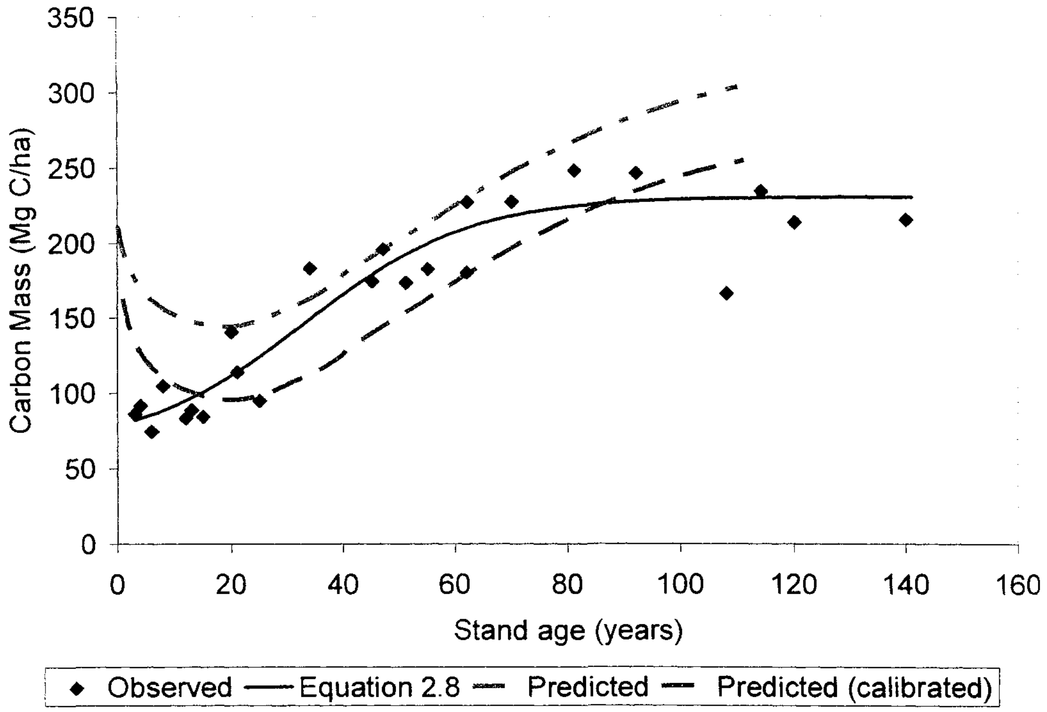


Figure 3.1 The simulated CMB-CFS III predictions of total site carbon (non-calibrated and calibrated) versus the observed field data and plot of Equation 2.8.

In order to understand why the CBM-CFS 3 simulated curve shows overall higher carbon stocks then the observed data from Chapter Two, analysis of the biomass and DOM carbon pools which make up total site carbon was necessary (Figure 3.2). To observe how these two carbon pools affect the higher carbon content detected in the simulated curve, compared with the observed data, each simulated carbon pool was plotted against its equivalent carbon pool from the observed field data in Chapter Two.

From visual inspection of the biomass carbon pool it appears that there is good agreement between the simulated curve and the field data within the simulation's range of data (Figure 3.3). Figure 3.4, however, demonstrates that the simulated DOM curve shows overall higher values then the observed DOM field data.

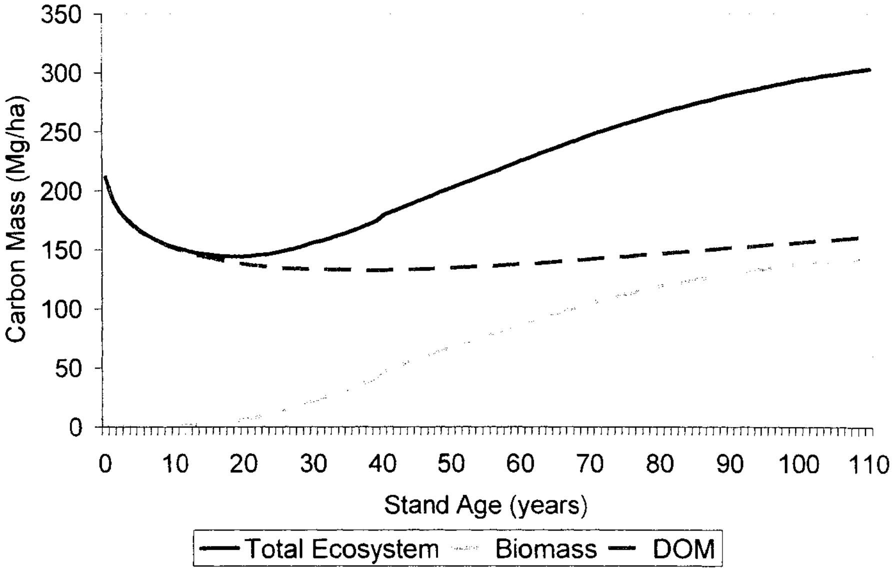


Figure 3.2 Simulated total site carbon and its two major components, biomass and dead organic matter (DOM).

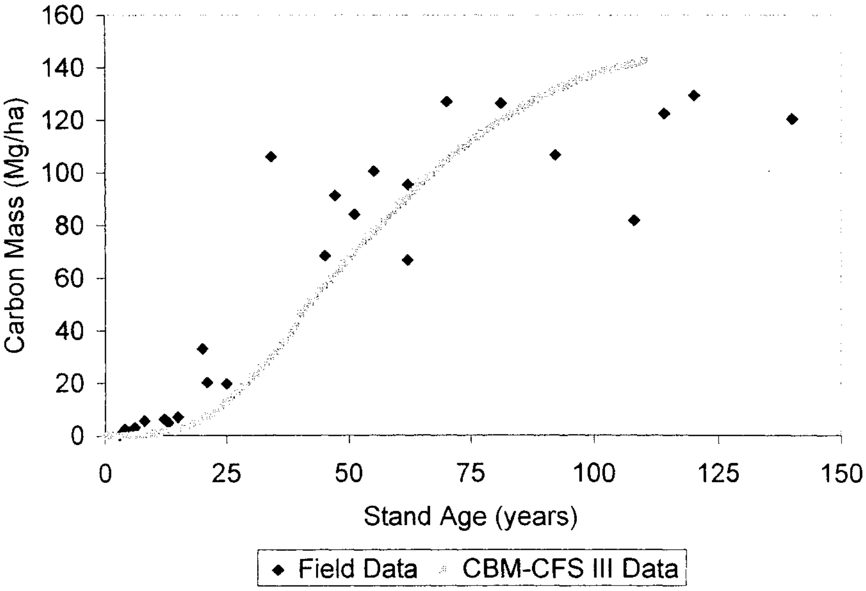


Figure 3.3 A comparison of the simulated total tree biomass with the field data total tree biomass.

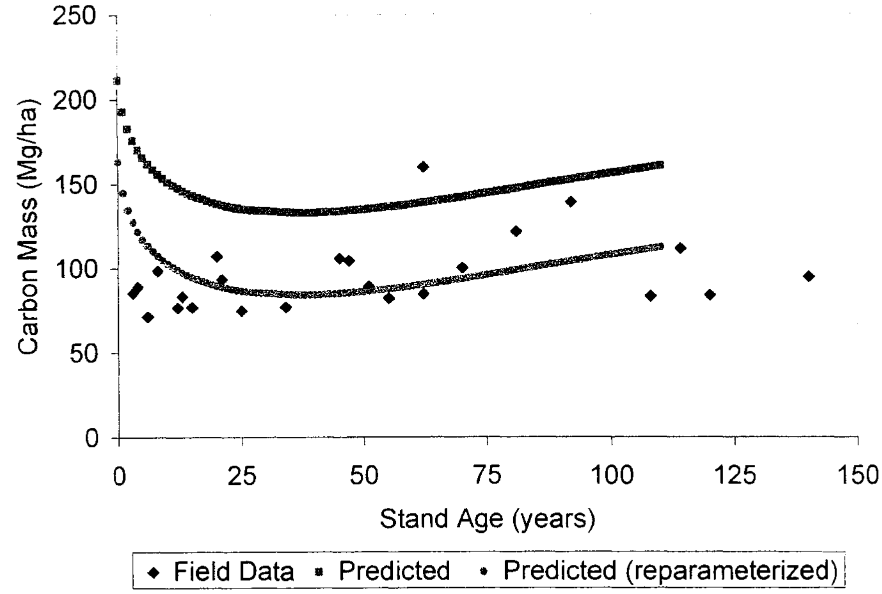


Figure 3.4 A comparison of the simulated DOM with the observed DOM field data.

The models DOM predictions are generally higher throughout stand development, particularly in the early stages of stand development. It should be noted here however, that leftover stumps and dead coarse root material were not accounted for in the observed field data, which is accounted for in the CBM-CFS 3. This might explain the lower field data values in the earlier stages of stand development after the clear-cut disturbance. All other DOM carbon pools measured in the field including downed woody debris, standing dead trees and snags and forest floor and mineral soil carbon were summed together to create the total DOM pool observed in the field.

Figure 3.5a displays four of the main DOM pools which make up the total DOM pool. These are the slow, medium, fast and very fast DOM pools which all vary with decomposition rate. Of these pools it can be observed that the slow DOM pool is significantly higher than the rest. Figure 3.5b displays the two types of slow DOM pools which make up the total slow DOM pool. These consist of the above and below ground slow DOM pools. Inspection of Figure 3.5b indicates that the below ground slow DOM pool makes up the largest portion of the total slow DOM pool (93.4% on average throughout the stands development).

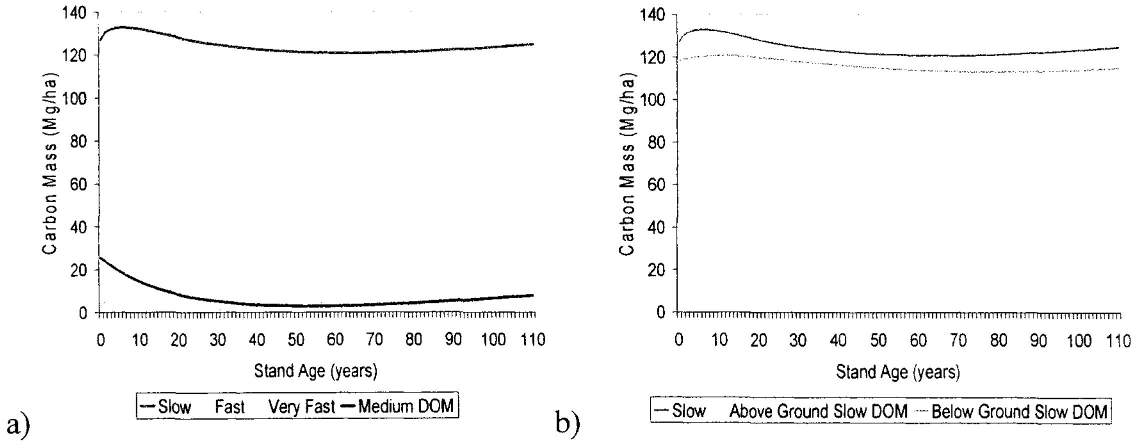


Figure 3.5 a) The various sub-DOM pools which make up total DOM. b) The various slow DOM pools which make up total slow DOM.

Considering the slow below ground DOM pool makes up the largest portion of total DOM carbon mass, the decomposition rates describing this carbon pool were reparameterized in order to bring the simulated total DOM carbon pool into better agreement with the observed data. To achieve this agreement in the DOM pool it was necessary to modify the slow below ground DOM base decomposition rate from 0.00678 (referenced at 10 °C mean annual temperature) to 0.01200/yr.

From visual inspection of Figure 3.4, the reparameterized DOM curve conforms to the observed data more closely than does the original simulation curve. Using the reparameterization it can be seen in Figure 3.1 that the calibrated total site carbon predictions are in closer agreement with the observed data and Equation 2.8.

Figures 3.6a and b show a direct comparison of the observed versus the predicted data for the non-calibrated and calibrated model.

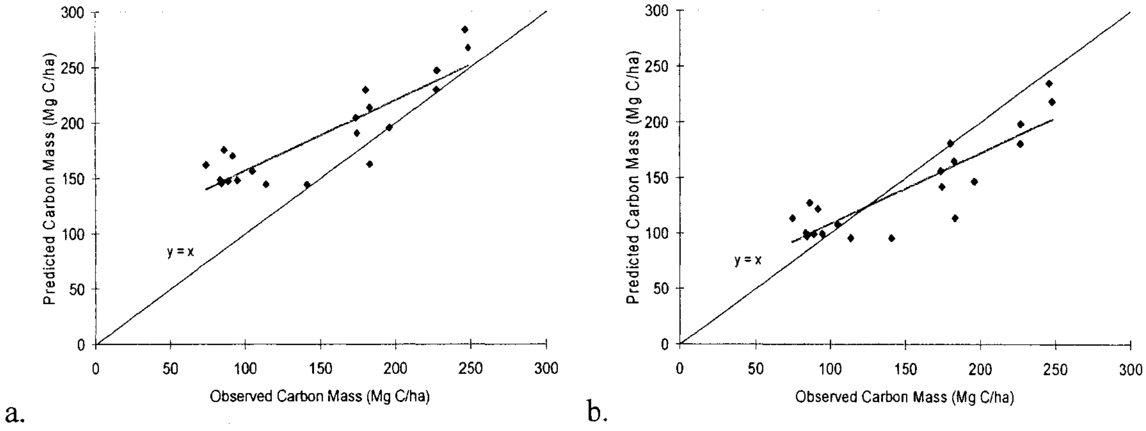


Figure 3.6 The observed versus the predicted total site carbon values for: a) the non-calibrated model, and b) the calibrated model. The red line represents the linear regression line.

