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Carbon Sequestration and the Optimal Economic Harvest Decision

by

Patrick Asante

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Examining Committee

Glen W. Armstrong, Renewable Resources

Wiktor L. Adamowicz, Rural Economy

Philip G. Comeau, Renewable Resources

Peter Boxall, Rural Economy

Cornelis G. van Kooten, Department of Economics, University of Victoria

Abstract

This thesis is a collection of four papers that explore the economics of forest carbon sequestration and optimal harvest decision, considering carbon storage in three major carbon pools: biomass, dead organic matter and wood product. The first three papers use a dynamic programming approach to determine the optimal harvest decision for a forest stand in the boreal forest of western Canada that provides both timber harvest volume and carbon sequestration services. The last paper uses an analytical model to confirm the findings in the first three papers that show that the optimal rotation age is dependent on the carbon stocks in the dead organic matter and wood product pools.

In the first paper, the state of the forest at any point in time is described by stand age and the amount of carbon in the dead organic matter pool. Stand age is used as the independent variable in merchantable timber volume and biomass functions. The results of the study indicate that while optimal harvest age is relatively insensitive to carbon stocks in dead organic matter, initial carbon stock levels significantly affect economic returns to carbon management.

In the second paper, the system is described by three state variables: stand age and the amount of carbon in the dead organic matter and wood product pools. The results of the study suggest that optimal behaviour of a landowner does not change much between cases where the market considers and ignores carbon storage in the

wood product pool or between cases where the market considers and ignores fossil fuel carbon emissions. The results also indicate that the optimal decision to harvest is sensitive to current stocks of carbon in the wood product pool, especially when carbon prices are high and the wood product stocks are also high.

The third paper demonstrates that alternative baselines have little or no effect on the optimal decision, but can have a large effect on financial return to landowner. In the third paper, the forest stand is described by four state variables: the age of the stand, the initial stand age, carbon stocks in the DOM pool and the initial carbon stocks in the DOM pool.

In the last paper, an analytical model is used to demonstrate that the optimal harvest decision is dependent on the initial DOM and wood product stocks. This finding is consistent with the results in the previous papers.

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CHAPTER 1

Introduction

Global climate change has emerged as a major scientific and public policy issue. Climate change is more than just a warming trend. Increasing temperatures may lead to changes in many aspects of the climate, such as wind patterns, the amount and type of precipitation, and the types and frequency of severe weather events that may be expected to occur in an area. These in turn can have significant effects on functioning ecosystems, the viability of wildlife, as well as human welfare.

Addressing climate change has been an international issue since February 1979 when the first World Climate Conference was held in Geneva, Switzerland. Since 1979, there have been several international attempts to address the issue of climate change including the formation of the International Panel on Climate Change (IPCC) and several decisions of the Conference of the Parties to the United Nations Framework Convention on Climate Change - UNFCCC (COP) meetings (Louw et al., 2009). It was at the third COP meeting in Kyoto, Japan that Canada and many other countries signed the Kyoto Protocol, thereby agreeing to reduce its emissions of carbon dioxide (CO_2). The Kyoto protocol is a legally-binding international treaty ratified by 184 countries and committing 37 industrialized countries and the European Union to reduce greenhouse gas (GHG) emissions by a total of 5.2% below 1990 levels by 2012. The Government of Canada ratified the Kyoto Protocol in December 2002. Canada is committed to reduce its GHG emissions to 6% below 1990 levels between January 2008 and December 2012 (Williams, 2005). The Kyoto protocol allows the use of forests to offset emissions of carbon from fossil-fuel combustion. There are three Articles of the Protocol directly relevant to forests and forest management:

- **Article 2.1** calls for the 'protection and enhancement of sinks and reservoirs of greenhouse gases' and the 'promotion of sustainable forest management practices, afforestation and reforestation'.
- **Article 3.3** states that 'the net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990, measured as verifiable changes in carbon stocks in each commitment period shall be used to meet commitments in this Article'.
- **Article 3.4** allows countries to account for carbon stock changes and non-CO_2 GHG emissions arising from other activities including the management of forests existing before 1990. The magnitude of any carbon sequestration due to human intervention must be verifiable.

One goal of this chapter is to acquaint the reader with the economics of carbon sequestration by briefly describing the role of forests, carbon offset markets and the challenges in implementing this market. Other goals are to acquaint the reader with the technique of dynamic programming, which is the optimization method used in this thesis, and the model assumptions and a description of the data used in the study. The rest of this chapter is organized as follows. It begins with a section on the role of forests in climate change. This is followed by a general description of the types of market-based mechanisms, challenges of the carbon offset market, economics of carbon sequestration, general overview of dynamic programming, model assumptions and a description of the timber and carbon yield curves which are central to the models developed in this study. This chapter ends with a summary of how this thesis is organized.

1.1 Role of forests in climate change

It is widely recognized that forests play an important role in the global carbon cycle by sequestering and storing carbon. It is this role of forests in climate change that influenced participants of the Kyoto Protocol to allow countries to count carbon sequestered in forest toward a country's emission reduction requirements. Forest ecosystems contain the majority (approximately 60%) of the carbon stored in terrestrial ecosystems (IPCC, 2000). Forests also account for 90% of the annual carbon flux between the atmosphere and the Earth's land surface (Winjum et al., 1993). In most forested ecosystems, the majority of the carbon is stored below ground as roots and decaying biomass or as dead organic matter (DOM). Within forest biomes as a whole, 68% of the carbon is in the DOM pool: the proportion is 50% in tropical forests, 63% in temperate forests, and 84% in the boreal forests (Kimble et al., 2003).

The carbon stored in forests is removed from the atmosphere through photosynthesis (the conversion of atmospheric CO_2 into plant material using energy from the sun, releasing oxygen in the process). When a tree dies and decomposes, or is burned or killed by disturbances such as fire, insect attacks, or harvests, carbon is released back into the atmosphere as CO_2. Some carbon remains in the forest litter and builds up in soils or DOM over the long term. The carbon sequestration rate refers to the rate at which carbon is stored in an ecosystem. In the life of a forest, this roughly follows the same trajectory as a growth and yield curve used in timber supply analysis.

When a tree is harvested, carbon is removed in the form of logs, but approximately 40% of the original tree biomass remains in the forest where it decomposes slowly and gradually releases nutrients and CO_2. The harvested areas also regenerate so that over time a substantial new pool of carbon is created. Harvested logs are sent to mills for conversion into wood products, such as lumber or paper. Depending on the use and disposal of these products, the carbon may be stored for a very long time, or it may be released into the atmosphere relatively quickly.

The role of forest and other carbon sinks associated with land use changes were first recognized by international treaties during the 1992 Earth Summit; the United Nation Framework Convention on Climate Change (UNFCCC) which recognized that activities in the Land Use Land Use Change and Forestry (LULUCF) sector may provide a relatively cost-effective way of offsetting emissions.

Markets for forestry carbon sequestration projects internationally are very modest. Currently, the ability of forestry to participate within international markets outside North America is severely constrained by Kyoto Protocol rules, as they mainly apply to afforestation and reforestation projects. Demand for forestry offset credits for afforestation and reforestation, and managed forest projects has mainly been driven by voluntary markets developed by a wide variety of non-governmental organizations.

1.2 Market-based mechanisms

Many economic tools have been proposed and implemented to mitigate climate change and of the approaches used, market-based mechanisms such as emissions trading, also known as carbon cap-and-trade systems are gaining the most popularity worldwide and have become widely promoted as a cost-effective method for addressing climate change and other environmental issues. Current programs include the European Union Emissions Trading Scheme and the North American Western Climate Initiative.

Carbon markets involve the buying and selling of carbon credits that are either distributed by a regulatory body in the form of emissions permits, or through the generation of GHG emissions reductions through offsets. The worldwide markets for forest carbon offsets can be divided into two: the regulatory (compliance) markets and the voluntary markets. The compliance market refers to the markets that exist to enable those with emission caps imposed on them by governments (or other regulatory bodies) to buy or sell carbon credits in order to meet their obligations. The voluntary carbon market, as the name implies, involves purchases that are made voluntarily by the buyer. Therefore, the voluntary carbon markets effectively function outside of the compliance market. They enable businesses, governments, NGOs, and individuals to offset their emissions by purchasing carbon offsets. Forest carbon offsets are very controversial and not permitted in all compliance markets. They have, however, captured a large share of voluntary markets. In 2006, 37% of all carbon-offset projects from voluntary markets were forestry related (Hamilton et al., 2007).

1.2.1 Compliance markets

A compliance market is a market created by a regulatory act. Participants' economic decision-making is shaped by the regulation and thus their behaviour in a compliance market occurs in order to comply with the regulation. In a cap-and-trade market, companies buy and sell carbon credits because of the imperative to comply with the legislatively imposed cap. Compliance markets are contrasted with voluntary markets, in which participants purchase emissions reductions for reasons such as personal commitments or for public relations purposes.

The Kyoto protocol

A global carbon market has emerged as a result of the Kyoto Protocol of the UNFCCC. Article 3 of the protocol introduced concepts of GHG emissions by sources and GHG removal by sinks, but it limited the role of forestry to afforestation, reforestation, and reducing emissions during deforestation activities conducted since 1990. To combat climate change, the Kyoto Protocol uses market-based mechanisms. They include emissions trading, Clean Development Mechanism (CDM) and Joint Implementation (JI) (UNFCCC, 2007).

Emissions Trading as set out in Article 17 of the Kyoto Protocol, is an allowance-based trading scheme in which countries with binding targets are allocated ‘assigned allowance units’ (AAU) and they may sell unused AAUs to countries that are over their targets. In addition to AAUs, countries are allowed to trade Certified Emissions Reductions (CERs) generated from CDM project activity, Emission Reduction Units (ERUs) from JI projects, and Removal Units (RMUs) based on land use, land-use change and forestry (LULUCF) activities like afforestation and reforestation.

The Clean Development Mechanism defined in Article 12 of the Protocol allows a country with an emission-reduction or emission-limitation commitment under the Kyoto Protocol to implement an emission-reduction project in developing countries. Such projects can earn certified emission reduction (CER) credits, each equivalent to one tonne of CO_2, which can be counted towards meeting Kyoto targets.

Joint Implementation defined in Article 6 of the Kyoto Protocol, allows a country with an emission reduction or limitation commitment under the Kyoto Protocol to earn emission reduction units (ERUs) from an emission reduction or emission removal project in other developed countries or in countries with transitional economies (mostly in Eastern European). Each ERU is equivalent to one tonne of CO_2, which can be counted towards meeting Kyoto targets.