It can be seen from Figure 3.6a that the observed versus the predicted data do not fit adequately with the line of best fit. This is confirmed by a two-tailed t-test ($P < 0.025$) where the slope from the regression analysis (slope = 0.638, $R^2 = 0.768$) is significantly different from the line of best fit, therefore indicating bias. Figure 3.6b shows that the calibrated models predictions appear to have changed with regard to their overall position, however, the pattern of observed versus predicted values has not changed. Regression analysis of the observed versus the calibrated predictions indicates that the slope has not changed (slope = 0.638, $R^2 = 0.766$) and it is therefore also significantly different from the line of best fit, indicating bias. Table 3.1 shows the results from regression analysis and also the MAE, MA%E and EF values for the non-calibrated and calibrated predictions. When comparing MAE and MA%E values for both simulations, the calibrated model shows comparatively lower measures of deviance then the non-calibrated model. The calibrated model also shows a higher EF value then does the non-calibrated model, thus indicating that the calibrated model shows less proportion of variation against the set line $y = \hat{y}$.

Table 3.1 Statistical measures of validation applied to a) the non-calibrated model predictions, and b) the calibrated model predictions.

Data set	Deviance measures		Linear regression				Modelling efficiency
	MAE	MA%E	R^2	Slope	Intercept	Bias[a]	
A	38.49	37.7	0.768*	0.638	92.81	4.39	0.32
B	10.13	0.44	0.766*	0.638	44.31	4.37	0.71

[a] Two-tailed t-test for slope = 1 ($|t| > t_{.025}$, $n = 20$)

* $P < 0.01$

3.4 DISCUSSION

The CBM-CFS 3 simulated total site carbon stocks for red spruce stands in Nova Scotia was shown to be different from the field measurements in Chapter two. Analysis of the various simulated carbon pools and the field data demonstrated that the largest discrepancies came from prediction of the Slow DOM carbon pools in the model. Therefore the model was calibrated to bring the simulated Slow DOM values into better agreement with the measured data.

3.4.1 COMPARISON BETWEEN NON-CALIBRATED SIMULATION RUN AND THE OBSERVED DATA

From Figure 3.1 it is apparent that the non-calibrated CBM-CFS 3 simulation predicted stocks of total site carbon, which were generally higher than the observed data. Therefore, an attempt was made to calibrate the model by adjusting the decay rate of the Slow DOM pool. Upon analysis of the simulation output data it was found that the higher predicted stocks of carbon were due primarily to the high Slow DOM pools simulated by the model. Within the CBM-CFS 3, the DOM pools represent different fractions of dead organic matter found within a forest ecosystem and are characterized by the types of biomass input and carbon turnover rates (Kurz and Apps 1999). Merchantable stem wood (including stem bark) is transferred to the Medium DOM pool. Such objects as, branches, tree tops, sub-merchantable trees and coarse roots are transferred to the Fast DOM carbon pool. Foliage and fine roots are transferred to the Very Fast DOM pool. During decomposition, carbon is either transferred into the atmosphere (83%) or transferred into the Slow DOM pool (17%).

The Slow DOM pool is separated into above and belowground fractions, which represent humified organic matter and mineral soil [Rampley (pers. □omm..., 7 Dec. 2004)]. Typically, the Slow Aboveground DOM pool receives carbon input from:

(1) Very Fast Aboveground DOM (a proportion of the fine root turnover).
(2) Fast Aboveground DOM (a proportion of the coarse root turnover, a proportion of branch snag decay and branch snag fall down).
(3) Medium DOM (a proportion of stem snag decay and stem snag fall down).
(4) Black C (which is introduced during stand initialization when the fire disturbance Matrix is used).

The Slow Belowground DOM pool consists of carbon from:

(1) Very Fast Belowground DOM (a proportion of the fine root turnover).
(2) Fast Belowground DOM (a proportion of the coarse root turnover).
(3) Slow Aboveground DOM (via a biomixing rate)

Close inspection of the DOM output showed that it was the Slow Belowground DOM pool, which mainly contributed to the high total DOM yield. Several factors explain why the DOM carbon content predicted by the model was significantly higher than the observed data.

The red spruce dominated stands studied in the field consisted mainly of shallow soils where, in most cases, the mineral soil layer was less than 20 cm thick. Only the organic horizons and the top 10 cm of mineral soil were sampled and measured for carbon content in this study. The CBM-CFS 3, however, initially uses assigned Slow DOM carbon content values taken from Zinke et al. (1986) and Siltanen et al. (1997) for the particular Eco-boundary in question. It uses these initial values and a simulation approach to create the initial Slow DOM pool and its dynamics for each stand. These initial soil values profile soil organic carbon to a depth of 1 m of mineral soil. This is considerably deeper than the sampling method used in this study. It, therefore, takes into consideration a larger portion of organic carbon contained within the mineral soil. It also assumes that the mineral soil layer is at least 1 meter in depth, which in most cases in the forest stands sampled, it was not.

Another difference between the predicted DOM pool sizes and the observed data is the spatial scale at which each data source represents. The CBM-CFS 3 red spruce stand simulation was spatially set up for the Atlantic Maritime Ecological Boundary. Within the model, there exist a given set of parameters, which describe the DOM pool sizes and dynamics. These parameters change according to the climatic data associated with the selected ecological boundary. The Atlantic Maritime Eco-boundary takes into consideration a large proportion of Atlantic Canada. On a national landscape scale, this type of generalization may not be significant; however, there exists much spatial heterogeneity with regard to soil pool size and dynamics within this Eco-boundary.

Chapter Two sampled red spruce stands within the Eastern Eco-region of Nova Scotia, which is a more geographical specific area. Due to the heterogeneity present within the larger generalized Eco-boundary, it is, therefore, not surprising that the observed DOM pool data are not consistent with that of the simulated predictions.

Of noticeable difference between the predicted total site carbon values versus the observed values in Figure 3.1 is the trend in the data over time. By observing the curve of values produced by the simulation data points versus the observed points and the curve produced from Equation 2.8, it can be noted that the simulated curve is clearly different in two particular stages throughout stand development.

Stage A

In Figure 3.1, it can be seen that within the first 20 years of stand development there is a notable difference in the pattern of carbon storage between the simulated data versus the observed data. The observed data begin at its lowest carbon mass in the early years of stand development, and then increase. The rate of increase changes over time (as summarized by Equation 2.8), but there is a constant accumulation of carbon. The simulated curve, however, starts year one following the clear-cut disturbance with a much higher carbon mass and then decreases rapidly until year 20. It then begins to accumulate carbon throughout the rest of the stand development. This initial high carbon content following the clear-cut disturbance is due to the sudden influx of carbon into the DOM pools from the stumps, branches, bark, sub-merchantable trees, foliage and other slash left over from the clear-cut harvesting process. These biomass components are transferred into the Very Fast, Fast and Medium DOM pools. Figure 3.5a shows the initial high values within these DOM pools and, also, how they rapidly decrease in size within the early stages of stand development, particularly the Very Fast and Fast DOM pools. The Very Fast DOM decreases rapidly, levelling off within the first three years, while the Fast DOM pool levels off within the first decade of stand growth.

There are several reasons why the initial influx of carbon is observed in the simulated data, but not in the observed data. The youngest sampled red spruce stand was three years old after the clear-cut disturbance. The next youngest stand sampled was 4 years old. This means that some of the foliage, small branches and other tree waste material left over from the harvest may have already decayed and, therefore, may not have been detected in the field data measurements. Second, in the field, stumps and the residual belowground biomass (roots) connected with these stumps was not measured, but is taken into consideration in the CBM-CFS 3. Therefore, an important source of carbon in the early stages of stand development was neglected in the field measurements and may cause discrepancy between the observed and predicted data. Third, the CBM-CFS 3 disturbance matrix which describes the effect of the clear-cut harvesting disturbance on the forest may not have accurately described the actual method of clear-cut harvesting carried out on the sampled stands. In reality, more of the merchantable wood and sub-merchantable wood may have been processed and removed from the forest site, than was described by the disturbance matrix in the model.

Stage B

Roughly between the stand ages of 60 to 80, there is another noticeable discrepancy between the simulated total site carbon data and the observations. Within this age range, the observed data begin to display a significant decrease in total site carbon. After 80 years, the observed data demonstrate only modest gains in carbon mass. This is contrary to the predictions, where there is no decrease in carbon accumulation within the 110-year simulation range.

The discrepancy between the predicted and observed data is largely due to the growth and yield information from the Revised Normal Yield Tables for Nova Scotia Softwoods imported into the model. The biomass carbon pool is largely based upon the growth and yield data imported. Through the use of a system of allometric equations and supporting parameter sets, volume curves provide the model with the information necessary to predict all aboveground biomass components such as stem wood, branches, foliage, tops and sub merchantable-size tree biomass. The estimation of belowground biomass of fine and coarse roots is estimated using regression equations developed for the model (Kurz et al. 1996, Li et al. 2003). While the biomass data measured in the field indicate a significant decrease in carbon accumulation between 60 to 80 years, the volume curves imported into the model do not display as significant a decrease in tree volume growth within the 110 year data range, and that is reflected in the predicted biomass data. This trend can be observed in Figure 3.3 where the predicted biomass values begin to deviate from the observed data after 80 years.

It is important to note that the DOM pools also influence the higher rate of carbon accumulation in the later stages of stand development in the predicted total site carbon data. From Figure 3.4 it can be seen how the predicted values reach their lowest point at year 39, then begin to increase until the last year of the simulation. The observed data, on the other hand, do not seem to show any particular pattern of increase throughout stand development.

3.4.2 CALIBRATION OF THE CBM-CFS 3

In order to bring the predicted values of total site carbon into closer agreement with the observed, an attempt was made to calibrate the CBM-CFS 3. Rykiel (1996) refers to the calibration of a model as the estimation and adjustment of model parameters and constants to improve the agreement between model output and a data set.

To bring the model output into better agreement with the observed field data, it was necessary to first identify which part of the model needed to be adjusted. Analysis of the output data, including the various carbon pools predicted by the model that contribute to total site carbon content, revealed that it was the DOM pool that most influenced the over estimation of predicted values, more specifically, the Slow DOM pools. An analysis of those parameters and constants that would improve the agreement between these DOM pools and the field data was undertaken.

The CBM-CFS 3 is a complex ecological model that involves the relationships of many system parameters. A full calibration and validation would require an intensive system analysis that is outside the scope of this study. Only a select few parameters were, therefore, considered for adjustment.

Since the CBM-CFS 3 simulation was initially set up for the Atlantic Maritime Eco-boundary, an attempt was made to identify and to change some parameters in order to closely describe the more specific geographic area of the Eastern Eco-region of central Nova Scotia. Adjustments were made to parameters in the Climate Assumptions, Disturbance Events and Management Activities, and DOM Turnover Assumptions in the model.

Climate Assumptions

The Climate Assumptions in the model provide information on mean annual precipitation (MAP) and temperature (MAT). The standard values used in the model for the Atlantic Maritime Eco-boundary are a MAP of 1344.84 mm and a MAT of 6.07 °C. Using the Ecological Land Classification for Nova Scotia (NSDNR 2003b), the average MAP, and MAT are 1445 mm, and 5.8 °C respectively. Substituting these values into the Climate Assumptions for the model and running another simulation demonstrated little change in the DOM pools or total site carbon content. Slight increases in DOM carbon were observed. These increases were likely due to the effect of MAT on the decomposition rates in the model, where these rates are temperature dependent and based upon a temperature-dependent modifier, which is calculated based on a Q_{10} value of 2.0 and the MAT. Currently MAP is not set up in the model as a modifier and has no effect on decay rates. Since the effect of using the new MAT was minor and the values themselves are similar, they were neglected and the original values in the model were maintained.

Disturbance Events and Management Activities

Adjustment of the Disturbance Events and Management Activities was also considered. In the initial setup of the first simulation, the historic disturbance type was wild fire. This disturbance is used in the stand initialization process to create the initial DOM pools before the main CBM-CFS 3 simulation runs. In the Eastern Eco-region of Nova Scotia, the dominant natural disturbances are wild fire and hurricanes (NSDNR 2003b). Since only one historic disturbance type can be selected at a time, the disturbance type was not changed and remained as wild fire. Currently, there is no disturbance matrix available within the model to describe wind throw damage; therefore, no attempt was made to create or to use wind throw disturbance in the simulation.

Also considered for adjustment was the historic stand-replacing interval, known in the model as the Stand Average Age. This parameter is used to describe the age to which each stand will grow during the stand initialization process in every pass except the last one. For the Atlantic Maritime Eco-boundary, the stand average age is 75 years. According to Wein and Moore (1979), Fernow (1912) calculated the fire rotation period for Nova Scotia as 200 years. Wein and Moore (1979) conducted a more recent survey that showed, because of human intervention, the average fire rotation period for Nova Scotia is 1000 years, depending on the geographical area of the province. Wind throw caused by hurricanes, North Easters and other storms are common to Nova Scotia, in particular to the Eastern Eco-region due to its vicinity to the coast and its abundance of shallow soils. Environment Canada (2004) states that in late summer and fall, the remnants of hurricanes or tropical storms are felt at least once a year. Due to the frequency of wind throw damage, the historic 200-year fire rotation period and the lack of information on average stand age intervals for this area the average stand age was maintained in the model at 75 years. To observe the effect of changing this parameter, the average stand age was adjusted to 200 years and 1000 years. It was found that smaller increases in the average stand age (less than 200 years) had small effects on DOM pool size. Larger increases such as 1000 years caused the DOM pool carbon content to increase.