Clean Development Mechanism and Joint Implementation allow credits to be acquired not only for reduced emissions, but also for projects that help in the sequestration of CO_2. Currently, forestry activities recognized under the CDM are limited to afforestation and reforestation. To be eligible, project developers must demonstrate that forests did not cover the converted land on or before December 31, 1989 (Neeff and Henders, 2007). Unlike CDM projects, JI recognizes not only afforestation and reforestation projects, but also forestry activities related to land-use, including forest management and agricultural carbon sequestration.

European union emissions trading scheme

The European Union Emission Trading System (EU ETS) is the largest multinational, emissions trading scheme or compliance market in the world, and is a major component of EU climate policy. It was created in January 2005 to assist the 27 European Union countries in meeting Kyoto Protocol mandated emission reduction targets (European Commission, 2005). To meet emission reduction targets, each European Union nation is issued European Union emissions allowances (EUAs) that may be traded with other European Union nations. In addition to EUAs, the EU ETS linking directive allows for the sale and purchase of carbon credits, both CERs and ERUs, generated by approved CDM or JI projects. The EU ETS emphasis on reducing GHG emissions from industry and energy, combined with methodological insecurities and permanence concerns in forest projects, motivated a ban against Land-Use, Land-Use Change and Forestry (LULUCF) offsets in the ETS until 2020.

Alberta offset carbon market

Alberta was the first province in Canada with a climate change action plan in 2002. Regulations were introduced that required industries with CO_2 emissions greater than 100 Kt/year to report their emissions on an annual basis starting in 2003.

In early 2007 the Climate Change Emissions Management Act was amended to require companies with CO_2 emission intensity greater than 100 Kt/year to reduce their emissions by 12% from their baseline (an average of 2003-2005 CO_2 emissions). Facilities constructed after year 2000 were given a three year grace period because it is believed that they will install the newest technology (Alberta Environment, 2007).

Under the Act companies with CO_2 emission intensity greater than 100 Kt/year have three options.

1. Obtain emission performance credits (buy, trade, etc) from other regulated companies that have reduced their emissions more than needed.

2. Pay into the Climate Change and Emissions Management Fund at a set price of 15 CAD/tCO_2. Funds collected are to be used to develop or invest in Alberta based technologies, programs, and other priority areas.

3. Companies may offset their emissions by purchasing emission reduction offsets. It is voluntary (eg. they could choose options 1 or 2 above) however, the offsets must be from Alberta and must be approved offsets.

Companies account for their emissions on a calendar year and have until the end of the following March to reconcile their account. Alberta Environment estimates that if all companies paid their current emission intensity liability into the Technology Fund it would amount to about 177 million CAD on an annual basis.

Regional greenhouse gas initiative

The Regional Greenhouse Gas Initiative (RGGI) is the first mandatory, market-based effort in the United States to reduce GHGs. Ten Northeastern and Mid-Atlantic states haved capped and will reduce CO_2 emissions from the power sector 10% by 2018. Emission reduction targets are limited to large power plants, i.e, those with energy production capacity greater than 25 megawatts that burn fossil fuels to generate more than half of their electricity. The RGGI rules allow for the use of emission reduction credits from offset projects based on market prices for those credits. Sequestration of CO_2 from forestry projects is limited to participating in afforestation projects. To date, no forest offset projects have been registered with the RGGI program.

The western regional climate change initiative

Six of the western United States including California, New Mexico, Oregon, Washington, Arizona, and Utah, along with the Canadian provinces of British Columbia, Manitoba, and Quebec, in February 2007 created the Western Regional Climate Initiative (WRCAI). The purpose of the WRCAI is to 'identify, evaluate and implement ways to collectively reduce GHG emissions and to achieve related cobenefits'. WRCAI participants agree to a regional emissions reductions goal of 15% by 2020 from a 2005 baseline. At present there are no forest carbon projects included but potential exists for WRCAI participants to purchase voluntary credits generated by forest-based activities in developing countries.

1.2.2 Voluntary markets for forest carbon

Voluntary carbon markets are developing globally to address the increased demand to reduce GHG emissions. The global voluntary carbon market includes over-the-counter transactions, California climate action registry, and emissions trading transactions through the Chicago Climate Exchange (Hamilton et al., 2008).

Chicago climate exchange

The Chicago Climate Exchange (CCX) is the first voluntary carbon market for trading GHGs in North America. Members make a voluntary but legally binding commitment to meet annual reduction targets of 6% below baseline emissions by 2010. Members that reduce below the targets have surplus allowances to sell or bank. Those that emit above the annual targets comply by purchasing emission reduction credit contracts, called carbon financial instruments.

Emission allowances are issued in accordance with a members emissions baseline and the CCX emission reduction schedule. Integrated commercial forest entities that own mills and comply with a sustainable forest management standard with third party verification have the option of claiming their forest operations as carbon stable or using an approved forest growth-and-yield model to account for the annual net change in forest carbon stocks as a part of an entity wide accounting of GHG emission allowances.

Nonmembers can also use the CCX trading platform. The forest carbon offset projects that are eligible to be registered and traded by approved aggregators or offset providers on CCX include afforestation, reforestation, sustainably managed forests, and forest conservation (avoided deforestation). The CCX forest carbon offset rules also allow for the counting of long-lived harvested wood products in use. Other carbon pools recognized are above and below ground living tree biomass. Verification of net changes in carbon stocks by an approved verification body is required before emission reduction credits can be registered and traded.

California climate action registry

In 2001, California Senate Bills SB1771 and SB527 created the California Climate Action Registry (CCAR), the nations first statewide GHG inventory registry. Like other registries, CCAR develops rules for the issuance, qualification, quantification, verification, and registration of emission allowances and emission reduction credits for forest carbon offset projects. Credits for afforestation, managed forests, and forest conservation (avoided deforestation) are allowed, and offset project rules are defined by CCARs Forest Sector Protocol (California Climate Action Registry, 2009). To date, credits from one forest carbon offset project have been registered and sold.

Over-the-counter markets

Society's heightened concern about global warming has led many organizations and individuals to look for ways to mitigate their own greenhouse gas emissions. Terms such as "carbon footprint" and "carbon neutral" have entered the vernacular. Many environmentally conscious organizations and individuals have sought to mitigate their personal contributions by participating in registries and carbon markets, and also through other voluntary direct sales, frequently referred to as over-the-counter (OTC) transactions. Over-the-counter transactions provide a wide range of global opportunities. Large organizations can invest directly in specific mitigation projects that meet their environmental, cost, and/or GHG mitigation objectives. Individuals can mitigate on a smaller scale.

1.3 Challenges of forest offset market

Addressing climate change through the use of offsets, especially forest offsets, is controversial because of challenges posed in managing the issues of additionality, baseline setting, leakage, and permanence. To date, only 12 afforestation projects have been approved under Kyoto, and one has been certified through UNFCCCs CDM executive board. The main reason for the paucity of sequestration projects is because of these challenges (Ingerson, 2007).

1.3.1 Additionality and baseline setting

Since reduction of GHGs in the atmosphere is the goal of any emissions reduction program, the net amount of carbon sequestered must be additional to what would have occurred without the offset project. For forest projects, additionality can be difficult to demonstrate. A carbon baseline must be established against which the net change in carbon stocks is measured so that emission reduction credits can be quantified, verified, and registered.

A baseline is the reference point(s) against which a projects carbon storage or GHG emission reductions are measured. Carbon sequestration levels or emission reductions in excess of the baseline level are considered additional and, thus, available for sale as offsets. Therefore, setting an accurate baseline is a crucial and controversial step in designing an offset project.

Two types of baselines are suggested for forest carbon projects. The first type is the “base year” approach , which compares actual measurements of a projects carbon stocks or emission levels from one reporting period to the next. The base year approach is also known as the fixed baseline approach. Under the fixed baseline approach, the baseline can be said to equal the total carbon on site at project inception. The second type of baseline is the “business-as-usual” (BAU) approach, which compares a projects carbon stocks or emissions to the estimated amount that would have occurred without the project. With both approaches, any net increase in carbon stocks or reductions in GHG emissions relative to the baseline are considered additional.

The fixed baseline (base year) approach is controversial because it does not consider the amount of sequestration or emissions that would have occurred had the project not been implemented, creating uncertainty about whether the project led to any real changes in sequestration or emission levels. Many BAU baselines are controversial because they use hypothetical projections of sequestration or emission rates made many years, sometimes decades, into the future. The future is impossible to predict with accuracy, and so it is impossible to predict with accuracy how much carbon would have been sequestered under a BAU scenario. Who can say with great certainty what BAU would be 10 years from now? This creates a situation with information assymetry, thus making it possible for a landowner to game the system. Therefore, for most forest offset projects, both approaches lack the ability to assess unequivocally whether, or to what extent, a project's impact is additional.

In principle, a landowner should only be credited for carbon sequestration over and above what occurs in the absence of carbon sequestration incentives. Thus, if it can be demonstrated that a forest would be harvested and converted to another use in the absence of specific policy to prevent this from happening, the additionality condition is met. Carbon sequestered as a result of incremental forest management activities (e.g., juvenile spacing, commercial thinning, fire control, fertilization) would be eligible for carbon credits, but only if the activities would not otherwise have been undertaken (van Kooten and Sohngen, 2007).

It is difficult to determine whether an activity is truly additional. For example, in British Columbia, if a forestry company after 1990 replants harvested blocks that were considered not sufficiently restocked, the activity would be eligible for carbon offset credits under Kyoto Protocol yet, this clearly does not meet the 'additionality' test since companies in British Columbia are required by law to satisfactorily restock harvested blocks regardless of carbon sequestration incentives.

1.3.2 Leakage

Leakage is the phenomenon through which efforts to reduce emissions in one place simply shift emissions to another location or sector where they remain uncontrolled or uncounted. The classic example of leakage in forestry is a project to increase protection of a clearly threatened forest. By protecting the forest from logging, the project developer in this case could be avoiding the release of CO_2 to the atmosphere (i.e., continued deforestation of the forest would be the baseline condition had the forest not been protected). However, if the demand for wood remains constant then the logging may simply be displaced to an area outside the protected (project) area. The CO_2 emissions that result from the displaced logging could partially or completely negate the benefits of avoiding CO_2 emissions in the protected forest.

Leakage estimates for forestry projects are exceedingly wide (5% to 93%), suggesting that project developers need to carefully consider leakages when designing carbon offset projects (Sohngen and Brown, 2006).

1.3.3 Permanence

The possibility of using forest to offset emissions from other sources has been criticized on the grounds of permanence. Most of the concerns have centered on the question of who bears the liability if for example, CO_2 from a forest is released prematurely. The critics argue that temporary sequestration of CO_2 does not have a place in a comprehensive policy for mitigating climate change.