The clear-cut harvesting disturbance matrix was also considered for adjustment. This matrix describes the transfer of the various forest carbon pools caused by the disturbance. It was thought that adjustments to some of the parameters within the matrix, which describes how much of each carbon pool is transferred to another, might affect how much carbon is in the DOM pool at the beginning of the simulation after the clear-cut disturbance. For instance, changes were made to the matrix so that more of the stemwood and sub-merchantable stemwood were removed from the stand. These changes had little effect on the size of the DOM pool over the development of the stand. Changes to transfer some of the faster decaying pools such as branches, bark, and foliage had an effect on the initial carbon levels of the Very Fast and Fast DOM carbon pools, but little effect on the Slow DOM carbon pools. The Slow DOM pools are primarily affected by the fire return interval, the site productivity and the decay rates. Since the clear-cut disturbance matrix only affects the last disturbance before the main simulation, it had little effect on the Slow DOM pool. It was concluded that changes to the disturbance matrix that would closely mimic the clear-cut harvesting techniques used on the stands measured in the field had no significant effect on the Slow DOM pools.

DOM Turnover Parameter Assumptions

Under the DOM Turnover Parameter Assumptions, adjustments were made to the Average Soil DOM value. This value is the average total of soil DOM carbon content for the default Eco-boundary that was initially selected. It is used as a seed value for each stand's Slow DOM pools during the stand initialization process. For the Atlantic Maritime Eco-boundary this value is 92 Mg C ha^{-1} and was determined from the Oak Ridge National Laboratory soil data set (Zinke et al. 1986). This value represents the humified soil organic matter in the forest soil. It is higher than the average value of soil carbon observed in the field (excluding the moss, litter and fermentation layers). Lower

Average Soil DOM values that were closer to the observed data were tried. Changes to these values did not have an impact on the end DOM pool predictions and, therefore, the default values were left unchanged.

As previously mentioned in the Materials and Methods section, Kurz and Apps (1999) found that in the CBM-CFS 2 estimates of DOM carbon pool sizes and their dynamics are associated with the biggest uncertainties in the model. They suggest that the source of these uncertainties involve the parameters defining the decomposition rates and the initial values assigned to the DOM pools. An attempt had already been made to alter the initial seed values assigned to the DOM pools with no impact on the predicted DOM pool size. Due to the uncertainties, which lie in the parameters that define the DOM pool decomposition rates, these rates were altered in order to observe the effects on DOM pool size.

Direct adjustment of the DOM pool decay rates had the most dramatic effect on the size of the simulated DOM carbon pools. Since it is the Slow Belowground DOM pool that makes up the largest portion of the total DOM carbon pool the decomposition rates for this pool were adjusted. Changing the decay rate lowered the DOM values until the predicted values visually appeared to better agree with the observed values. Figure 3.4 shows the predicted DOM carbon pool values for the original decay rate of 0.678% per year and the reparameterized decay rate of 1.2% per year. It can be seen that the reparameterized values appear to better fit the observed field data measurements.

3.4.3 COMPARISON OF THE CALIBRATED SIMULATION

Using the same settings and parameters as the initial simulation, except for the new Slow Belowground DOM pool decay rate, a new simulation was created and was run. Figure 3.1 displays the calibrated CBM-CFS 3 total site carbon mass for a natural red spruce stand in Nova Scotia. The original non-calibrated curve and the observed data are also shown. From this figure, it appears that the new predicted curve fits more closely to the observed data than the non-calibrated curve.

The new curve appears to fit better with the observed data values than the first simulation; however, the overall shape of the simulated curve remains unchanged. Discrepancies still exist in the pattern of carbon accumulation between the simulated data and the observed data. These discrepancies were outlined earlier in the Discussion and exist in the early and late stages of stand development and may in fact be a problem with the field data (e.g. no stump carbon measured). Potential corrections to this pattern would require re-sampling of the field data for missing carbon from the stumps and dead coarse roots not measured. Also required would be a more thorough investigation of the actual parameters and settings within the model that influence the distribution of the predicted values over time. These corrections might include a more comprehensive examination of the clear-cut disturbance matrix, the DOM Turnover Parameters and decomposition rates, the volume to biomass parameters and alternate growth and yield input information. More intensive field sampling would be required in order to justify any changes to the model's parameters based on observations in the field.

Although the calibrated curve still maintains its original shape, overall its predicted values appear to closely align with the observed data. In order to justify whether or not the calibrated model is more suitable for predicting total site carbon as opposed to the non-calibrated model, a validation technique is required. The subject of model validation and evaluation is a controversial topic, especially in regard to complex ecological models such as the CBM-CFS 3. According to Mayer and Butler (1993), "models can never be proven valid, only invalid. Failure to prove a significant difference between real and model data may only be due to insufficient replication or lack of power of the applied statistical test". The goal, here, is not to validate the CBM-CFS 3 predictions for operational use, but rather to evaluate the accuracy of the model's predictions with the observed data and to examine whether the calibrated model provides more accurate estimations.

To achieve this, the statistical validation methods outlined by Mayer and Butler (1993) were adopted to provide an evaluation of the accuracy of the non-calibrated and calibrated predictions compared with the observed field data. The test included visual comparisons, measures of deviance between the simulated and observed data, and statistical test.

A time series plot (Figure 3.1) indicates that, from visual inspection, the calibrated total site carbon curve agrees more closely with the observed data than the non-calibrated curve. When the predicted values are plotted against the observed data (see Figure 3.6a and b) for both curves, it is possible to determine whether or not the predicted values display bias against the observed values. This type of plot displays the goodness of fit, as well as the vertical deviations from the perfect 1:1 ratio line. Although the calibrated predictions plotted in Figure 3.6b show the same pattern of data distribution, overall the predictions have decreased by the same amount, associating them more closely with the line of best fit. This is further emphasized by a regression analysis of the two data sets. In both figures, the regression line maintains the same slope of 0.638. A standard two-tailed t-test testing whether the slope of each regression line is significantly different from the line of best fit, indicates that even though the calibrated model's predictions appear to align more closely with the perfect fit line, both the calibrated and non-calibrated equations are significantly different from this line, indicating that both show bias from the observed data. Although it was not tested statistically, it can be observed from Figures 3.6a and b that the Y-intercept for both regression lines for each data set are also significantly different from the Y-intercept of zero, therefore, also indicating the models predictions are biased. It can be noted, however, that these discrepancies are mostly in the observations less then 100 Mg C ha^{-1}. If the missing stumps and dead coarse roots carbon data were added to the observed values some of the biased may be removed.

In order to measure the deviance of the predicted values from the observed, mean absolute error (MAE) and mean absolute percent error (MA%E) were used. These two measures were mainly used to compare the two simulations to see which one displayed the least difference between the predicted and observed values. Table 3.1 shows the calculated values for each measurement for each data set. It is clear that the calibrated model's predictions show the least deviation from the observed. The lower MAE and MA%E values indicate this.

To directly measure how the predictions relate to the observed data, a dimensionless modelling efficiency (EF) statistic was used. The EF statistic measures the proportion of variation explained by the predicted versus the observed data against the line of perfect fit. The perfect fit results in a value of one. The degree of fitness declines as the EF value falls away from one. In Table 3.1, it can be seen that the calibrated model displays the highest EF value at 0.71 as opposed to 0.32 for the non-calibrated model; thus, indicating that the calibrated model predictions show an overall better exactness of fit.

3.5 CONCLUSION

A stand-level stock estimate of a naturally grown red spruce stand following a clear-cut disturbance in Nova Scotia was simulated using the CBM-CFS 3. Total site carbon predictions from the simulation were compared with field data from a chronosequence of red spruce stands from the Eastern Eco-region of central Nova Scotia. The simulation yielded significantly higher carbon stock than the observed data. Differences were also observed in the pattern of carbon accumulation throughout stand development.

The higher carbon stocks predicted by the model may have been due to over estimation of the DOM pool, more specifically, the Slow Belowground DOM pool. These stocks may also be higher due to smaller depth of mineral soil carbon sampled in the field compared with that represented in the model. Differences in the pattern of carbon accumulation may have been due to several explanations, which included: discrepancies between the harvesting disturbance matrix in the model and the actual harvesting technique used in the field, sampling methods used in the field (e.g. not measuring the stumps and dead coarse roots), and the influence of the growth and yield volume information imported into the model.

To compensate for the differences between the simulation predictions and the observed data, an attempt was made to calibrate the CBM-CFS 3 in order that it would more closely represent red spruce stands in the Eastern Eco-region of Nova Scotia, rather than the more broad Atlantic Maritime Eco-boundary used in the model. Through adjustment and sensitivity analysis of various parameters in the model, it was found that reparameterization of the Slow Belowground DOM pool (which showed the largest discrepancy) had the most effect on lowering carbon stock predictions.

A new simulation was run using the calibrated model to compare its predictions with the observed data. From visual inspection the calibrated models predictions agreed more strongly with the observed data than they did with the non-calibrated. Measures of deviance and modelling efficiency also indicated this. When both data sets were plotted against the observed data simple regression analysis showed that significant differences were found between the slope of their regression lines and the 1:1 line of best fit, indicating that both the non-calibrated and calibrated model showed bias in their predictions.

The calibrated model displayed improvement in predicting carbon stock estimates over the original non-calibrated model. Overall, its predictions remained bias to a lesser extent, indicating that further calibration would be necessary. Further calibration would require an extensive in-depth diagnostic and the examination of the various setting and parameters within the model, which would control the change in carbon stocks over time. Before any calibration could be further justified, more field data upon which to base the calibration and inclusion of the stumps and dead coarse roots carbon left behind after the clear-cut, would also be required.

CHAPTER FOUR

EXPLORATORY ANALYSIS OF HARVESTING SYSTEMS ON CARBON STORAGE

4.1 INTRODUCTION

With the anticipated change in global climate, governments are now pursuing ways in which to mitigate the effects of rising greenhouse gas (GHG) concentrations in the atmosphere. Increasing the amount of carbon stored in terrestrial vegetation may help in reducing global concentrations of atmospheric carbon dioxide. Enhancing carbon sinks and reducing carbon sources in forest ecosystems may be achieved through forest management activities while still maintaining a continuous flow of biomass carbon in order to meet the timber, fibre and energy needs of society (Kurz et al. 2002). Forest ecosystems are dynamic environments, constantly being subjected to natural disturbances and anthropogenic influences, such as harvesting. In order to better understand how we can use forests to help offset GHG emissions, more knowledge is required about the impact of forestry practices on the carbon cycle in these systems.

It has been suggested by Papodopol (2000) that intensive forest management can increase productivity in forests. For example, assisted regeneration and tree planting, vegetation management and fertilization on some soil types may increase productivity, shorten rotation and therefore increase the potential of a forest to sequester and store carbon. When studying different management activities and their influence on forest carbon sequestration and storage, the intensity at which harvesting takes place must also be considered. Harvesting methods such as clear-cutting tend to remove most of the standing biomass per unit area at one time. Other harvest methods such as selection or partial-cutting, remove less biomass at one time, but do so more frequently.

Which method of harvesting provides and maintains the most carbon sequestration and storage is currently unclear. Many arguments exist today as to which system of harvesting is the most effective in creating and maintaining a carbon sink. Other factors must also be taken into consideration, such as their effect on other natural systems within the environment (e.g. biodiversity and habitat), or economic practicality.

Papadopol (2002) states that selection or partial-cutting leaves a continual amount of growing biomass in the forest. This reduces the exposure to the soil of sun and thus helps to prevent enhanced decomposition. Alternatively, clear-cutting removes most of the biomass in one cut, therefore exposing much of the forest soil to the sun, potentially increasing the rate of decomposition of the forest floor and the site acts as a net source of CO_2, at least until new regeneration becomes established. Covington (1981) found that in hardwood forest in New Hampshire after clear-cutting, 40-50% of the original forest floor organic mass had decreased 15 years after the disturbance. Work done in the same area by Yanai et al. (2000), however, found that the 40-50% losses predicted by Covington (1981) were not supported.

Studying boreal mixedwood forest in northern Ontario, Lee et al. (2002) found that there was no significant difference in the decomposition rates of litter fall between clear-cut and partial-cut harvesting within five years following these treatments. They suggest that this may be attributed to the quick regeneration cover provided by early succession species present in the clear-cut area. However, when observing absolute quantities of CO_2 liberated through decomposition it may well be higher in the clear-cut area due to the greater amount of necromass added to the forest floor.

Harmon and Marks (2002), examined the effects of various silvicultural treatments on carbon pools in the Pacific Northwest forest sector in the U.S. using the model STANDCARB. They found that in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) and hemlock (*Tsuga heterophylla* (Raf.) Sarg) forests, the best silviculture system in terms of balancing carbon storage against forest timber production was partial-cutting. They state that non-traditional systems such as partial harvesting (with minimum slash and burn) can provide as much timber as more intense traditional harvesting systems, and also increase carbon storage to twice the level that can be maintained in a traditional system such as clear-cutting.

Selection or partial-cut silviculture systems fall under one of the silviculture credit categories in the Nova Scotia Forest Sustainability Regulations. This type of harvesting is being encouraged in the province as an alternative to clear-cutting practices, when applicable. Some local foresters believe that partial-cut systems are a more appropriate management system for the native Acadian forest type. Indiscriminate use of clear-cutting is a threat to the natural diversity and sustainability of the Acadian forest, favouring the growth of shrubs and shade intolerant tree species. Such stands require much tending (manual weeding and herbicide treatments) in order to ensure that some of the more desired softwood species persists. Use of harvesting methods such as shelterwood and selection-cutting may provide the shade necessary to give more desired shade tolerant species, such as spruce, a growth advantage.

Which system of harvesting is most beneficial in terms of carbon sequestration and storage is still an issue for debate and is dependent on many factors, such as forest type, tree species and location. The objective of this chapter is not to make any clear inferences indicating which system is most appropriate, but rather to explore the effects of clear-cutting and partial-cutting on carbon storage and sequestration in red spruce forest ecosystems using the CBM-CFS 3. This exercise will use the CBM-CFS 3 to simulate clear-cutting and partial-cutting regimes in natural red spruce dominated forest in Nova Scotia. Results from the simulations will be compared in order to examine the effects of each system of harvesting on carbon sequestration and storage in this forest type. These results will also be compared with the literature to examine how the model results compare with other studies.

The specific objectives are as follows:

- To use the CBM-CFS 3 to create and run clear-cutting and partial-cutting management scenarios for natural red spruce stands in Nova Scotia.
- To compare the carbon pools from these two management scenarios in order to examine any potential advantages or disadvantages with regard to carbon sequestration and storage.

4.2 MATERIALS AND METHODS

A comparison between a clear-cutting system and a partial-cutting system was conducted in this chapter. A natural red spruce dominated stand in Nova Scotia, as described in the previous chapters, was selected in order to demonstrate the effects of these two harvesting systems on carbon sequestration and storage. In order to achieve this comparison a model scenario was created for each type of harvesting system. The scenarios attempted to represent how each system might be carried out on a red spruce stand in Nova Scotia.

Both scenarios were created to explore a 240-year simulation period, over which, each harvesting system would be carried out. In both scenarios the red spruce stands originate from a clear-cut disturbance. Table 4.1 describes each harvesting scenario. The partial-cut system involves five harvesting rotations over the 240-year period. The first rotation is 80 years, while the remaining four rotations are each 40 years long. During each harvest at the end of each rotation, 50% of the biomass is removed. At the beginning of each rotation it is assumed that the stand regenerates naturally and is 100% stocked. During the first rotation, this represents harvesting 50% of the 80-year old red spruce stand. This leaves half of the stand with 80-year old red spruce, and the other half with new regeneration. Forty-years later, the next harvest again removes 50% of the biomass carbon, which in reality involves harvesting the older 120-year old red spruce left over from the first rotation and leaving 40-year old red spruce and new regeneration. By the time of the next harvest, year 160 of the scenario, the 40-year old red spruce are now 80 years old and ready to be harvested, leaving the stand with 40-year old red spruce and new regeneration. This harvesting cycle continues for the rest of the 240-year scenario.

The clear-cutting scenario involves three rotations, each being 80-years in length. At the end of each rotation all of the merchantable biomass is removed from the stand. At the beginning of each rotation it is assumed that the stand regenerates naturally and is 100% stocked.

Table 4.1 Description of each harvesting scenario.

Harvesting System	Scenario Length (years)	Rotations	Rotation Length (years)	Year of Harvest	Age Class Removed	Residual Age Classes
Partial-cutting	240	1	80	80	80	80 and 0
		2	40	120	120	40 and 0
		3	40	160	80	40 and 0
		4	40	200	80	40 and 0
		5	40	240	80	40 and 0
Clear-cutting	240	1	80	80	All age classes	0
		2	80	160	All age classes	0
		3	80	240	All age classes	0

In order to accomplish the simulations two import files were created for the CBM-CFS 3 that represented red spruce stands under the harvesting scenarios described. Both import files contained similar information which described the characteristics of the red spruce stand. They both described a one ha red spruce stand with the same growth and yield information as used in Chapter three. The main differences between the two files were the disturbance events and transition rules which represented each harvesting scenario.

Once the files were imported into the model the Slow DOM pool parameters were adjusted to the recalibrated values described in Chapter 3. This was done to better represent the conditions of a red spruce stand in the Eastern Eco-region of Nova Scotia. Also, the last disturbance type, which describes the last disturbance event to affect the stand before the beginning of the model simulation, was changed to a clear-cut disturbance in order to represent stands which originated from this type of disturbance. After these changes were made to the model the simulations were run.

4.3 RESULTS

The results from the two simulations indicate that, overall, total site carbon increased in the partial-cut scenario, while in the clear-cut scenario it decreased. It must be noted however, that this is a beta version of the CBM-CFS 3 and that results from the model are considered here for exploratory purposes only.

Figure 4.1 shows the change in total site carbon over time of each rotation for each harvesting scenario. In this figure, the five partial-cut rotations and the three clear-cut rotations can be recognized. It can be seen from year one following the initial clear-cut disturbance until the first harvest in year 80, that both simulations display the same pattern of carbon accumulation. This is expected since both simulations represent the same stand. However, after the first rotation the two simulations begin to diverge. The clear-cut simulation displays a major decrease in carbon mass, mainly due to the large removal of biomass. The partial-cut simulation displays a much smaller decrease in carbon and also shows a faster recovery in carbon mass following the harvesting disturbance. By the time of the second clear-cut harvest and the third partial-cut harvest, the partial-cut stand shows higher peak carbon storage at 226 Mg C ha^{-1}, while the clear-cut stand shows a carbon storage value of 199 Mg C ha^{-1}. At the end of the 240-year simulation period the partial-cut stand displays a maximum carbon storage value of 232 Mg C ha^{-1}, while the clear-cut stand is 198 Mg C ha^{-1}. On average the partial-cut stand stores 202 Mg C ha^{-1} between years 80 and 240, while the clear-cut stand only stores 123 Mg C ha^{-1}.

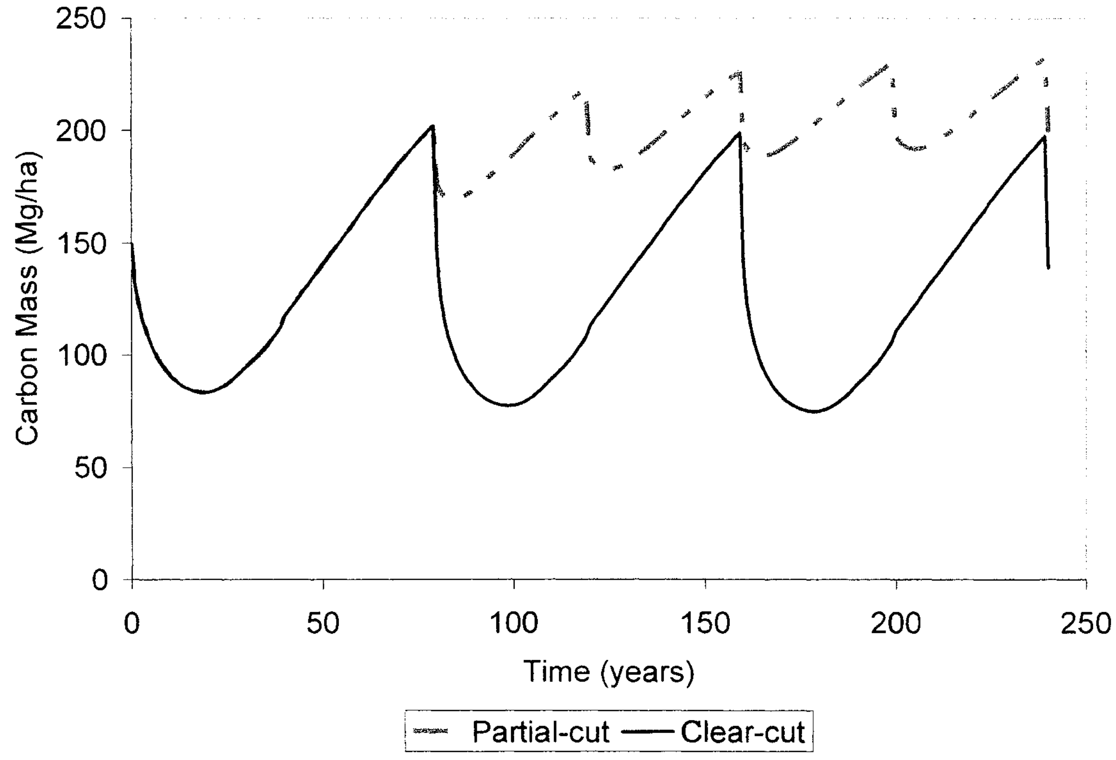


Figure 4.1 The change in total site carbon storage over time for both the partial-cut and the clear-cut stands.

Figure 4.2 shows the change in biomass carbon for each simulation over time. It can be seen from each clear-cut harvest, that all the biomass carbon is removed, decreasing from 118 Mg C ha^{-1} to zero. The partial-cut harvest only removes 50% of the biomass carbon, displaying a decrease from 118 Mg C ha^{-1} to 60 Mg C ha^{-1}. Throughout the 240-year simulation period the clear-cut stand accumulates the same amount of carbon at the end of each rotation. The partial-cut stand, however, demonstrates a small increase in carbon storage at the end of every rotation, reaching a maximum value of 127 Mg C ha^{-1} in the last rotation. Figure 4.3a and b show the change in total biomass and merchantable stemwood carbon over the length of the simulation for both harvesting methods. The same trend in tree biomass carbon as demonstrated in Figure 4.2 can be noticed in the merchantable stemwood carbon in Figure 4.3a and b. Table 4.2 shows that the partial-cut harvest yields slightly more merchantable stemwood then does the clear-cut harvest scenario during each 80-year rotation period.

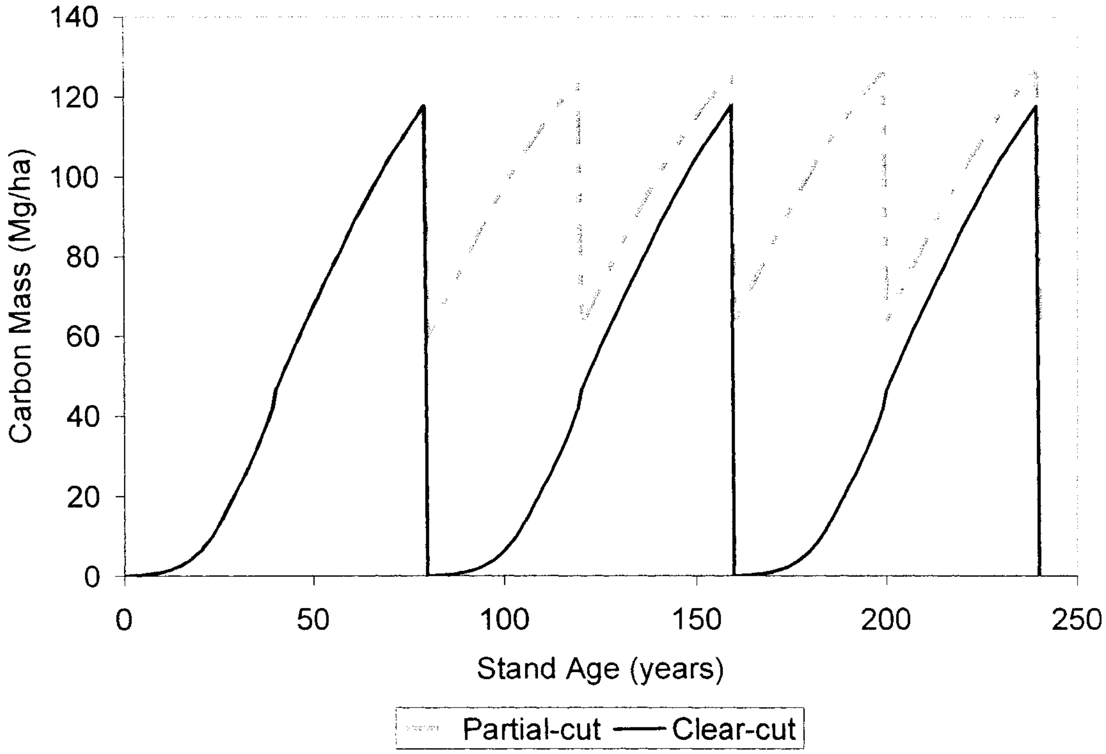


Figure 4.2 The change in tree biomass carbon storage over time for both the partial-cut and the clear-cut stands.