To address the issue of non-permanence of forest carbon sinks, some innovative accounting frameworks have been proposed in literature. One of these accounting methods is referred to as the tonne-year accounting method. This accounting method specifies a conversion factor that translates years of temporary carbon storage into a permanent equivalent (IPCC, 2000; Moura-Costa and Wilson, 2000). This factor is derived from "equivalent time" concept, i.e., the length of time that CO_2 must be stored as carbon in biomass or DOM for it to prevent the cumulative radiative forcing effect exerted by similar amount of CO_2 during its residence in the atmosphere. The tonne-year method does not require redemption of all carbon credits upon harvest, because payment occurs based only on the 'equivalent' amount of permanently avoided emission during a given time period. The tonne-year accounting method has been rejected by most countries because the credits accumulate very slowly and lack of symmetry in credits and debits (Marland et al., 2001). Marland et al. (2001) point out that the tonne-year accounting system is flawed because tonne-year credits can be accumulated while trees grow, but can be counted as a credit a second time if the biomass is subsequently burned in place of an energy-equivalent amount of fossil fuel, where the credit is the saving in CO_2 emissions from not burning fossil fuels. Yet, the concept of tonne-years has a certain appeal, primarily because it provides a simple, albeit naive, accounting solution to the problem of permanence.

A second approach that has been discussed extensively in literature is that project participants may select to use "temporary certified emission reduction units", denoted tCER. The idea is that a temporary offset credit is purchased for a set period of time. The liability to replace the credits upon reversal of the removal is always with the buyer of the credits and a check, whether the certified forest is still present, takes place in 5-year intervals. Upon expiry, buyers of tCERs would have to reacquire the same number of tCERs. Compared to tonne-years, monitoring and verification are more onerous because a complex system of bookkeeping will be required at the international level to keep track of credits. Countries favour this approach over other approaches because they can obtain carbon credits early, while delaying payment to a future date. In essence, a country that uses tCERs to meet its CO_2-emissions reduction target in Kyotos first commitment period (2008-2012) defers its obligations to future commitment periods (van Kooten and Sohngen, 2007). The challenge is that tCERs only postpone the obligation to reduce emissions, they do not fulfill the obligation to reduce emissions, as credits from other CDM projects. This is one reason why the price of tCERs are lower compared to permanent units (Michael and Schlamadinger, 2003; Sedjo and Marland, 2003; Chomitz and Lecocq, 2004).

A third approach to the problem of temporary versus permanent removal of CO_2 from the atmosphere is to employ a market device that would obviate the need for an arbitrary conversion factor. This accounting method is often referred to as the “stock change method” as it is based on calculating the changes in carbon stocks of a project and its baseline from one period to the next. Marland et al. (2001) and Sedjo and Marland (2003) designed a method to accommodate the lack of permanence of sequestered carbon, by providing full credit at the time of sequestration in return to full liability if sequestered carbon is later released. Although not all carbon is released back to the atmosphere at harvest, this payment system assumes that the contract ends when the carbon sequestered is no longer under the control of the landowner. In other words, the contract between an investor and the landowner expires when the forest is harvested.

Given the political acceptance, simplicity, flexibility and relatively low impact on the financial feasibility of projects, the stock change method may be the most appropriate accounting method for forestry-based carbon offset projects. Its adoption could remove some of the uncertainties related to the use of sinks, and accelerate its acceptance in the Kyoto process and international carbon market.

1.4 Economics of carbon sequestration

Various studies have examined the economics of forest carbon sequestration. In most of these studies the central focus has been on the effect of carbon values on optimal rotation lengths when both timber and carbon values are considered. Much of this work has been built on variations of the model developed by Hartman (1976), which demonstrated that optimal rotations may be extended beyond timber-only management regimes when flows of non-timber value are associated with the standing forest.

Some of the studies include the work by van Kooten et al. (1995) who investigated the impact of carbon on optimal forest rotations and carbon sequestration by demonstrating that carbon taxes and subsidies will affect the optimal forest rotation and, consequently, the carbon stored in forests. Other authors such as Plantinga and Birdsey (1994) used the framework of Hartman (1976) to show that the socially optimal rotation age is always greater than the privately optimal rotation age, but less than or equal to the rotation age when carbon is valued. Englin and Callaway (1995) addressed the impacts of external benefits provided by forests such as trout, diversity, visual aesthetics, soil stability, deer populations, elk populations, and water yield, by extending the Hartman (1976) model of forest management to include carbon sequestration activities. Creedy and Wurzbacher (2001) developed a model that considered water and carbon sequestration to show that the inclusion of carbon values will lengthen the optimal harvest rotation versus a rotation which maximizes the net present value of timber alone.

The cost of producing carbon offsets through forest management activities is another issue that has received substantial attention in the literature (Sedjo, 2001; Sohngen and Mendelsohn, 2003; van Kooten et al., 2004; Krcmar and van Kooten, 2005). Starting in the late 1980s, many U.S. researchers began studying the potential and costs of afforestation activities for sequestering carbon. Most early cost estimates were in the range of about 0.30 CAD/tCO_2 to about 30 CAD/tCO_2.

van Kooten and Sohngen (2007) provide a good review of the relevant literature and cite the costs of implementing carbon sequestion projects to be most expensive in Europe, with costs ranging from about 50-280 CAD/tCO_2. This could be the result of higher land prices in Europe and might explain why Europe has generally opposed biological sinks as a substitute for emissions reductions. In Canada and the U.S., carbon sequestration costs range from a low of about 2 CAD/tCO_2 to nearly 80 CAD/tCO_2. Generally, the cost of generating CO_2 offset credits is lowest in the tropics because land is cheap. Costs are about 35-80 CAD/tCO_2 lower than projects in other regions.

In Sohngen and Brown (2006), the results indicate that very little land would likely be set aside at about 14 CAD/tCO_2, however, at about 55 CAD/tCO_2, the results indicate that nearly 1 million hectares of land could be set-aside in the U.S., with 83% of this land occurring in the Western U.S.

1.5 General overview of dynamic programming

The starting point of the problems considered in this study begin with the development of a stand-level optimization model in a deterministic setting. Stand-level optimization is a process in forestry where the objective is to develop the very best management plan for each individual forested stand in isolation of other stands across a landscape. The process involves assessing the rotation age, or number and timing of entries, along with the types of treatments that can be applied to a stand.

Stand level optimization models were chosen for this study because understanding stand level carbon dynamics is essential to addressing forest carbon sequestration. This is because many management actions that influence aggregate carbon stocks at the forest level are carried out at the stand level.

Stand level optimization models fit the framework for dynamic programming (DP). Dynamic programming is a powerful approach to stand level optimization problems (Brodie and Haight, 1985). It allows one to solve many different types of sequential optimization problems in time for which a naive approach would take exponential time.

Dynamic programming is a recursive optimization approach that simplifies complex problems by transforming them into a sequence of smaller simpler problems. The solution procedure begins by finding the optimal policy for either the first or last stage. These techniques are called forward recursion and backward recursion respectively. The term Dynamic Programming was originally coined in the 1940s by Richard Bellman to describe the process of solving problems where one needs to find the best decisions one after another. By 1953, he had refined this to the modern meaning, which refers specifically to nesting smaller decision problems inside larger decisions, and the field was thereafter recognized by the Institution of Electrical Engineers as a systems analysis and engineering topic. Bellman's contribution is remembered in the name of the Bellman equation, a central result of dynamic programming which restates an optimization problem in recursive form. The basic features which characterize DP problems are:

1. The problem can be divided into **stages** with a **policy decision** required at each stage. Often in forestry DP problems, stages represent time periods in a planning horizon but they can represent anything which divides the problem up into sections with a decision required at each section. The policy decision is what action to take at each time period. A further characteristics of DP problem is that the sequence of policy decisions are interrelated,

2. Each stage has a number of **states** related to it. The states are a description of the various possible conditions the system may be in at a given stage. It is a description of the system. An example of such a description is the stand age. The state description is a vital component of the DP formulation. It must be detailed enough to accurately describe the system being modelled but simple enough to limit the number of states at each stage. As the number of states grows the problem is beset with the 'curse of dimensionality' and becomes difficult if not impossible to solve (Bellman, 1961),

3. Whenever a policy decision is taken, the current state is transformed into a state associated with the next stage. The new state entered may be determined by both the policy decision and a probability distribution. For example a decision to fertilize a stand at age 5 will influence the characteristics of that stand at age 10. The probability distribution recognizes that we do not know with certainty what the stand will look like,

4. Given the current state, the optimal policy for all remaining stages is entirely independent of policies adopted in previous stages. This feature of DP is commonly referred to as the 'principle of optimality' (Dykstra, 1984). It is this property that allows DPs to be broken up into a series of smaller, simpler problems,

5. The solution procedure must begin by finding the optimal policy for either the first or last stage, and

6. Finally a recursive optimization procedure can be developed which builds to an overall solution of the problem by sequentially including one stage at a time and solving one stage problem until the overall optimum has been found.

The forward recursion DP formulation is the most common method of structuring stand-level optimization problems. Forward recursion have been favoured in the forestry DP literature because this does not require a separate pass through the network, for each candidate optimal rotation (Brodie et al., 1978). Forward recursions require only paths of interest to be searched. It minimizes the solution time and provides optimal paths to rotations shorter than those being investigated. It fails however to provide optimal regimes for states not on the optimal path. Forward recursion does have problems in handling stochastic formulations and is driven by past, not future, stand values.

In the backward case, we compute the optimal decision starting from each state recursively, beginning at the last period. In the last stage, there are no decisions left to be made, so the value function for all states is set to zero. Thus, the model works backward, solving for each previous time step one after another, i.e. from a point in the future back towards the present. This is because the paths that lead from the present state to the future goal state are always just a subset of all of the paths leading forward from the current state. Hence it is more efficient to work backwards along this subset of paths. Backward recursion provides optimal regime for all states considered in the problem. It is superior to forward recursion if the problem being considered can be solved within a reasonable time frame. For this reason, this study uses the backward recursion method. For very large problems the time savings involved in forward recursions are significant when only one pass through the network is required.

1.6 Model assumptions

The models considered in this study are all deterministic. While we do not live in a deterministic world, models of this type are very useful and give correct "average" results (Buongiorno and Gilless, 2003). In a deterministic model, all factors influencing the solution of the model are known and constant. Specifically the stand grows in a predictable fashion. There are no shocks in the form of periods of exceptionally good (or bad) growing conditions, random pest attacks or fires. Prices are assumed constant as are the costs of timber harvesting and stand establishment. The discount rate is also known and constant.

The question of the proper discount rate to be used in the context of forestry investments has enjoyed a long debate in literature. Review of the subject by Fraser (1985); Heaps (1985) support a range between 5% and 10% real with Heaps leaning towars the lower figure because although there are substantial risk inherent in the growth of a forest stand (pest, fire, etc.) these become negligible across many stands. Five percent is used as the base rate in this study because it reflects a market rate of time preference. Assumptions on costs and revenue are addressed in the thesis, growth and yield curves are addressed in the section that follows.

1.7 Modelling timber yield and carbon stocks

A yield curve is a projection of how a forest stand will develop through its lifetime. In its most fundamental form, it identifies the merchantable volume of the stand at any point in its development. More elaborate yield curves can also provide point-in-time information on stand structure including dominant height, stand density (by species), mean diameter, mean piece size, gross total volume, merchantable total volume, as well as other stand and tree parameters. Although a yield curve may be developed for any given stand, typically it describes the average developmental profile of a grouping of stands that are similar enough in terms of species composition, structure and growth characteristics to be considered in a single stand type or stratum.

In this study, information on merchantable timber yield is critical to making a harvest or no harvest decision. The section that follows shows how the merchantable timber yield function is generated.

1.7.1 Merchantable timber yield

The timber yield information used in this study comes from the TIPSY growth and yield simulator (BC MoFR, 2007) developed by the British Columbia Ministry of Forests and Range for use as input to forest management plans. The data used in this thesis represent a lodgepole pine stand in the BWBS biogeoclimatic zone, in the Dawson Creek Forest District of the Prince George Forest Region of British Columbia, Canada. A medium site class (site index is 16 m at 50 years breast height age) and a planting density of 1600 stems/ha is assumed.

The tabular representation of the merchantable timber yield table from TIPSY is approximated using a Chapman-Richards growth function, $V(a) = v_1(1 - e^{-v_2 a})^{v_3}$, in which $V(a)$ represents the merchantable timber volume at age a and v_1, v_2 and v_3 are parameters, which were set at 500.4, 0.027 and 4.003 respectively. These parameters give an acceptable representation of the yield table generated by TIPSY (Fig. 1.1) for the purposes of this study.

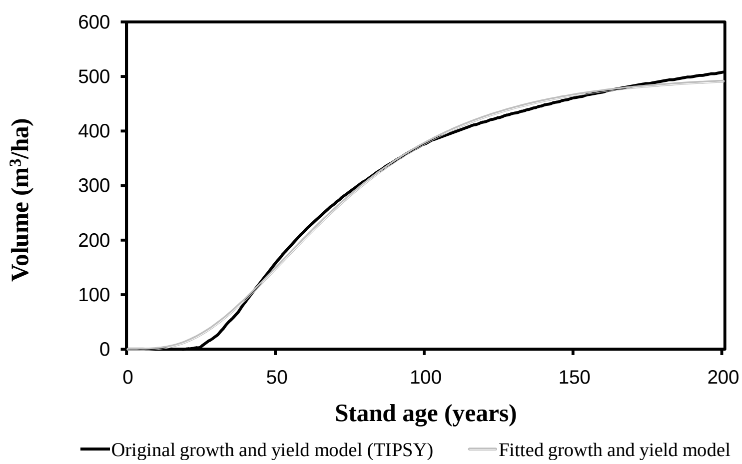

Figure 1.1: Comparison of TIPSY projection of merchantable stand yield with Chapman-Richards approximation.

Fig. 1.1 assumes that the yield curve does not decline when the stand reaches old growth, which implies that the stand will continue to accumulate carbon stocks in the DOM pool as the stand ages. This assumption is contrary to the long-standing view that tree growth declines when a stand reaches old growth. It is also generally thought that when a stand reaches old growth it ceases to accumulate carbon stocks in the DOM pool. This view is contrasted by the findings of Luyssaert et al. (2008). They report that old growth forest can continue to accumulate carbon in the DOM pool for centuries. This makes the choice of this timber yield function adequate for the purposes of the current exposition.

1.7.2 Carbon stocks

The decision to harvest is also dependent on the change in carbon stocks. The TIPSY yield table was used as input to the Carbon Budget Model of the Canadian Forest sector (CBM-CFS3) to track and report changes in forest carbon stored in each of the carbon pools (Kull et al., 2007). The CBM-CFS3 uses a spin-up procedure (Kurz and Apps, 1999; Kurz et al., 2009) to estimate the quantity of carbon in the dead organic matter pools before simulating scenarios. It requires a user-specified assumptions about historic disturbance-return intervals, the type of disturbance occurring during the spin-up procedure, and the type of last disturbance that preceded the establishment of the current stand. To initialize the DOM pool for the simulations in this study, a 200 year historic fire return interval was assumed. It was also assumed that wildfire is the main disturbance type occurring during the spin-up procedure and it is also the last disturbance preceding the establishment of the lodgepole pine stand. These assumptions produced an initial DOM of 370 tC/ha for a lodgepole pine stand in the Dawson Creek Forest District. This value is very near the IPCC (2001) estimate of average carbon stocks of 344 tC/ha in the boreal forest. For a Canada wide average, Dixon et al. (1994) estimates the quantity of carbon in soil organic matter (up to 1 metre soil depth) as 484 tC/ha. This value includes carbon in peat, coarse woody debris and fine litter.

A review of literature shows that the average quantity of soil carbon in a lodgepole pine stand is relatively low compared to the boreal forest average. This may be due to the fact that lodgepole pine grows on drier sites at higher elevations and is often considered to be a pioneer species. In a study done in Medicine Bow national Forest in southeastern Wyoming, Chatterjee et al. (2009) estimates the average soil organic carbon stock for an unmanaged forest as 110 tC/ha. In a boreal cordilleran forest type in northeastern British Columbia, Canada, Seely et al. (2002) calibrated the initial quantity of soil carbon and litter in a lodgepole pine stand as 225 tC/ha.

In this study, a simplified representation of the carbon pool structure of CBM-CFS3

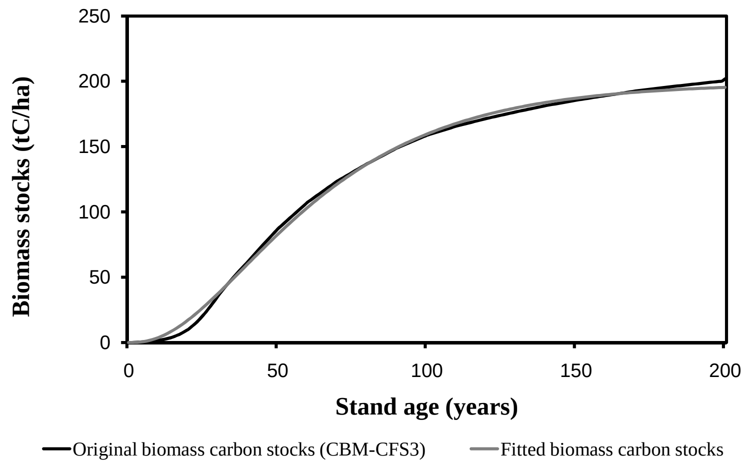

Figure 1.2: Comparison of biomass carbon stock projections using CBM-CFS3 and estimated approximation.

was created using two carbon pools: a biomass pool representing carbon stored above and below ground in living trees, and a dead organic matter pool representing all other carbon stored in standing dead trees, on the forest floor, and in the soil. The label "dead organic matter" is used even though it is recognized that some of the carbon in this DOM pool is contained in living organisms.

Another Chapman-Richards function is estimated to represent the biomass carbon pool as a function of stand age: $B(a) = b_1(1 - e^{-b_2 a})^{b_3}$, where $B(a)$ is the mass of carbon stored in the living trees at age a, and b_1, b_2 , and b_3 are coefficients set at 198.6, 0.0253, and 2.64 respectively. This function provides a reasonable representation of the tabulated biomass at different stand ages from CBM-CFS3. Figure (1.2) compares the projection of the biomass carbon stocks generated by CBM-CFS3 with the Chapman-Richards function. In general, the estimated curve corresponds well to the CBM-CFS projection.

Three processes are assumed to affect the development of the DOM pool: decay, litterfall, and harvest. DOM is assumed to decay at a rate, α, which represents a fixed proportion of the DOM pool each year. DOM is added to the pool as the proportion of the biomass of the stand that dies naturally each year. This proportion is expressed as the litterfall rate, β. With no timber harvest, the DOM pool grows

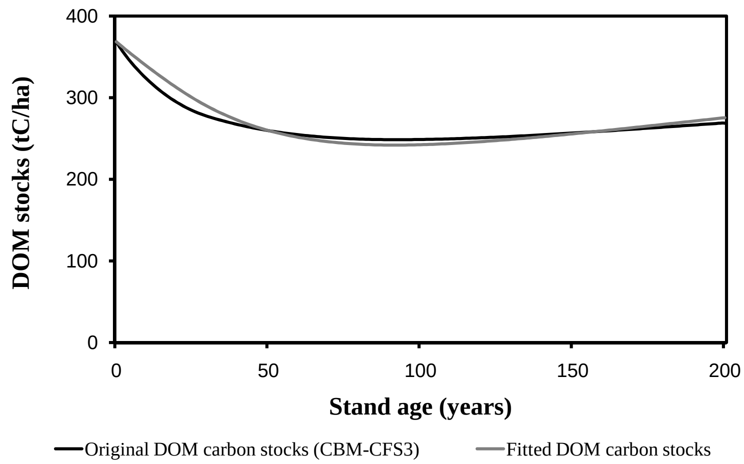

Figure 1.3: Comparison of DOM carbon stock projections using CBM-CFS3 and estimated approximation.

according to equation (1.1).

$$D_{t+1} = (1 - \alpha)D_t + \beta B(a) \tag{1.1}$$

The decay and litter fall rates were estimated using the method of least squares to find the parameters α and β which result in the closest match to the DOM projections of CBM-CFS3 for the pine stand. The estimated parameters are $\alpha = 0.00841$ and $\beta = 0.01357$. Figure (1.3) compares the estimated DOM curve to that generated by CBM-CFS3. In general, the estimated curve corresponds reasonably well to the CBM-CFS3 projection, although it overestimates DOM C stocks for stands younger than 50 years. This may be because the simplified model does not consider faster decay rates associated with younger, more open stands as CBM-CFS3 does (Kurz et al., 1992).

1.8 Thesis structure

This thesis is a collection of four papers, tied together with this introductory chapter and a concluding chapter. The second chapter presents the results from a dynamic programming model used to determine the optimal harvest decision for a forest stand in the boreal forest of western Canada that provides both timber harvest volume and carbon sequestration services. The state of the system at any point in time is described by stand age and the amount of carbon in the dead organic matter pool. The results of the study indicate that while optimal harvest age seems to be relatively insensitive to carbon stocks in dead organic matter, initial carbon stock levels significantly affect economic returns to carbon management.