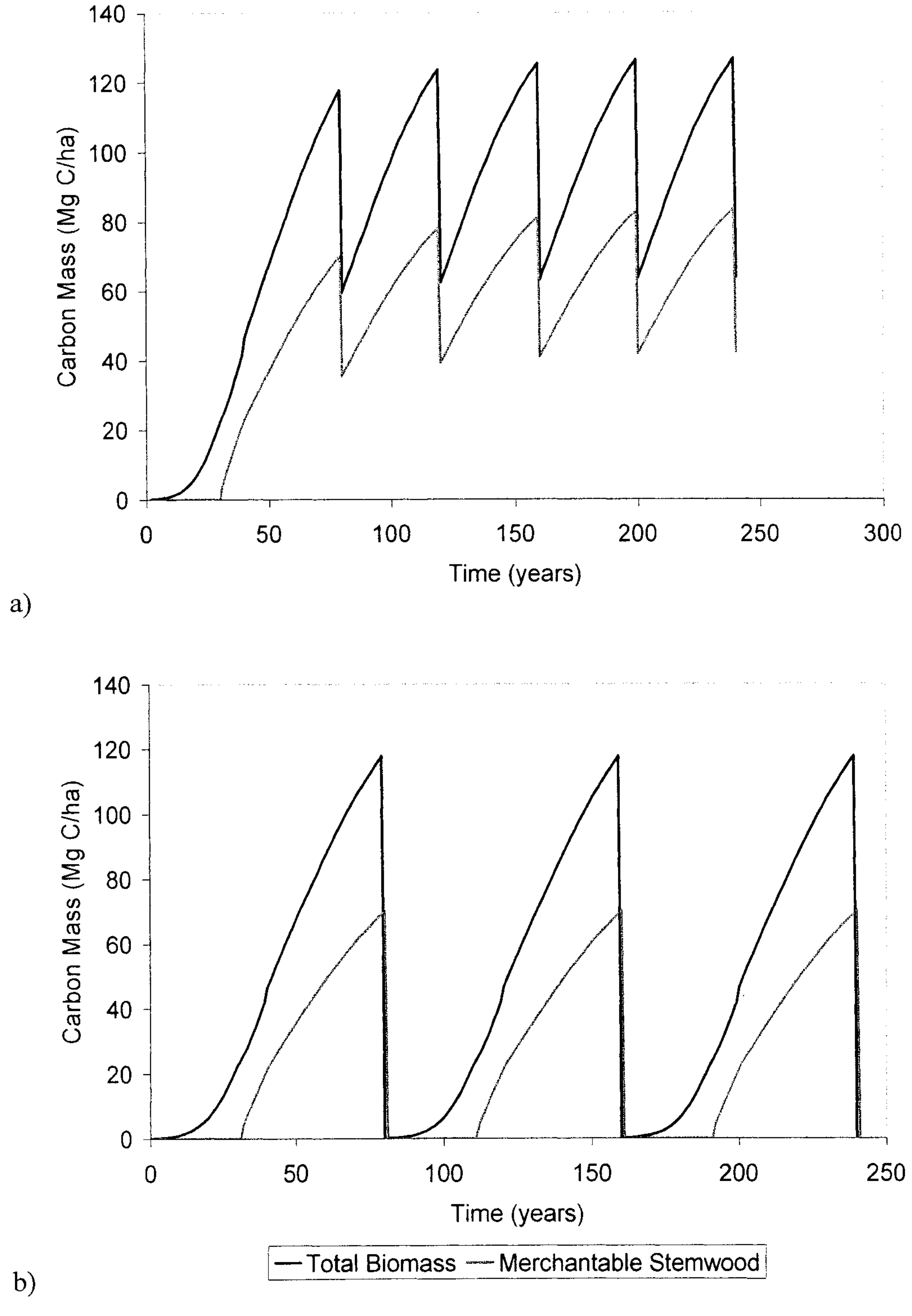


Figure 4.3 The change in carbon mass over time in total tree biomass and merchantable stemwood for the a) Partial-cut stand and b) Clear-cut stand.

Table 4.2 Harvested merchantable stemwood for each rotation of each harvesting method during the 240-year simulation.

Clear-Cut		Partial-Cut	
Rotation Period (years)	Merchantable Stemwood removed (Mg C/ha)	Rotation Period (years)	Merchantable Stemwood removed (Mg C/ha)
80-160	59.69	80-120	31.26
		120-160	32.55
160-240	59.69	160-200	33.19
		200-240	33.51
Total:	119.38		130.51

Differences in the pattern of DOM carbon storage over time can be distinguished between the two harvesting systems. Figure 4.4 shows the effect of each harvesting system on DOM carbon storage in the red spruce stand. It can be seen from this figure that following the initial clear-cut disturbance in year one, DOM carbon is highest, but decreases rapidly until reaching a low in year 39 at 71 Mg C ha^{-1}. It then begins to accumulate slowly until the first harvest. Dead organic matter carbon increases immediately in both simulations following harvest, showing the highest jump in the clear-cut stand primarily due to the addition of stumps and roots from the cut trees. Following this sharp increase in DOM carbon, due to the harvesting disturbance, it then begins to decrease in both simulations; however, it decreases the most in the clear-cut stand. Overall, the partial-cut stand maintains a higher carbon storage. It does not show the high peak values attained by the clear-cut stand after each harvest, but shows a steady overall increase in DOM carbon after each harvest, increasing from 116 to 136 Mg C ha^{-1}. Contrary to this, the clear-cut stand shows a steady decrease in peak DOM carbon following each harvest, decreasing from 144 to 139 Mg C ha^{-1}.

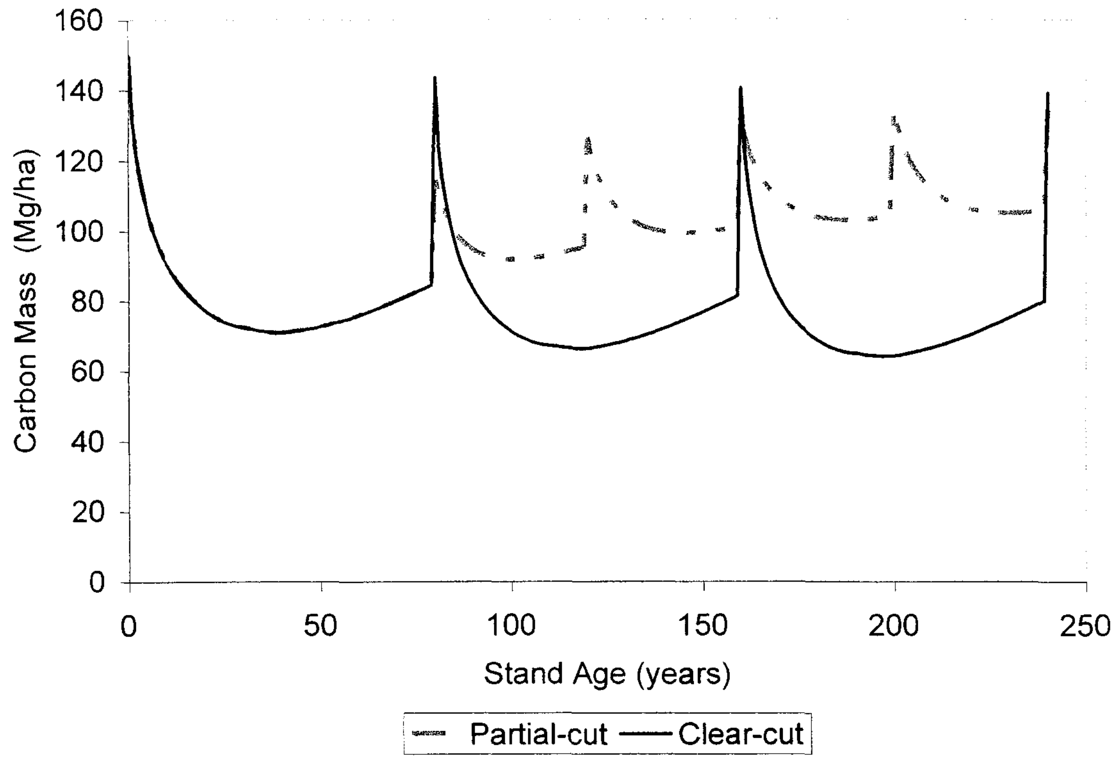


Figure 4.4 The change in DOM carbon storage over time for both the partial-cut and the clear-cut stand.

In order to examine more closely how the DOM carbon pool is affected by each harvesting system a closer examination of the various sub-DOM carbon pools was necessary. Figures 4.5a and b show the four main DOM pools which make up total DOM carbon. Figure 4.5a shows the change in these carbon pools over time due to the partial-cut harvesting regime. Figure 4.5b shows changes in the same pools for the clear-cut harvesting regime.

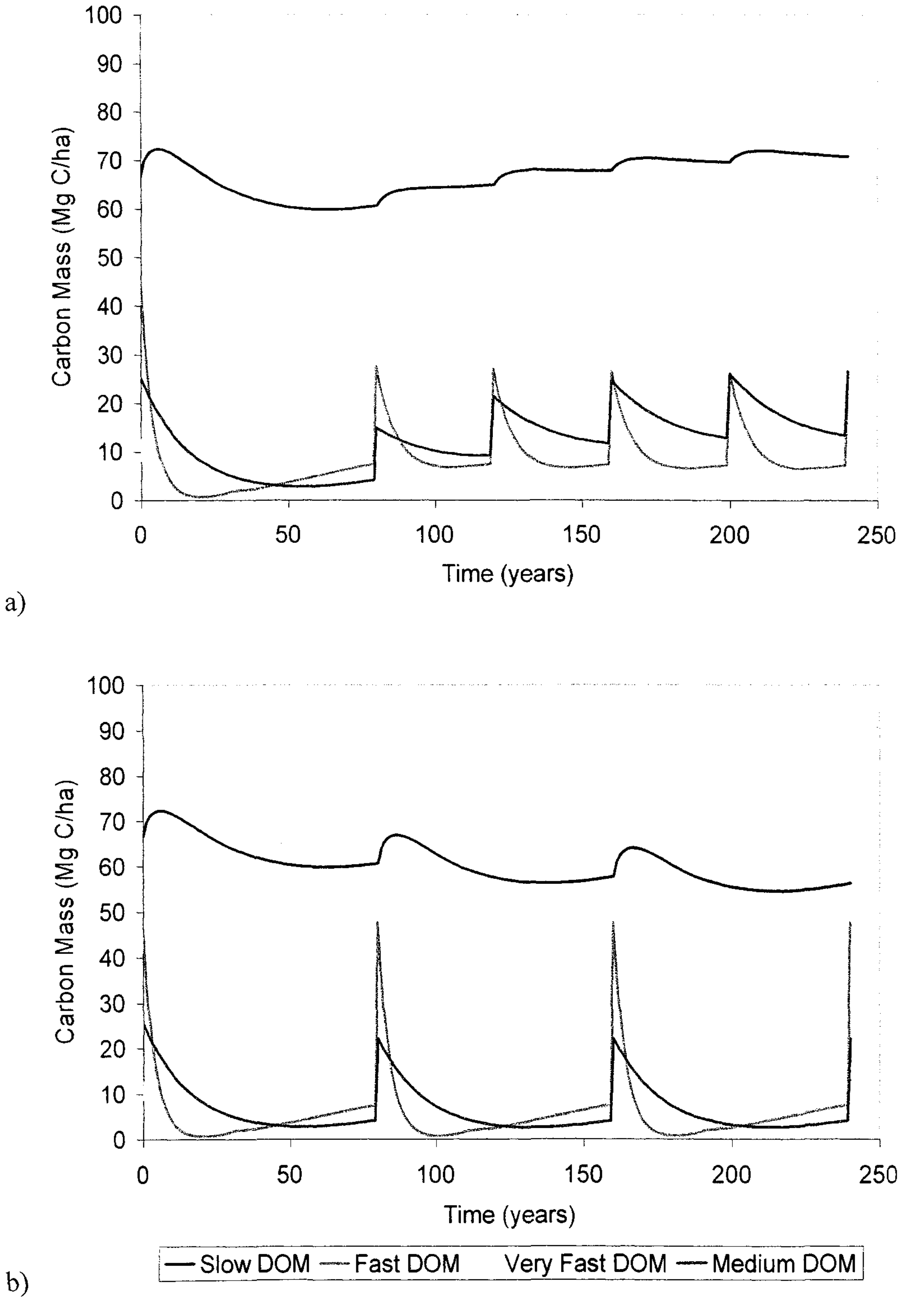


Figure 4.5 The change in carbon storage over time for the Slow, Medium, Fast and Very Fast DOM carbon pools for the a) Partial-cut stand and b) Clear-cut stand.

When compared, differences in each carbon pool between the two harvesting regimes can be detected. One of the most noticeable differences is in the Fast DOM carbon pool. This pool consists of input from snag branches, tree branches, sub-merchantable trees and coarse roots. In Figure 4.5b it can be seen that after each clear-cut harvest this pool increases substantially, more so then it does after each partial-cut harvest. This same trend is also noticeable in the Very Fast DOM pool. These spikes in Fast and Very Fast DOM input, however, are of short duration and decrease quickly due to the short-turnover (fast decomposition) rates that characterise these carbon pools. These spikes are not as dramatic in the partial-cut stand. In between harvesting disturbances, however, a higher carbon mass is sustained than that found in between the clear-cut harvest.

When examining the Medium and Slow DOM pools, it can be seen that after the first harvest, these pools are higher in the clear-cut stand; however, after each proceeding harvest these pools begin to decrease in the clear-cut stand and increase in the partial-cut stand. These DOM pools have longer carbon turn-over (slow decomposition) rates and make up the largest portion of total DOM carbon. Thus, indicating that the partial-cut stand has a higher capacity for storing carbon in the long term.

4.4 DISCUSSION

Total Site Carbon

The use of different harvesting methods can have significant affects on carbon sequestration and storage in a forest ecosystem. This study found that partial-cut harvesting had a positive influence on carbon stocks, compared with clear-cut harvesting. Based on the results from the beta-version of the CBM-CFS 3, over a 240-year simulation period, the partial-cut rotation cycle displayed a continued growth in carbon accumulation. By examining the peak carbon mass accumulation at the end of each harvest cycle, the partial-cut stand increased from 202.28 to 232.38 Mg C ha^{-1} (Figure 4.1). Alternatively, the clear-cut rotation cycle demonstrated an overall decrease in carbon mass, from 202.28 to 197.75 Mg C ha^{-1}. On average the partial-cut stand stored 202 Mg C ha^{-1} between years 80 and 240, while the clear-cut stand stored only 123 Mg C ha^{-1}.