In developing incentives to reduce carbon emissions and increase carbon sequestration, policy makers omitted carbon stored in wood products and the associated fossil fuel carbon emissions. The third chapter presents the results from a discrete dynamic programming model used to determine the optimal harvest decision for a forest stand that provides benefits from timber harvest and carbon sequestration in forest and wood products. The state variables are stand age, the amount of carbon in the dead organic matter and wood product pools. The results of the study suggest that optimal behaviour of a landowner is marginally affected by the inclusion of wood product pool or by accounting for fossil fuel carbon emissions.

Choosing an appropriate baseline is critical to the credibility of any offset carbon market. In chapter 4 a discrete dynamic programming model with four state variables is used to demonstrate that the choice of a baseline will affect the potential size of the offset credits but will not affect the optimal behaviour of a landowner. In order words, different baselines policies will have the same impact of mitigating the effect of greenhouse induced climate change.

In the last chapter, an analytical model is used to verify a major finding in the previous chapters. The results of the analytical model suggests that the optimal harvest age is dependent on the starting DOM and starting wood product stocks.

The concluding chapter summarizes the findings and offers some general conclusions.

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CHAPTER 2

Carbon sequestration and the optimal forest harvest decision: a dynamic programming approach considering biomass and dead organic matter[1]

2.1 Introduction

In response to global concern about climate change, policy makers and scientists are searching for ways to slow or reverse the trend of increasing concentrations of greenhouse gases, especially carbon dioxide (CO_2), in the atmosphere. Forests are viewed as potential carbon sinks. As trees grow, photosynthesis converts CO_2 into cellulose and other plant material, temporarily removing it from the atmosphere. In addition, a substantial amount of carbon is stored in forests as dead organic matter (DOM) in standing snags, on the forest floor, and in the soil until the process of decomposition releases it back to the atmosphere.

The Intergovernmental Panel on Climate Change (IPCC) provides guidelines for the calculation and reporting of changes in stocks of forest carbon (IPCC, 2006) as it

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relates to national greenhouse gas inventories. The IPCC identifies three tiers for reporting changes in stocks of forest carbon. These tiers reflect the relative importance of forest carbon stocks to greenhouse gas inventories and the sophistication of the data collection and monitoring infrastructure of countries.

Canada has elected to use tier 3 methodologies (with the most detailed reporting requirements) for reporting changes to carbon stocks on managed forest lands. The IPCC specifies five carbon pools that must be accounted for: above-ground biomass, below-ground biomass, dead wood, litter, and soil carbon. The Canadian Forest Service developed the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) to track and report changes in forest carbon stocks (Kull et al., 2007). CBM-CFS3 is a detailed model that recognizes more than 20 different carbon pools within a forest stand and tracks the transfer of carbon between these pools and the atmosphere (Fig. 2.1).

A classic problem in forest economics is the determination of the harvest age for an even-aged forest stand which maximizes the net present value of an infinite series of timber regeneration, growth, and harvest cycles. Faustmann (1849) is usually attributed with the first correct solution to this problem when only timber values are considered. Samuelson (1976)) provides a more formal mathematical specification of the problem. Hartman (1976) extends the model to include values associated with standing trees (*e.g.* wildlife habitat) as well as the extractive value of timber harvest.

In the forest economics literature, most of the analysis of carbon sequestration has focused on the carbon pools in living biomass. However, the DOM carbon pool can represent a substantial proportion of the total carbon stored in forest stands and management decisions such as harvest age can have a substantial effect on soil carbon stocks (Aber et al., 1978; Kaipainen et al., 2004). Covington (1981) found that forest floor mass declines sharply following harvest, with about half of forest floor organic matter lost in the first 20 years. DOM may increase immediately following harvest as a result of slash and other debris left on site (Black and Harden, 1995). Despite the importance of the DOM pool in the carbon cycle of a forest stand, it has received limited attention in the literature on the economics of forest carbon sequestration, perhaps because of the difficulty of tracking a large number of carbon pools in an optimization model.

The Hartman model is used by van Kooten et al. (1995) in an early exploration

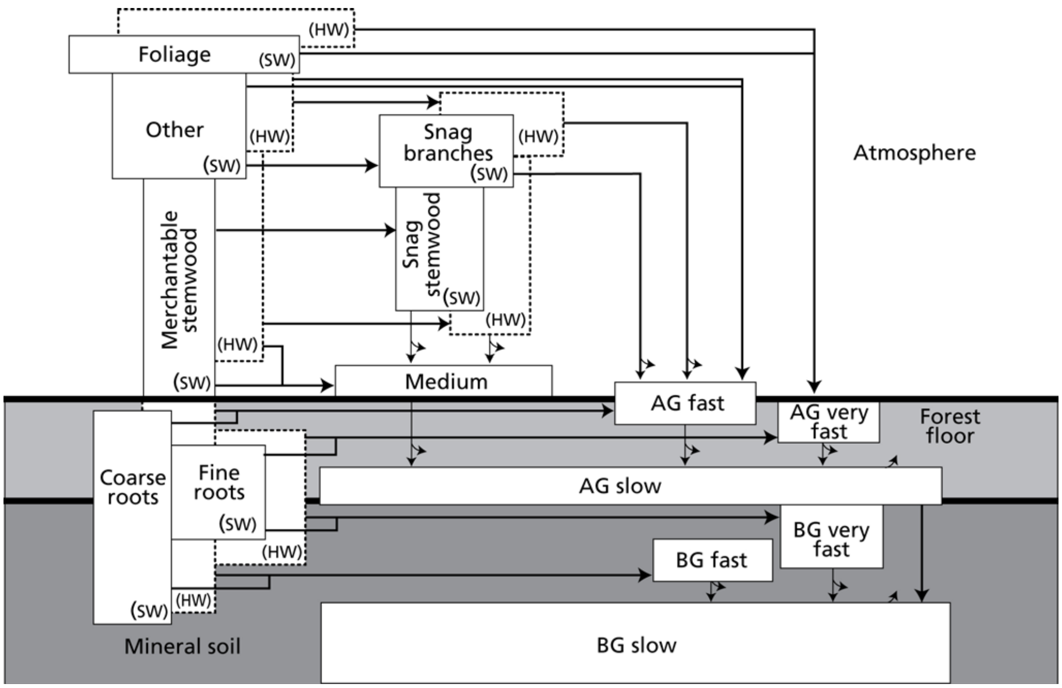


Figure 2.1: The carbon pool structure of the CBM-CFS3. Very fast, fast, medium, and slow refer to relative decomposition rates for pools. Curved arrows represent transfers of carbon to the atmosphere, and straight arrows represent transfers from one pools to another. SW is softwood, HW is hardwood, AG is above ground, and BG is below ground. Illustration courtesy of the Canadian Forest Service, reproduced with permission from (Kull et al., 2007, Fig. 1-1).

of the effect of carbon prices on optimal forest harvest age in western Canada. In their analysis, the amount of carbon stored in the forest stand is proportional to volume of merchantable timber on the site at a particular stand age. The forest owner is paid for the accumulation of carbon in biomass associated with growth, and pays for carbon released to the atmosphere at harvest. Some of the harvested timber is assumed to be permanently stored in structures and landfills. There is no recognition of DOM or soil carbon in the van Kooten analysis.

Dynamic programming has been used in some recent papers as an approach to stand level optimization with respect to timber values and carbon sequestration. Spring et al. (2005b) formulated and solved a stochastic dynamic program to maximize the expected net present value of returns from timber production and carbon storage in a forest stand subject to stochastic fire. They modeled the decision problem using stand age as the state variable: timber production and carbon storage were both treated as functions of stand age. In Spring et al. (2005a), the same authors used stochastic dynamic programming to determine the rotation age considering timber production, water yield, and carbon sequestration under stochastic fire occurrence, again using stand age as the only state variable. Chladná (2007) used dynamic programming to examine the optimal forest stand harvest decision when timber and carbon prices are stochastic. Chladná used stand volume per hectare, timber price, and carbon price as state variables. Yoshimoto and Marusak (2007) optimized timber and carbon values in a forest stand using dynamic programming in a framework where both thinnings and final harvest were considered. In this case, the state variables for the problem were stand age and stand density (number of trees per ha).

Gutrich and Howarth (2007) develop a simulation model of the economics of timber and carbon management for five different forest types in New Hampshire, USA. Their model includes representation of carbon stored in live biomass, dead and downed wood, soil carbon, and wood products. Annual transfers of carbon between pools are modelled. For each timber type, an initial stock of carbon in the dead and downed wood pool is assumed. A grid search is performed to find the harvest age that maximizes net present value given the initial stock of carbon in the non-biomass pools. To the best of my knowledge, Gutrich and Howarth (2007), were the first to publish a study where the amount of carbon stored in the DOM pool was considered in determining the economically optimal timber harvest age. They do not, however, consider the effect of different initial stocks in the DOM pool. van Kooten et al. (1999) investigated the potential for and costs of terrestrial carbon sequestration in northeastern British Columbia and Alberta by considering DOM pool. They do not, however, determine optimal harvest age.

At the forest level, McCarney (2007) uses a linear programming model which includes carbon stocks in both DOM and biomass pools in a model optimizing the net present value of timber harvest and carbon sequestration. Initial DOM stocks are fixed in McCarney's analysis.

In this study, a dynamic programming model is developed to find the optimal stand management policy when both timber harvest and carbon sequestration values are considered. The forest stand being modeled is described in terms of its age and the mass of carbon stored in the DOM pool. The management decisions available to the decision maker are to clearcut a stand of a given age and with a DOM pool of a given size, or to defer the harvest decision. Because the amount of carbon stored in the DOM pool is a substantial fraction of the carbon stored by the stand, consideration of the DOM pool could be of considerable economic interest. To the best of my knowledge, this is the first study to examine the role of variable DOM stocks in the optimal forest harvest decision at the stand level.

The dynamic programming model presented here is used to:

1. examine the sensitivity of optimal harvest age to stocks of carbon in DOM and carbon prices,

2. examine the sensitivity of the net present value of forested land to stand age, stocks of carbon in DOM, and carbon prices,

3. examine projected trajectories of carbon stocks in DOM given optimal harvest rules for a given carbon price, and

4. examine the impact of ignoring carbon stocks in DOM on the optimal harvest decision.

2.2 Data

2.2.1 Timber yield and cost functions

The timber yield and the cost information used in this study come from the TIPSY growth and yield simulator (BC MoFR, 2007) developed and used by the British Columbia Ministry of Forests and Range for use as input to forest management plans. The data used represent a lodgepole pine stand in the BWBS biogeoclimatic zone, in the Dawson Creek Forest District of the Prince George Forest Region of British Columbia, Canada. A medium site class (site index is 16 m at 50 years breast height age) and a planting density of 1600 stems/ha is assumed.

The tabular representation of the merchantable timber yield table from TIPSY is approximated using a Chapman-Richards growth function, $V(a) = v_1(1 - e^{-v_2 a})^{v_3}$, in which $V(a)$ represents the merchantable timber volume in m^3/ha at age a and v_1, v_2 and v_3 are parameters, which were set at 500.4, 0.027 and 4.003 respectively. These parameters give an acceptable representation of the yield table generated by TIPSY (see Fig. 1.1).