These results agree with those findings of Lee et al. (2002). They found that partial-cut harvesting, in boreal mixedwood forests in Northwestern Ontario, displayed higher annual carbon sequestration then clear-cut harvesting in the same forest type. Lee et al. (2002) only studied these stands within a five-year period following the harvesting disturbances; however, during that time the gross production of woody biomass was greater in the partial-cut area (18.64 Mg ha^{-1}) then the clear-cut area (3.15 Mg ha^{-1}). This represented an estimated removal of 34.2 Mg CO_2 ha^{-1} from the atmosphere for the partial-cut, as apposed to 5.8 Mg CO_2 ha^{-1} for the clear-cut area. It can be expected, however, that when the regeneration in the clear-cut area enters into its exponential growth phase of biomass accumulation, carbon sequestration may surpass that of the partial-cut treatment.

Harmon and Marks (2002) also found partial-cut harvesting to be more effective in sequestering and storing carbon then more intensive harvesting methods such as clear-cutting. By using the ecosystem model STANDCARB, they found that in Douglas-fir and hemlock forests, partial-cutting systems increase carbon stores to twice the level maintained in more traditional short-rotation, high-utilization systems. Through examining various harvesting influences on these forest types, Harmon and Marks (2002), found that three factors most important in developing an optimum carbon sequestration system are: 1) rotation length, 2) amount of detritus removed by slash-burn fires and 3) amount of live biomass harvested. The amount of biomass removed from a site due to harvesting methods, directly relates to what was examined in this study. They found that when 100% of the tree mass was cut and 100% of the bole mass was removed from the forest site, such as in a clear-cut system, carbon storage and sequestration decreased. By cutting only 80% of the tree mass and removing 80% of the felled bole mass, carbon storage was increased. They attribute this to the fact that the low-utilization systems leave some live trees, which continue to grow and sequester carbon. These residual trees provide a continued input of detritus material to the forest floor, and provide enough shade to allow the detritus to decompose slowly in place.

To understand how the CBM-CFS 3 simulations predicted higher carbon sequestration and storage in the partial-cut stand than in the clear-cut stand, it is necessary to examine the various carbon pools which make up total site carbon and how these are affected by the harvesting disturbances.

Tree Biomass Carbon

The tree biomass pool represents all the living above and belowground tree biomass in the stand, including merchantable and submerchantable trees. It is clear from Figure 4.2 that the clear-cut harvest removes all the biomass carbon at one time, while the partial-cut harvest only removes 50% (as was defined through user input in the partial-cut disturbance matrix). Also evident from this figure is the difference in biomass growth rate in each harvest for each harvest method. When examining the first 40-years following the first rotation in the simulations, it can be noticed that the partial-cut stand has a steeper, thus faster rate of biomass recovery then does the clear-cut stand. The clear-cut stand exhibits a slower growth rate following the harvest. These results are due primarily to the way in which the CBM-CFS 3 uses growth curves to describe post-harvest biomass growth. In the clear-cut stand, for example, after the harvesting disturbance has removed 100% of the biomass carbon, the stand age is reset to zero. The model then corresponds that age to the existing biomass growth curve used in the model to describe the growth of that stand. Since the stand is at age zero, the biomass growth will start at age zero on the growth curve [Rampley (pers. comm.., 7 Dec. 2004)]. Following a partial-cut disturbance the model will try to determine a new "stand age" based on how much tree biomass is left in the stand. It determines what age corresponds to the remaining biomass. It will then set the stand to the corresponding age and begin post-disturbance tree biomass growth from that point on the growth curve. It is possible to specify a specific age for the stand following the disturbance manually; however, this option was not available in the model during the time of this study.

The method in which the model determines the new growth rate following a disturbance is why noticeable differences in tree biomass growth between the two harvesting methods are recognized. Since the clear-cut stand is set to age zero after the harvest disturbance, the stand starts growing from year zero on the growth curve, which is characterized by slow initial growth of the regenerating seedlings. In the partial-cut stand, the amount of residual biomass determines what age the stand is set to. When the remaining tree biomass carbon is 60 Mg C ha^{-1}, the model searches for the corresponding age on the biomass growth curve. The tree biomass growth curve is non-linear in nature, therefore this part of the growth curve is characterized by a faster growth rate; therefore, the partial-cut stand displays a faster rate of growth following the harvest (as you would expect given the size of the trees).

In reality, following a clear-cut disturbance in a red spruce stand, a new even-aged stand would be initiated. Therefore, in the CBM-CFS 3 simulation, following the clear-cut disturbance, the initiation of a new red spruce stand at year zero using a single growth curve is, to some extent, representative of reality. In the partial-cut situation, after first harvest of the red spruce stand, 50% of the biomass carbon has been removed, leaving roughly half the stand as 80-years old and half as new regeneration. The older residual trees would be growing at a different rate then the new regeneration. The CBM-CFS 3 is a stand-level model and is not spatially specific. Currently it has no method of implementing growth curves for two cohorts within the same stand. Therefore, it uses a single growth curve based on the residual biomass following the disturbance. Whether or not this is an adequate representation of reality is questionable. Given the potential heterogeneity in the growth of the remaining live trees and new growth in a real life stand, the new growth curve designated to the post-disturbance stand may on average summarize the overall biomass growth of the stand adequately. Following the partial-cut disturbance there is still roughly 50% 80-year old trees and 50% new regeneration, it seems biologically reasonable that the partial-cut stand displays a higher rate of biomass carbon growth in the years after cutting then the clear-cut stand.

From Figure 4.2 it can be seen that tree biomass carbon is overall, higher in the partial-cut stand then in the clear-cut stand. By examining the peak biomass carbon values at the end of each rotation, the partial-cut stand surpasses the clear-cut stand and shows an increase in peak biomass carbon throughout the simulation. This can be explained by the new age and growth rate designated to the post-disturbance stand as discussed above. Therefore, it may be considered that the interaction of the new growth rate associated with the new stand and the level of residual tree biomass carbon that exist, is the reason why the partial-cut stand demonstrates an overall increase in biomass carbon over time.

The clear-cut stand does not show an increase in tree biomass carbon for each rotation: each rotation follows the same growth curve. This is due to the fact that after each clear-cut harvest the stand is set to age zero. It is then grown again to age 80 years and harvested. Since all of the biomass carbon is removed after each harvest, the stand starts from zero biomass and uses the same growth curve in each rotation.

Harmon and Marks (2002) indicate from their analysis that partial-cut systems can provide as much timber harvest as clear-cut systems over a given amount of time. When comparing the amount of biomass carbon harvested from each stand within an 80-year rotation in this study, the highest yield comes from the partial-cut stand (Figure 4.2). Within one 80-year rotation, there is a single clear-cut harvest for every two partial-cut harvests. Between the years 80 and 160 of the simulation, the single clear-cut removes all of the 117.78 Mg C ha^{-1} of tree biomass carbon present in the stand. Figure 4.3b shows the change in merchantable stemwood carbon mass caused by the clear-cut. According to the disturbance matrix which describes the clear-cut harvest in the model, 85% of the merchantable stemwood biomass is removed from the stand as potential product, while the remaining biomass is transferred to various DOM carbon pools. This represents an approximate value of 59.69 Mg C ha^{-1} of product for that 80 year period.

The partial-cut disturbance matrix describes that at each harvest 50% of the merchantable stemwood biomass remains in the stand while 40% is transferred to potential products and 10% is transferred to the DOM pool. Figure 4.3a shows the change in merchantable stemwood carbon mass caused by the partial-cut harvest disturbance. Between the years 80 to 160 of the simulation, the two partial-cuts remove approximately a combined 63.23 Mg C ha^{-1} of product. This represents an additional 3.54 Mg C ha^{-1} sequestered as potential forest products in the partial-cut stand. Therefore the results from this model analysis indicate that partial-cut harvesting has the potential to provide as much timber as clear-cut harvesting while maintaining higher carbon storage within the stand.

DOM Carbon

Figure 4.4 shows the changes in DOM carbon over time in the red spruce stands due to the different harvesting disturbances. The CBM-CFS 3 simulation results indicate that overall, after the first 80-year rotation, the partial-cut stand displays the largest carbon storage capacity. Although, after each clear-cut harvest, DOM increases substantially, reaching higher peak values of DOM carbon, it is for only a short time and the level of DOM carbon decreases dramatically, below that of what is sustained in the partial-cut stand.

The sudden influx of carbon into the DOM pool in the clear-cut stand is the result of a large transfer of woody material caused by the clear-cut disturbance, mainly roots, sub-merchantable stems, branches and foliage. This material adds a significant portion of carbon into the DOM pool, however, it is short lived. Most of this material is characterized under the Very Fast and Fast DOM pools in the CBM-CFS 3.

Figures 4.5a and b show changes in carbon mass of the various DOM pools which make up total stand DOM for each of the harvesting methods. From both of these figures it can be seen that the Slow DOM pool contains the largest portion of carbon and remains at a fairly consistent level throughout the 240-year simulation. This is mainly due to the slow decomposition rates associated with this pool, allowing carbon in this pool the longest residence time. Although this pool is the most consistent in terms of carbon levels over time, noticeable differences can be detected between the two harvesting methods. Following the first 80-year rotation, the partial-cut stand demonstrates a steady increase in carbon accumulation in the Slow DOM pool. After every partial harvest there is an increase in carbon, which continues to grow throughout the rotation. In the clear-cut stand, however, there is a steady decrease in carbon mass. Each subsequent harvest displays overall decrease in carbon storage throughout the rotation.

Several reasons may explain these different trends in each stand. Within the partial-cut stand there is always residual tree biomass remaining. These remaining trees provide a continual input of annual litter fall and shade. This effect can be noticed in the Very Fast and Fast DOM pools of the partial-cut stand (Figure 4.5a) compared with the clear-cut stand (Figure 4.5b). The clear-cut harvest provides a large initial input of carbon into these pools directly after harvest, demonstrated by a large spike in carbon mass; however, once all of the biomass has been removed from the stand after harvest, annual litter fall decreases and the pools shrink as a direct result. Since the partial-cut stand always has residual trees remaining, there is always an input of litter fall. This effect can be seen in Figure 4.5a where even after the initial spike in carbon mass following harvesting, the pools remain consistently higher than in the clear-cut stand. Because there is a continual input of litter fall in the partial-cut stand, the decomposition of this material provides continual input of organic matter into the Slow DOM pool.

Another reason for the trend in the Slow DOM pool in the partial-cut stand has to do with the shade provided by the residual trees. In the clear-cut stand all of the over-story is removed from the harvest. This exposes the forest floor to much more solar radiation than is exposed in the partial-cut stand. As a consequence of this, decomposition of the organic matter in the forest floor is accelerated in the clear-cut stand. The shade provided by the residual trees in the partial-cut stand prevents such acceleration. The CBM-CFS 3 takes this effect into consideration by modifying the decomposition rates of all but the Slow DOM pools in order to compensate for such changes in solar radiation (and therefore soil temperature) (Kurz and Apps 1999). The model increases decomposition rates when more aboveground biomass is removed from the stand. As aboveground biomass accumulates as a result of growth and the forest canopy begins to close, the accelerated decomposition rates are slowed down.

4.5 CONCLUSION

Comparison between partial-cut and clear-cut harvesting methods on red spruce stands in Nova Scotia was examined in this chapter through the use of the CBM-CFS 3. Modeling results indicate that partial-cut harvesting had a positive influence on total site carbon storage compared with clear-cut harvesting over a 240-year simulation period. The partial-cut red spruce stand displayed an overall increase in carbon mass at the end of the simulation period, peaking at 232.38 Mg C ha^{-1}. The clear-cut scenario, however, demonstrated a decrease in carbon storage over time, showing only 197.75 Mg C ha^{-1} at the end of the simulation period. On average the partial-cut stand stores 202 Mg C ha^{-1} between years 80 and 240, while the clear-cut stand only stores 123 Mg C ha^{-1}.

Examination of the various carbon pools associated with total site carbon indicates that tree biomass and DOM carbon pools both increased over time in the partial-cut stand. In the clear-cut stand, maximum tree biomass carbon storage remained consistent after each harvest rotation, however, DOM carbon storage decreased. This decrease was greatest in the Slow DOM carbon pool. It is speculated in this study from review of the literature and the CBM-CFS 3 model itself that the decrease in DOM carbon is most likely attributed to loss of tree cover, which translates into increased exposure of the forest floor to sunlight and decreased detrital material input into the DOM pool due to the 100% removal of tree biomass from the stand in the clear-cut scenario. Contrary to this, the partial-cut stand retained 50% of its tree biomass following each harvest and therefore, maintained a higher level of crown cover and detrital input from the residual tree biomass.

While the partial-cut harvesting scenario displayed a higher capacity to sequester and store carbon over clear-cut harvesting, it also demonstrated the potential to produce slightly more merchantable stemwood over an 80-year rotation period. Within a single 80-year rotation period two partial-cut harvests would take place for each single clear-cut harvest. It was found that in this amount of time, the clear-cut harvest would yield 59.69

Mg C ha^{-1} of merchantable stemwood, while the partial-cut harvest would yield 63.23 Mg C ha^{-1}. This indicates that partial-cut harvesting has the potential to increase carbon storage in red spruce forests, and also produce as much merchantable wood product as clear-cut harvesting over the long term.

The partial-cut and clear-cut harvesting simulations using the CBM-CFS 3 found that partial-cut harvesting has the most potential to sequester and store carbon in red spruce stands in Nova Scotia, while producing more merchantable stemwood. These finding are based solely on results from the CBM-CFS 3 simulations and are merely exploratory in nature. Investigation as to which harvesting system is most advantageous with regard to carbon storage and timber production would require much more in-depth analysis of the actual harvesting systems themselves and potential product yields.

LITERATURE CITED

Anonymous. 1992. A Map of the Province of Nova Scotia. Fourth edition. Nova Scotia: Formac Pub. Co. Ltd.

Banfield, G.E., J.S. Bhatti, H. Jiang and M. J. Apps. 2002. Variability in regional scale estimates of carbon stocks in boreal forest ecosystems: results from West-Central Alberta. For. Ecol. Manage. 169: 15-27.

Barnes, B.V., D.R. Zak, S.R. Denton, S.H. Spurr. 1998. Forest Ecology. 4th ed. John Wiley and Sons, Inc. New York. 774 pp.

Binkley, D. 2004. A hypothesis about the interaction of tree dominance and stand production through stand development. For. Ecol. Manage. 190: 265-271.

Boone, R.D., P. Sollins, K. Cromack. 1988. Stand and soil changes along a mountain hemlock death and regrowth sequence. Ecology 69: 714-722.

Chen, W., J.M. Chen, D.T. Price and J. Cihlar. 2002. Effects of stand age on net primary productivity of boreal black spruce forests in Ontario, Canada. Can. J. For. Res. 32: 833-842.

Cooper, F.C. 1983. Carbon storage in managed forest. Can. J. For. Res. 13: 155-166.

Covington, W.W. 1981. Changes in forest floor organic matter and nutrient content following clear-cutting in northern hardwoods. Ecology. 62: 41-48.

Davis, M.R., Allen, R.B., and P.W. Clinton. 2003. Carbon storage along a stand development sequence in a New Zealand Nothofagus forest. For. Ecol. Manage. 177: 313-321.

Dixon, R.K., S. Brown, R. A. Houghton, A. M. Solomon, M. C. Trexler and J. Wisniewski. 1994. Carbon pools and flux of global forest ecosystems. Science. 263: 185-190.

Environmental Stratification Working Group. 1996. A national ecological framework for Canada. Agriculture and Agri-Food Canada and Environment Canada. Ottawa/Hull. Report and national map at 1:7 500 000 scale.

Environment Canada. 1990. The Climates of Canada. Canadian Government Publishing Center. Ottawa, Canada. 176pp.

Environment Canada. 2004. The Climate of Nova Scotia. The Green Line. http://www.atl.ec.gc.ca/climate/ns.html. November 25, 2004.

Federer, C.A. 1984. Organic matter and nitrogen content of the forest floor in even-aged northern hardwoods. Can. J. For. Res. 14: 763-767.

Fernow, B.E. 1912. Forest conditions of Nova Scotia. Comm. Conserv. Canada.

Ford, E.D. and P.J. Newbould. 1977. The biomass production of ground vegetation and its relation to tree cover through a deciduos woodland cycle. J. Ecol. 65: 201-212.

Fowler, A., K. Low and J. Stone. 2002. Building a national forest sector carbon monitoring, accounting and reporting system. Information Forestry. Natural Resources Canada, Canadian Forest Service. 12pp.

Freedman, B., P.N. Duinker, H. Barclay, R. Morash, and U. Prager. 1982. Forest biomass and nutrient studies in central Nova Scotia. Maritimes Forest Research Center Information Report. M-X-134.

Freedman, B. and R. Morash. 1985. Forest biomass and nutrient studies in central Nova Scotia. Part 4. Biomass and nutrients in ground vegetation, forest floor, soils, and litterfall in a variety of forest stands. Canadian Forestry Service, Maritimes Forest Research Centre. ENFOR Project P-40. 14pp.

Freedman, B. and E.S. Wallace. 1986. Forest floor dynamics in a chronosequence of hardwood stands in central Nova Scotia. Can. J. For. Res. 16: 293-302.

Fujimori, T. 2001. Ecological and Silvicultural Strategies for Sustainable Forest Management. Elsevier, Amsterdam. 398pp.

Government of Canada. 2002a. A Discussion Paper on Canada's Contribution to Addressing Climate Change. http://www.climatechange.gc.ca/. January 25, 2003.

Government of Canada. 2002b. Climate Change Plan for Canada. http://www.climatechange.gc.ca/. February 28, 2003.

Grigal, D.F., and L.F. Ohmann. 1992. Carbon Storage in upland forest of the lake states. Soil Sci. Soc. Am. J. 56: 935-943.

Griss, P. 2002. Forest carbon management in Canada: Final report of the Pollution Probe Forest Carbon Management Workshop Series. Pollution Probe, Toronto. http://www.pollutionprobe.org/whatwedo/Kyoto.htm. February 1st, 2005.

Harmon, M.E., B. Marks. 2002. Effects of silviculture practises on carbon stores in Douglas-fir – western hemlock forests in the Pacific Northwest, U.S.A.: results from a simulation model. Can. J. For. Res. 32: 863-877.

Homann, P.S., R.B. McKann and P. Sollins. 2000. Belowground processes in forest-ecosystem biogeochemical simulation models. For. Ecol. Manage. 138: 3-18.

Hunt, R. 1982. Plant Growth Curves. The Functional Approach to Plant Growth Analysis. University Park Press, Baltimore. 248pp.

Husch, B., T.W. Beers and J.A. Kershaw, Jr. 2003. Forest Mensuration. 4th edition. John Wiley and Sons, Inc. 443pp.

IPCC. 2001. Climate Change 2001: The scientific basis. Contribution of working group I to the third assessment report of the International Panel on Climate Change. Edited by J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. vander Linden, X. Dai, K. Maskell, and C.A. Jonson. Cambridge University Press, Cambridge, U.K. 881pp.

Jiang, H., M.J. Apps, C. Peng, Y. Zhang, J. Liu. 2002. Modeling the influence of harvesting on Chinese boreal forest carbon dynamics. For. Ecol. Manage. 169: 65-82.

Johnson, D.W. 1992. Effects of forest management on soil carbon storage. Water Air Soil Poll. 64: 83-120.

Johnson, C.E. 1995. Soil nitrogen status 8 years after whole-tree clear-cutting. Can. J. For. Res. 25: 1346-1355.

Ker, M.F. 1984. Biomass equations for seven major maritime tree species. Canadian Forest Service. Maritimes Forest Research Center Information Report. M-X-148. 54pp.

Kurz, W.A., M.J. Apps, T.M. Webb and P.J. McNamee. 1992. The carbon budget of the Canadian forest sector: phase I. Northern Forestry Center. Information Report. NOR-X-326. 93pp.

Kurz, W.A., and M.J. Apps. 1999. A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. Ecol. Appl. 9(2): 526-547.

Kurz, W.A., M. Apps, E. Banfield, and G. Stinson. 2002. Forest carbon accounting at the operational scale. Forest. Chron. 78: 672-679.

Kurz, W.A., Beukema, S.J., and M.J. Apps. 1996. Estimation of root biomass and dynamics for the Carbon Budget Model of the Canadian Forest Sector. Can. J. For. Res. 26: 1973-1979.

Lamberty, B., .K. Wang and S.T. Gower. 2004. Net primary production and net ecosystem production of a boreal black spruce wildfire chronosequence. Glob. Change Biol. 10: 473-487.

Lee, J., I.K. Morrison, J.D. Leblanc, M.T. Dumas and D.A. Cameron. 2002. Carbon sequestration in trees and regrowth vegetation as affected by clearcut and partial cut harvesting in a second-growth boreal mixedwood. For. Ecol. Manage. 169: 83-101.

Li, Z., W.A. Kurz, M.J. Apps and S.J. Beukema. 2003a. Belowground biomass dynamics in the Carbon Budget Model of the Canadian Forest Sector: recent improvements and implications for the estimation of NPP and NEP. Can. J. For. Res. 33: 126-136.

Li, Z., M.J. Apps, W.A. Kurz, E. Banfield and Z. Li. 2003b. Temporal changes of forest net primary production and net ecosystem production in West Central Canada associated with natural and anthropogenic disturbances. Can. J. For. Res. 33: 2340-2351.

Loucks, O.L. 1962. A forest classification for the maritime provinces. Proceedings of the Nova Scotia Institute of Science, Halifax, Nova Scotia. Ed H.S. Heaps.

Lowe, J.J., K. Power and S.L. Gray. 1996. Canada's Forest Inventory 1991: The 1994 Version. Canadian Forest Service. Information Report BC-X-362.

Maclean, D.A. 1980. Vulnerability of fir-spruce during uncontrolled spruce budworm outbreaks: a review and discussion. Forest. Chron. 56: 213-221.

Masera, O.R., J.F. Garza-Caligaris, M. Kanninen, T. Karjalainen, J. Liski, G.J. Nabuurs, A. Pussinen, B.H.J. de Jong and G.M.J. Mohren. 2003. Modeling carbon sequestration in afforestation, agroforestry and forest management projects: the CO2FIX V.2 approach. Ecol. Model. 164: 177-199.

Mayer, D.G. and D.G. Butler. 1993. Statistical validation. Ecol. Model. 68: 21-32.

Mund, M., E. Kummetz, M. Hein, G.A. Bauer, and E.-D. Schulze. 2002. Growth and carbon stocks of a spruce forest chronosequence in central Europe. For. Ecol. Manage. 171: 275-296.

Nelson, H. and I. Vertinsky. 2003. The Kyoto Protocol and climate change mitigation: implications for Canada's forest industry. Sustainable Forest Management Network. Research Communications. 60pp.

Nilsson, S., M. Jonas, V. Stolbovoi, A. Shvidenko, M. Obersteiner and I. McCallum. 2003. The Missing "Missing Sink". Forest. Chron. 79: 1071-1074.

NRCAN. 1999. Climate Change and Forest: Context for the Canadian Forest Service's Science Program. Science Branch, Canadian Forest Service, Natural Resources Canada. Ottawa. 14pp.

NRCAN. 2001. Carbon Budget Model of the Canadian Forest Sector. http://www.nrcan.gc.ca/cfs-scf/science/brochure_carbon_budget/carbon_e.html. April 14, 2003.

NSDNR. 2003. Nova Scotia Department of Natural Resources. www.gov.ns.ca/natr/forestry/nsfactsheet.htm.

NSDNR. 2003b. Ecological Land Classification for Nova Scotia. Volume 1 – Mapping Nova Scotia's Terrestrial Ecosystems. Report DNR 2003-2. 83pp.

NSDNR. 2000a. An Overview of the Nova Scotia Registry of Buyers (for Primary Forest Products). Nova Scotia Department of Natural Resources. http://www.gov.ns.ca/natr/forestry.html. January 25, 2003.

NSDNR. 2000b. Nova Scotia Forest Inventory. Report FOR 2000-1. 40pp.

NSDNR. 1992. A survey of pre-commercially thinned stands in Nova Scotia. Nova Scotia Department of lands and Forest. Forest Research Report. No. 36. 15pp.

NSDNR. 1990. Revised Normal Yield Tables for Nova Scotia Softwoods. Nova Scotia Department of Lands and Forest. Forestry Canada. 45pp.

NSDNR. 1988. Fifteen year assessment of thirty year old red spruce stands cleaned at various intensities in Nova Scotia. Nova Scotia Department of lands and Forest. Forest Research Report. No. 2. 8pp.

Nyland, R.D. 1996. Silviculture: Concepts and Applications. The McGraw-Hill Companies, Inc. New York. 633pp.

Oliver, C.D. 1981. Forest development in North America following major disturbances. For. Ecol. Manage. 3: 153-168.

Papadopol, C.S. 2002. Climate Change Mitigation: Are there any forestry options? http://www.eco-web.com/editorial/05934-03.html. October 15, 2002.

Parker, W.C., S.J. Colombo, M.L. Cherry, M.D. Flannigan, S. Greifenhagen, R.S. McAlpine, C. Papadopol, & T. Scarr. 2000. Third MillenniumForestry: What climate change might mean to forests and forest management in Ontario. Forest. Chron. 76: 445-463.

Paul, K.I., P.J. Polglase and G.P. Richards. 2003. Predicted change in soil carbon following afforestation or reforestation, and analysis of controlling factors by linking a C accounting model (CAMFor) to models of forest growth (3PG), litter decomposition (GENDEC) and soil C turnover (RothC). For. Ecol. Manage. 177: 485-501.

Peng, C.H., J.X. Liu, M.J. Apps, Q.L. Dang and W.A. Kurz. 2000. Quantifying Ontario's forest carbon budget. 1. Carbon stocks and fluxes of forest ecosystems. Forest Research Note. Ontario Forest Research Institute. No. 158. 20pp.

Peng, C.H., Q.L. Dang, J.X. Liu, X.L. Zhou, J.X. Chen. 2003. Quantifying Ontario's forest carbon budgets: I. Developing and testing a dynamic forest carbon budget model for Ontario. Forest Research Note. Ontario Forest Research Institute. No. 65. 4pp.

Prisley, S.P. and M.J. Mortimer. 2004. A synthesis of literature on evaluation of models for policy applications, with implications for forest carbon accounting. For. Ecol. Manage. 198: 89-103.