All costs and prices in this paper are expressed in Canadian dollars (CAD). A derived residual value approach (Davis et al., 2001, pp. 418–427) is used to estimate the net value of timber harvest. The residual value is the selling price of the final products (in this case lumber and pulp chips) less the costs of converting standing trees into the final products, expressed in CAD/m^3 of merchantable timber.

The average lumber price of kiln dried, standard and better, western spruce-pine-fir, 2×4 random length lumber for the period April 1999 to March 2008 was approximately 375 CAD/thousand board feet (MBF) (BC MoFR, 2009). Based on the observed range of lumber prices for this time period, a low and high lumber prices (250 and 500 CAD/MBF) were also used in sensitivity analyses (not reported here). The price of wood chips was assumed to be 70 CAD/bone dry unit (BDU). At 87 years of age (the volume maximizing harvest age), the pine stand modeled with TIPSY will yield 0.210 MBF of lumber and 0.152 BDU of pulp chips per cubic metre of roundwood input. The base selling price of the final products expressed in equivalent roundwood input terms is 89.40 CAD/m^3. The selling price of final products expressed in terms of wood input is represented by the parameter P^w. The total revenue (CAD/ha) at any harvest age is calculated as $P^w V(a)$.

The cost of converting standing trees into end products is the sum of all costs associated with harvesting, hauling, and milling. Road construction and harvesting costs reported by TIPSY for the pine stand were 1,150 and 5,100 CAD/ha. Log hauling, milling and overhead costs as 4.84, 34.65, and 8.06 CAD/m^3 respectively. The costs reported on a CAD/ha basis are assumed to be closely related to the area harvested; the costs reported as CAD/m^3 are assumed to be more closely related to volume harvested: F^a is used to represent area based costs and F^v to represent volume based costs. The total harvesting and processing costs at any harvest age (CAD/ha) are calculated as $F^a + F^v V(a)$. Based on the costs used here, F^a was set to 6,250 CAD/ha and F^v to 47.55 CAD/m^3. Stands are assumed to be reestablished immediately following harvest at a cost, E, which was set to 1,250 CAD/ha, based on the default parameters used by TIPSY.

2.2.2 Carbon pool dynamics

The TIPSY yield table was used as input to CBM-CFS3 in order to generate projections of carbon stored in each of the pools represented in Fig. 2.1. Figure 2.1 shows that DOM is initialized at 370 tC/ha for a lodgepole pine stand in the Dawson Creek Forest District. This value came from the assumption that wildfire is the main disturbance type occurring during the spin-up procedure of CBM-CFS3 and it is also the last disturbance preceeding the establishment of the lodgepole pine stand. A 200 year historic fire return interval was also assumed. The intial DOM stock is very near the IPCC (2001) estimate of average carbon stocks of 344 tC/ha in the boreal forest. For a Canada wide average, Dixon et al. (1994) estimates the quantity of carbon in soil organic matter to a depth of one metre as 484 tC/ha. This value includes carbon in peat, coarse woody debris and fine litter.

A review of literature shows that the average quantity of soil carbon in a lodgepole pine stand is relatively low compared to the boreal forest average. This may be due to the fact that lodgepole pine grows on drier sites at higher elevations and is often considered to be a pioneer species. In a study done in Medicine Bow national Forest in southeastern Wyoming, Chatterjee et al. (2009) estimates the average soil organic carbon stock for an unmanaged forest as 110 tC/ha. In a boreal cordilleran forest type in northeatern British Columbia, Canada, Seely et al. (2002) calibrated the initial quantity of soil carbon and litter in a lodgepole pine stand as 225 tC/ha.

In this study,a highly simplified representation of the carbon pool structure of CBM-CFS3 with just two carbon pools was created: a biomass pool representing carbon stored above and below ground in living trees, and a dead organic matter pool representing all other carbon stored in standing dead trees (snags), on the forest floor, and in the soil. The label dead organic matter is used even though it is recognized that some of the carbon in this DOM pool is contained in living organisms.

Another Chapman-Richards function is estimated to represent the biomass carbon pool as a function of stand age: $B(a) = b_1(1 - e^{-b_2 a})^{b_3}$, where $B(a)$ is the mass of carbon in tC/ha, stored in the living trees at age a, and b_1, b_2 , and b_3 are coefficients set at 198.6, 0.0253, and 2.64 respectively. This function provides a reasonable representation of the tabulated biomass at different stand ages from CBM-CFS3 (see Fig. 1.2). Timber harvest is assumed to reset the age of the stand, and therefore its biomass, to zero.

Three processes are assumed to affect the development of the DOM pool: decay, litterfall, and harvest. DOM is assumed to decompose at a rate, α, which represents a fixed proportion of the DOM pool each year. DOM is added to the pool as the proportion of the biomass of the stand that dies naturally each year. This proportion is expressed as the litterfall rate, β. With no timber harvest, the DOM pool grows according to equation (2.1).

$$D_{t+1} = (1 - \alpha)D_t + \beta B(a) \tag{2.1}$$

The decay and litter fall rates were estimated using the method of least squares to find the parameters α and β which result in the closest match to the DOM projections of CBM-CFS3 for the pine stand. The estimated parameters are $\alpha = 0.00841$ and $\beta = 0.01357$. In general, the estimated curve corresponds well to the CBM-CFS3 projection (see Fig. 1.3).

When timber harvest occurs, the merchantable timber volume is removed from the site and processed into lumber and wood chips. The roots, stumps, tops, branches and leaves are assumed to die at the time of harvest and become part of the DOM pool. The mass of carbon removed from the site as merchantable timber volume is calculated as $\gamma V(a)$ where γ is a constant used to convert wood volume to the mass of carbon stored in wood. We use $\gamma = 0.2$ which is consistent with a carbon content of wood of approximately 200 kg m^{-3} (Jessome, 1977). With timber harvest, the

DOM pool grows according to Eq. 2.2.

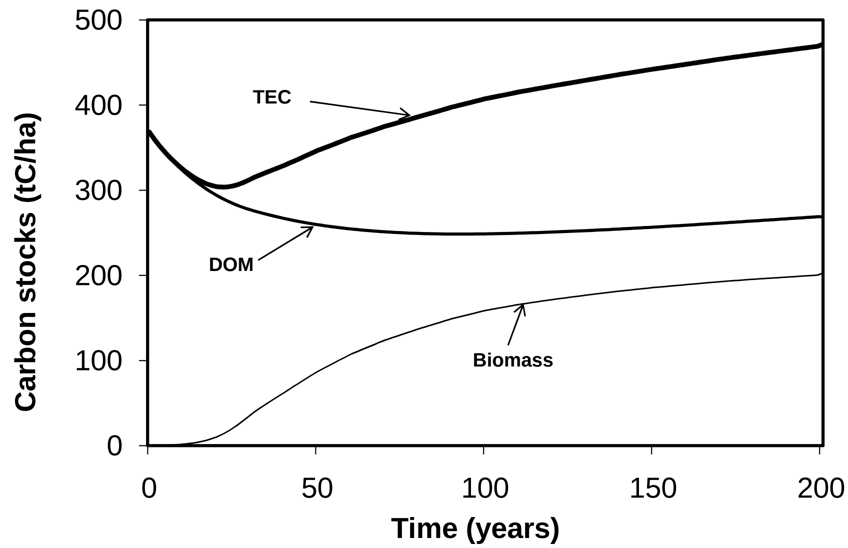
$$D_{t+1} = (1-\alpha)D_t + B(a) - \gamma V(a) \tag{2.2}$$

For the carbon market we assume here, the landowner is paid or pays for annual changes in stocks of total ecosystem carbon (TEC). The annual change in TEC is simply the sum of the changes in biomass and DOM carbon. With no harvest, the change in biomass is given by $\Delta B(a) = B(a+1) - B(a)$. With harvest, the age of the stand is set to 1 for the subsequent year, so the change in biomass becomes $\Delta B(a) = B(1) - B(a)$. The change in DOM for no harvest is given by $\Delta D_t = -\alpha D_t + \beta B(a)$. It is $\Delta D_t = -\alpha D_t + (1+\beta)B(a) - \gamma V(a)$ for the harvest case.

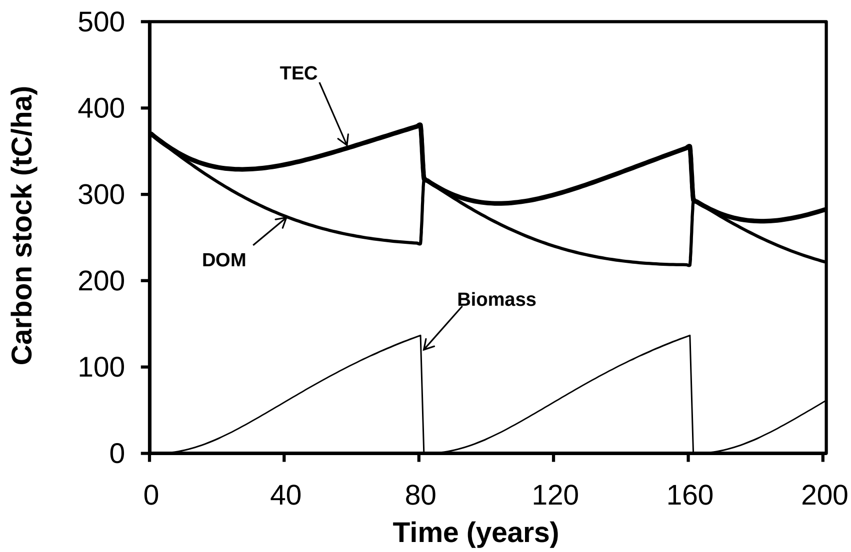
Fig. 2.2 shows the development of aggregated carbon pool stocks for a lodgepole pine stand that is left unharvested (panel a) and one that is harvested on an 80 year rotation (panel b) given an initial age of 0 years and an initial DOM stock of 370 tC/ha. In the early stages of stand development, the stand is a net source of CO_2 as a result of decay processes (Kurz et al., 1992). As the stand ages, TEC stocks increase with increasing biomass, and the decline in DOM stocks slows and reverses as carbon is added to the DOM pool in the form of litterfall, dead branches and natural tree mortality. Panel b illustrates what happens to the DOM pool after a harvest. The figure shows that timber harvest on an 80 year harvest cycle produces a sharp increase in the amount of DOM at harvest, because of the input to the DOM pool of newly dead roots, stumps, tops, and logging slash.