Ratkowsky, D. 1990. Handbook of Non-linear Regression Models. Marcel Dekker Inc. New York. 241pp.

Richards, F.J. 1959. A flexible growth function for empirical use. J. Exp. Bot. 29: 290-300.

Richards, G.P. 2001. The FullCAM carbon accounting model: Development, calibration and implementation for the national carbon accounting system. Australian Greenhouse Office. National Carbon Accounting System. Technical Report No. 28. http://www.greenhouse.gov.au/ncas/reports/tr28final.html.

Rizzo, B. and Wiken, E. 1992. Assessing the sensitivity of Canada's ecosystems to climate change. Climatic Change. 21: 37-55.

Rothstein, D.E., Z. Yermakov and A.L. Buell. 2004. Loss and recovery of ecosystem carbon pools following stand-replacing wildfire in Michigan jack pine forests. Can. J. For. Res. 34: 1908-1918.

Ruel, J.C. 1995. Understanding windthrow: Silvicultural implications. Forest. Chron. 71: 434-445.

Ryan, M.G., D. Binkley and J.H. Fownes. 1997. Age-related decline in forest productivity: pattern and process. Adv. Ecol. Res. 27: 213-262.

Rykiel, E.J. 1996. Testing ecological models: the meaning of validation. Ecol. Model. 90: 229-244.

Saunders, G. 1970. Trees of Nova Scotia. 3rd revised edition. Nimbus Publishing Limited. Halifax. 102pp.

Schroeder, P. 1991. Can intensive management increase carbon storage in forest? Environ. Manage. 15: 475-481.

Siltanen, R.M., M.J. Apps, S.C. Zoltai, R.M. Mair, and L. Strong. 1997. A soil profile and organic carbon database for Canadian forest and tundra mineral soils. Natural Resources Canada. Canadian Forest Service. Northern Forestry Centre. Edmonton, Alberta, Canada. 50pp.

Seely, B., C. Welham, and H. Kimmins. 2002. Carbon sequestration in a boreal forest ecosystem: results from the ecosystem simulation model, FORECAST. For. Ecol. Manage. 169: 123-135.

Smith, F.W. and J.N. Long. 2001. Age-related decline in forest growth: an emergent property. For. Ecol. Manage. 144: 175-181.

Smith, D.M., B.C. Larson, M.J. Kelty and P.M.S. Ashton. 1997. The Practice of Silviculture: Applied Forest Ecology. John Wiley and Sons, Inc. New York. 537pp.

Stewart, B.J., P.D. Neily, E.J. Quigley, A.P. Duke and L.K. Benjamin. 2003. Selected Nova Scotia old-growth forests: Age, ecology, structure, scoring. Forest. Chron. 79: 632-644.

Timmer, V.R. and Y. Teng. 2003. Increasing carbon sequestration through enhanced stand establishment practises: nursery nutrient loading. Forest Research Report. Ontario Forest Research Institute. No. 161. 15pp.

Tremblay, S., R. Quimet and D. Houle. 2002. Prediction of organic carbon content in upland forest soils of Quebec; Canada. Can. J. For. Res. 32: 903-916.

UNFCCC. 1997. The Kyoto Protocol. http://unfccc.int/essential_background/kyoto_protocol/items/2830.php. January 18th, 2005.

UNFCCC. 2002. Report of the conference of parties on its seventh session, held at Marrakesh from 29 October to 10 November 2001. http://unfccc.int/resource/docs/cop7/13.pdf. February 18th, 2005.

UNFCCC. 2004. Methods and Science. http://unfccc.int/methods_and_science/items/2722.php. January 18th, 2004.

Wang, J.R. and J.P. Kimmins. 2002. Height growth and competitive relationship between paper birch and Douglas-fir in coast and interior of British Columbia. For. Ecol. Manage. 165: 285-293.

Wang, C., B. Bond-Lamberty and S.T. Gower. 2003. Carbon distribution of a well- and poorly-drained black spruce fire chronosequence. Glob. Change Biol. 9: 1066-1079.

Watson, R.T., I.R. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo and D.J. Dokken. 2000. Land Use, Land-Use Change and Forestry. A Special Report of the IPCC. Cambridge University Press, New York.

Wein, R.W. and J.M. Moore. 1978. Fire history and recent fire rotation periods in the Nova Scotia Acadian Forest. Can. J. For. Res. 9: 166-178.

Yanai, R.D., M.A. Aurthur, T.G. Siccama, C. A. Federer. 2000. Challenges of measuring forest floor organic matter dynamics: Repeated measures from a chronosequence. For. Ecol. Manage. 138: 273-283.

Yanai, R.D., W.S. Currie and C.L. Goodale. 2003. Soil carbon dynamics after forest harvest: An ecosystem paradigm reconsidered. Ecosystems. 6: 197-212.

Zinke, P.J., A.G. Strangenberger, W.M. Post, W.R. Emanuel and J.S. Olson. 1986. Worldwide organic soil carbon and nitrogen data. ORNL/CDIC-18, NDP-018. Carbon Dioxide Information Analysis Center (CDIC) Numeric Data Collection. Oak Ridge National Laboratory (ORNL), Oak Ridge, Tennessee, USA.

APPENDICES

APPENDIX I

Silviculture Activities and Credits in Nova Scotia

Silviculture Credits to Calculate the Value of Silviculture Program - 2005

Category	**Description**	**Silviculture Credits/ha** (1ha=2.471 acres)
1	Natural Regeneration Establishment	
	a) fill plant 0 to < 500 trees per ha	50
	b) fill plant greater than or equal to 500 trees per ha	300
2	Established Plantation	650
3	Early Competition Control: Plantation & Natural	300
4	Plantation (2): Density Control & Release	500
5	Natural (1): Density Controlled & Released	750
6	Commercially Thinned	400
7	Quality Improvement:	
	a. Crop Trees Released	300
	b. Crop Trees Pruned	300
	c. Selection Managed	300

Note: All site locations can only be submitted for one credit category in any given year with the exception of 1 & 3, 2&3, 6&7b, 7a&b or 7b&c.

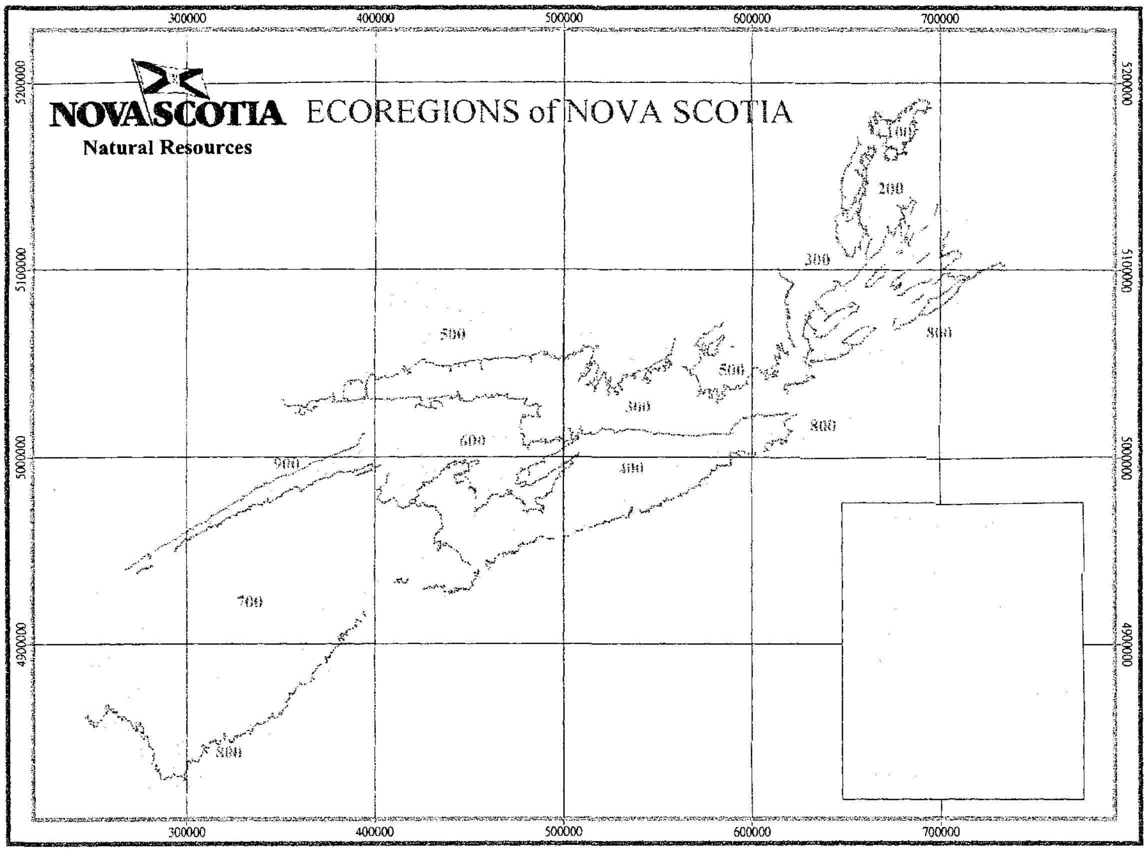
Note: All silviculture categories can only be claimed once during the life of the forest stand except for 7a & 7c where reclaim periods apply.

Note: Hardwood silviculture sites must contain at least 25% hardwood species on each site, and softwood silviculture sites must have at least 25% softwood species.

Note: Hardwood silviculture program only applies to Categories 1, 5, 6, & 7; all categories apply to the softwood silviculture program.

Appendix II

Eco-regions of Nova Scotia



APPENDIX III

Overview of CBM-CFS 3

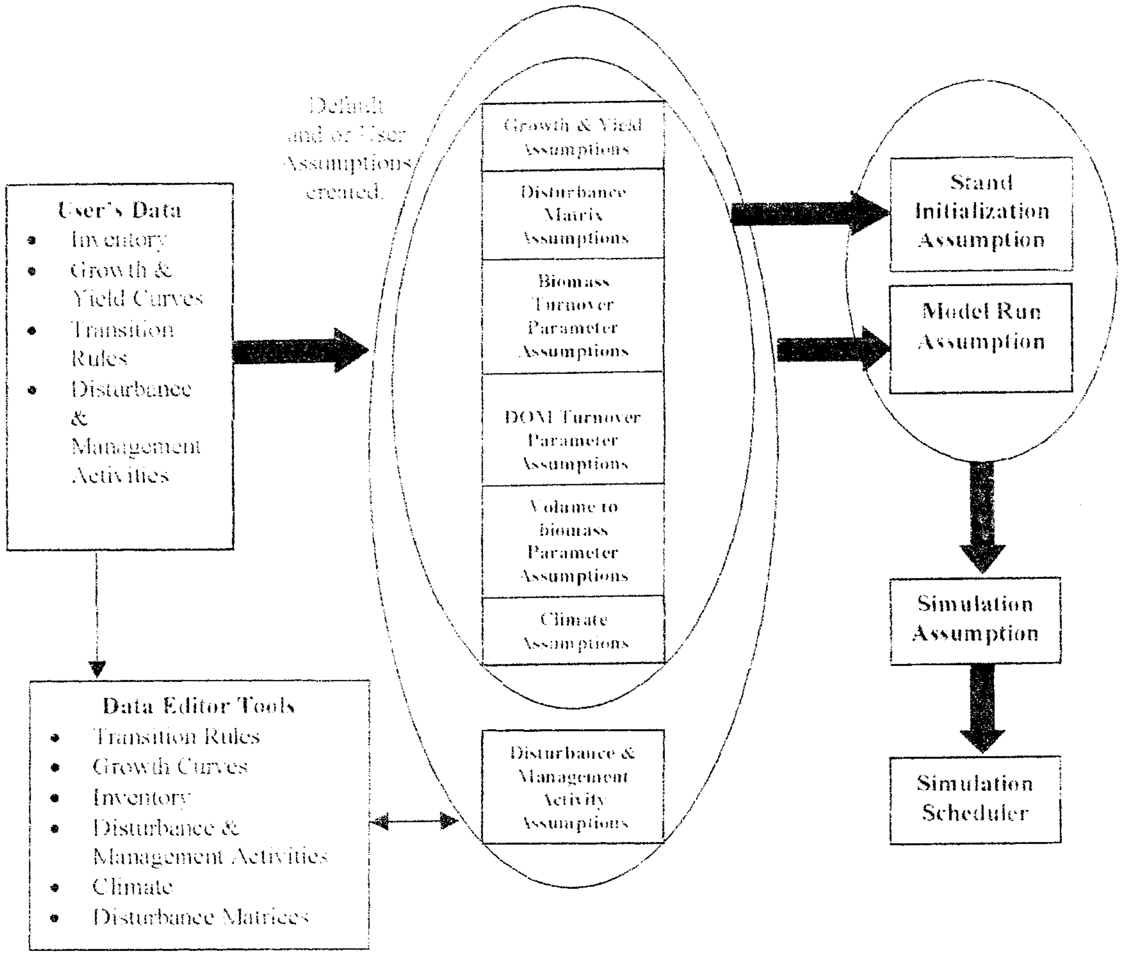


Diagram of the CBM-CFS 3 Assumptions Composer Tools, Simulation Composer and Simulation Scheduler. (Source: Personal communication: Stephen J. Kull, Natural Resources Canada, Canadian Forest Service, Northern Forest Centre, Edmonton, Alberta, February 14, 2005. Operational Scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) User's Guide (Draft), January 2005 version, 2005.