2.2.3 Valuation of carbon

The carbon market posited here pays landowners for net sequestration of CO_2 and requires payment for net release of CO_2 in the previous year. The price received per tonne of sequestered CO_2 is the same as the price paid per tonne of released CO_2. In this study, a broad range of prices for CO_2 are used in sensitivity analyses. Prices of CO_2 ranging between 0 and 50 CAD per tonne of CO_2 (tCO_2) were examined. The price of permanent carbon credits traded on European Climate Exchange (ECX) between January 2005 and April 2008 ranged from 10 to 45 CAD/tCO_2 (Point Carbon, 2009). Prices for carbon credits traded on the Chicago Climate Exchange



(a) No timber harvest.



(b) Timber harvest on an 80 year rotation.

Figure 2.2: Projections of carbon pool development over time. Panel a) is projection without harvest. Panel b) is the projection with timber harvest on an 80 year rotation.

(CCX) for the same time period ranged from 1 to 5 CAD/tCO_2 (CCX, 2009). The range of prices chosen encompass the range of observed prices including any discounting that may occur in order to account for the temporary nature of carbon sequestration in forests. It is conventional to express carbon prices in currency units per tCO_2 and stocks as tonnes of carbon (tC). The practice reporting is continued here, but for modeling purposes, I define equivalent prices for carbon (CAD/tC) as $P^C = 3.67P^{C0_2}$ because the molecular weight of CO_2 is approximately 3.67 times the atomic weight of C.

2.3 The model

The basic assumption of the model is that a forest landowner is participating in a carbon market where the landowner is paid for carbon sequestered by the forest and pays when carbon is released. The landowner is assumed to manage the forest jointly for timber production and carbon sequestration in a manner that earns maximum discounted financial return. The forest is managed using an even-aged silvicultural system. Each rotation begins with the establishment of a stand on bare forest land and ends with a clearcut harvest after a number of years of growth. The beginning of a new rotation coincides with the end of the previous rotation. The cycle of establishment, growth, and harvest is assumed to repeat in perpetuity.

The decision problem is represented as a dynamic program, and state variables are used to describe the system at each stage of the decision problem. It is theoretically possible to develop a dynamic program with state variables representing carbon stock in each of the more than 20 carbon pools represented in CBM-CFS3, but program solution becomes impractical due to Bellman's "curse of dimensionality" (Bellman, 1961). However, the two-pool representation of total ecosystem carbon used here is easily formulated and quickly solved with dynamic programming.

2.3.1 Dynamic programming model

The model developed here is a discrete backwards recursion dynamic programming model. The stages represent time, in one year time steps. The forest stand is described by a combination of two state variables, the age of the stand (years) and carbon stocks in the DOM pool (tC/ha). There are 251 discrete one-year wide age classes, j, with midpoints $a_j = j,\ j = 0, 1, \ldots, 250$ years. There are 501 DOM classes, i, with midpoints $d_i = i,\ i = 0, 1, \ldots, 500$ tC/ha. Timber harvest volume and carbon stored in the biomass pool are calculated as a function of stand age.

At each point in time, a decision is made by the landowner whether to clearcut the stand or let the stand grow for another year. Clearcutting yields immediate timber revenue. Both the clearcut and the leave decisions will result in a change in TEC and the appropriate carbon credit or debit. If harvesting does occur (i.e., decision, $k = 1$) in stage t, it is assumed that replanting occurs immediately and the stand age is set to 1 in stage $t + 1$. If harvesting does not occur (i.e., decision, $k = 0$) in stage t, the stand age is incremented by one year in stage $t + 1$.

The change in total ecosystem carbon, ΔC_{ijk} depends on current DOM class i, age class j, and harvest decision k. It is the sum of the changes in DOM and biomass. For the no harvest case:

$$\Delta C_{ij0} = B\left(\left(\min\left(a_j + 1\right), 250\right)\right) + \beta B\left(a_j\right) - \alpha d_i - B\left(a_j\right). \tag{2.3}$$

For the harvest case:

$$\Delta C_{ij1} = B\left(1\right) - \alpha d_i - \gamma V\left(a_j\right). \tag{2.4}$$

The net harvest revenue for age class j, (H_j) is calculated as

$$H_j = \left(P^W - F^v\right) V\left(a_j\right) - F^a - E. \tag{2.5}$$

Establishment costs are included here because it is assumed that reforestation is required, and occurs, immediately after timber harvest.

The stage return or periodic payoff (N_t) is calculated as shown in Eq. 2.6. The payoff is calculated for the midpoints of each DOM class (i) and stand age (j) and for each of the possible harvest decisions (k). If a stand is not harvested $(k = 0)$, the periodic payoff would be based on ΔC_{ijk} only. If the stand is harvested $(k = 1)$, the payoff includes payments or charges based on ΔC_{ijk} as well as the net revenue associated with timber harvesting, processing, and reestablishment.

$$N\{i, j, k\} = \begin{cases} P^C \Delta C_{ij0} & : \quad k = 0 \\ P^C \Delta C_{ij1} + H_j & : \quad k = 1 \end{cases} \tag{2.6}$$

In this analysis, it is assumed the objective at each stage, is to determine, for each possible combination of stand age and level of DOM stock, the harvest decision that results in the maximum net present value of land and timber and carbon storage for the remainder of the planning horizon. The stages in this dynamic programming model correspond to the time periods in which decisions are made. It is a finite horizon, deterministic model with time t measured in years.

Because we are using discrete DOM classes, we convert the projections from Eqs. 2.1 and 2.2 to the proportion of the source DOM class area that moves into two adjacent target DOM classes. We use l_{ijk} to represent the lower target class, and u_{ijk} to represent the upper. We calculate ρ_{ijk} to represent the proportion that moves into the upper class and $\left(1-\rho_{ijk}\right)$ as the proportion that moves into the lower class. In the notation used here, $\lfloor x \rfloor$ indicates the floor of a real number x, i.e. the largest integer less than or equal to x. The fractional part of x is indicated by $\langle x \rangle$ such that $x = \lfloor x \rfloor + \langle x \rangle$.

$$
\begin{aligned}
l_{ij0} &= \min\left(\lfloor (1-\alpha)\, d_i + \beta B\left(a_j\right) \rfloor, 500\right) && (2.7)\\
l_{ij1} &= \min\left(\lfloor (1-\alpha)\, d_i + B\left(a_1\right) - \gamma V\left(a_j\right) \rfloor, 500\right) && (2.8)\\
u_{ijk} &= \min\left(l_{ijk}+1, 500\right) && (2.9)\\
\rho_{ij0} &= \langle (1-\alpha)\, d_i + \beta B\left(a_j\right) \rangle && (2.10)\\
\rho_{ij1} &= \langle (1-\alpha)\, d_i + B\left(a_1\right) - \gamma V\left(a_j\right) \rangle && (2.11)
\end{aligned}
$$

We calculate a weighted return from the target states associated with the harvest decision, k. For the no harvest decision, $k = 0$,

$$W_{ij0} = \left(1-\rho_{ij0}\right) R_{t+1}\{l_{ij0}, \min(\left(j+1\right), 250)\} + \rho_{ij0} R_{t+1}\{u_{ij0}, \min(\left(j+1\right), 250)\} \tag{2.12}$$

For the the harvest decision, $k = 1$,

$$W_{ij1} = \left(1-\rho_{ij1}\right) R_{t+1}\{l_{ij1}, 1\} + \rho_{ij1} R_{t+1}\{u_{ij1}, 1\} \tag{2.13}$$

The return for the last stage in the problem is initialized to zero,

$$R_T\{i, j\} = 0. \tag{2.14}$$

This assumption is justified on the basis that T is large (500 years) and the discounted value of R_T for reasonable discount rates for this problem is near zero (e.g. the present value of 1 CAD received 500 years in the future is 2.5×10^{-11} CAD given a 5% discount rate).

The discount factor, $\delta = (1 + r)^{-1}$, represents the relative value of a dollar received one year from now (given an annual discount rate of r) to a dollar today. The discount rate, r, used for the analysis is 5% per annum: for this analysis, $\delta = 0.9528$. This is the rate that is intended to reflect a market rate of time preference.

The recursive objective function for this problem is given in Eq. 2.15.

$$R_t\{i,j\} = \max_k N\{i,j,k\} + \delta W_{ijk}, \; t = T-1, T-2, \ldots, 0 \tag{2.15}$$

The recursive objection function selects the harvest decision at each stage for each possible combination of state variables that maximizes the net present value at that stage, assuming that optimal decisions are made in all subsequent stages. It calculates a return for each of the harvest decisions and selects the harvest decision that results in the maximum return as the optimal choice for the state combination in that stage.

Eq. 2.16 below modifies the stage return at time zero for stands of age 0, and represents the soil expectation value for each initial DOM class. This incorporates establishment costs for time zero. For subsequent stages, establishment costs are incorporated in Eq. 2.6.

$$\forall i \; : \; R_0\{i,0\} \leftarrow R_0\{i,0\} - E \tag{2.16}$$

2.4 Results and discussion

The dynamic program presented above is used to determine the optimal harvest policy for a profit-maximizing landowner managing a forest stand for production of wood volume and sequestration of CO_2. The optimal policy is summarized by a decision rule which shows the combinations of stand age and DOM states for which the optimal decision is to harvest, and those combinations for which the optimal decision is to defer harvest until at least the next period. The change in policy is examined in response to changing prices for CO_2 storage and also to alternative methods of accounting for DOM. The results presented in this section were calculated using an implementation of the dynamic programming model programmed in MATLAB (Pratap, 2006).

The optimal harvest policies for a number of different carbon prices are presented in Fig. 2.3. The decision rule when P^{CO_2} is 0 CAD/tCO_2 corresponds to the case when timber is the only value considered: it is always optimal to harvest stands older than the Faustmann rotation age of 73 years given the data used here. As P^{CO_2} increases, the optimal harvest age increases. When P^{CO_2} is 35 CAD/tCO_2 or greater, the optimal decision is to never harvest. The optimal policy is sensitive to DOM stocks at the lower levels. This happens because the amount of CO_2 released to the atmosphere through decay is lower with lower DOM stocks: the marginal gain in CO_2 sequestration from delaying harvest is greater with lower DOM stocks.

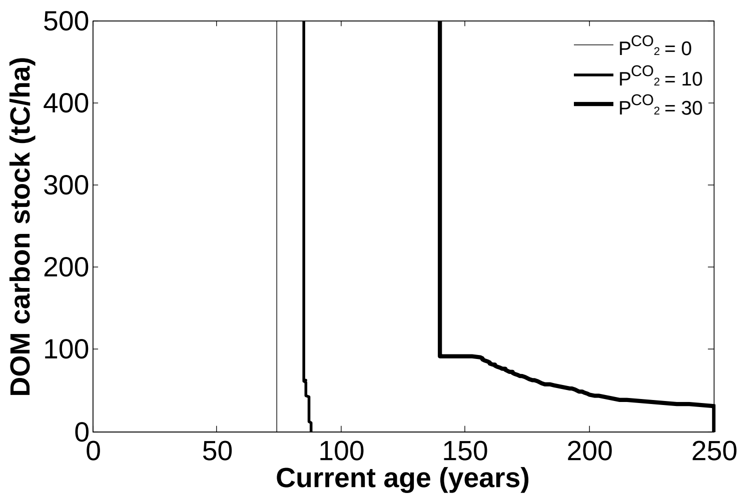


Figure 2.3: Optimal harvest policies for different carbon prices. The region to the right of and above the line corresponding to each carbon price represents the combinations of current age and DOM carbon stock for which the optimal decision is to harvest. In the region to the left of and below the line, the optimal decision is to delay harvest. For carbon prices of 35 CAD/tCO_2 or greater, it is never optimal to harvest.

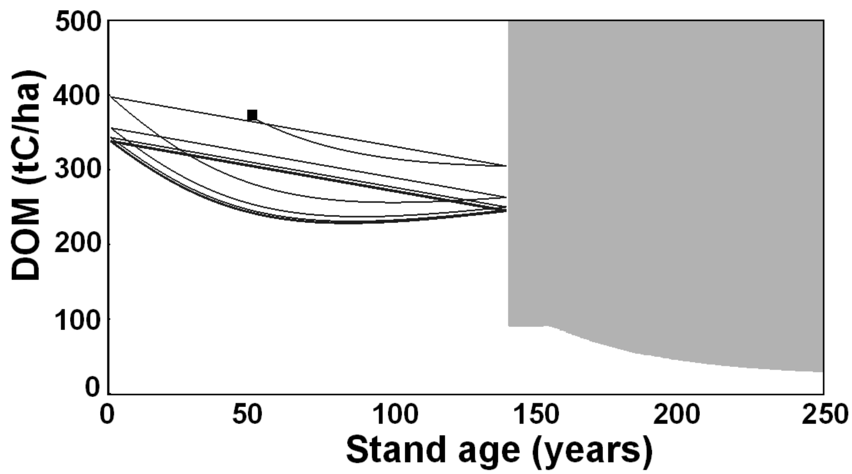
Fig. 2.4 shows the decision rule for $P^{CO_2} = 30$ CAD/tCO_2 as the shaded grey area. The optimal decision is to harvest when the combination of DOM and age falls within this part of the state space. This figure also shows how two stands with different initial states would develop given this decision rule. The initial state in panel (a) is a stand that is 50 years old with initial DOM stocks of 370 tC/ha. It grows until it reaches 144 years, at which point it is harvested and regenerated on a continuing 144 year cycle. After the third harvest, the stand reaches an equilibrium condition where the DOM at the beginning and end of each rotation is essentially constant from one rotation to the next. The starting point in panel (b) is 125 years of age and 25 tC/ha of DOM. The first harvest occurs at a older age (150 years), but after the third or fourth harvest, the same equilibrium is reached.

Table 2.1 summarizes the equilibrium conditions for different carbon prices. A higher P^{CO_2} gives a longer rotation, with prices 35 CAD/tCO_2 resulting in a condition where the optimal decision is to never harvest. Because of the longer rotation age, carbon stocks are greater at both age zero and the rotation age with higher carbon prices. The variation in equilibrium rotation ages and carbon stored is substantial across the range of P^{CO_2} examined.

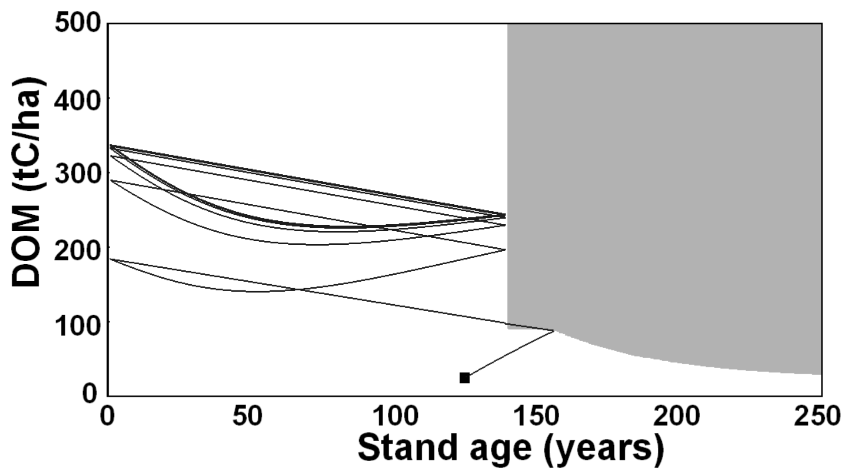
Table 2.1: Summary of harvest age and carbon stock and mean annual increment equilibria for different carbon prices. DOM and TEC are equal at age 0 because there is zero biomass at this point. DOM refers to the amount of carbon stored in the dead organic matter pool. TEC refers to total ecosystem carbon, or the sum of DOM and biomass pools.

P^{CO_2} (CAD/tCO_2)	Rotation age (years)	DOM & TEC at age 0 (tC/ha)	DOM at rotation (tC/ha)	TEC at rotation (tC/ha)	MAI (m^3/ha/yr)
0	73	259	187	315	3.76
1	74	260	188	316	3.77
2	75	262	189	320	3.79
5	78	269	192	327	3.82
10	84	276	198	342	3.85
20	102	300	215	377	3.78
30	144	341	249	434	3.27

The MAI column in table 2.1 refers to the mean annual increment of the stand. MAI is used by foresters to describe the productivity of a stand in terms of average annual physical product output for different rotation ages. It is calculated as $MAI = V(R)/R$ where R is the chosen rotation age. For the yield table used in this study, the MAI is maximized at 87 years, which is close to the equilibrium rotation age when $P^{CO_2} = 10$ CAD/tCO_2. The MAI is irrelevant to the decision maker modeled in this paper, but may be relevant to society as a whole. Forest products such as



(a) Initial state: 50 years and 370 tC/ha.



(b) Initial state: 125 years and 25 tC/ha.

Figure 2.4: Decision rule for $P^{CO_2} = 30$ CAD/tCO_2 with trajectories of stand development in state space. The grey polygon indicates the portion of the state space where the optimal decision is to harvest. The initial state is indicated by the small square. The lines indicate the state space trajectories. As the stand ages, it moves to the right on the x-axis, and the size of the DOM pool changes as a result of decomposition and litterfall. When the stand moves into the grey polygon, it is harvested. In the following year, the age of the stand is set to one year and DOM is increased from the pulse of input from the portion of biomass left on site after harvest.

lumber can serve as stores of carbon. There may be an advantage to choosing a harvest age that provides a larger MAI, and therefore more lumber production, if the carbon storage potential of wood products is taken into account. This is explored in Chapter 3.

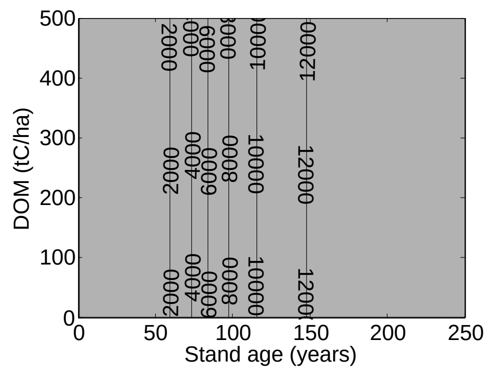
Fig. 2.5 summarizes $R_0\{d_i, a_j\}$ from equation 2.15: the value of land, timber, and carbon sequestration services (LTCV, hereafter) for the entire state space, for carbon prices of 0, 2, 10, and 40 CAD/tCO_2. Panel (a) represents the case where $p^{CO_2} = 0$. Because carbon has no value, in this case, the LTCV is independent of the amount of DOM stored.

In Fig. 2.5(d), P^{CO_2} has been set to 40 CAD/tCO_2 where the optimal decision is to permanently defer timber harvest. Note that for DOM stocks of above about 380 tC/ha, there is no stand age where this stand has a positive LTCV. If the decision maker had a choice of participating in this carbon market at this P^{CO_2}, or not, he would be unlikely to do so unless the initial state of DOM was less than 380 tC/ha as all positive LTCVs occur at DOM levels below this. This threshold is very near the IPCC (2001) estimate of average carbon stocks of 344 tC/ha in the boreal forest but greater than the Seely et al. (2002) estimate of initial carbon stocks of 225 tC/ha for a lodgepole pine stand in the boreal forest.

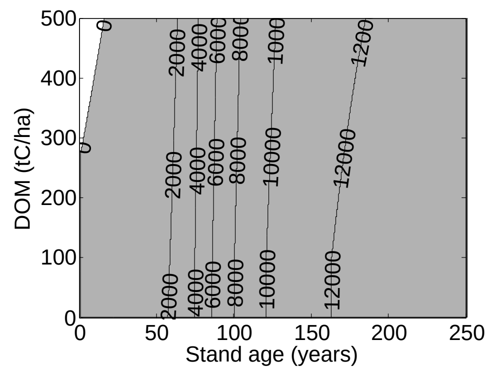
For intermediate carbon prices of 2 and 10 CAD/tCO_2, the picture is somewhat complicated (Figs. 2.5(b) and 2.5(c)). Young stands with low DOM stocks have a greater LTCV than they would have with $P^{CO_2} = 0$. The DOM stocks would have to be lower than about 300 tC/ha for the decision maker to see any advantage in participating in this carbon market. The cost associated with paying for carbon released from decaying DOM stocks is too high in much of the state space to make participation in such a market worthwhile.

Fig. 2.5 shows that LTCV decreases with increasing DOM stocks when the carbon price is positive. This might seem counter-intuitive as more carbon storage is generally thought of as a good thing. However, a larger stock of DOM will generally release a greater absolute quantity of CO_2 to the atmosphere than a smaller stock. A large stock of decaying dead organic matter is a liability for the landowner represented in this model.

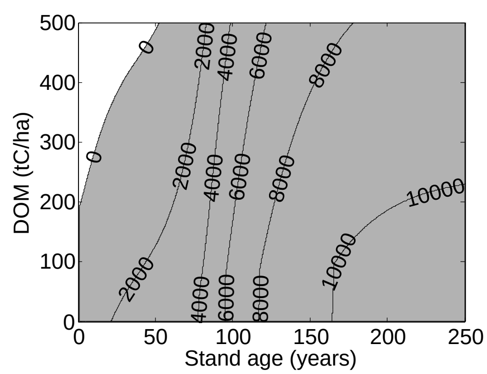
Fig. 2.6 presents the information from Fig. 2.5 in a manner which highlights the portion of the state space for which participating in the carbon market would be



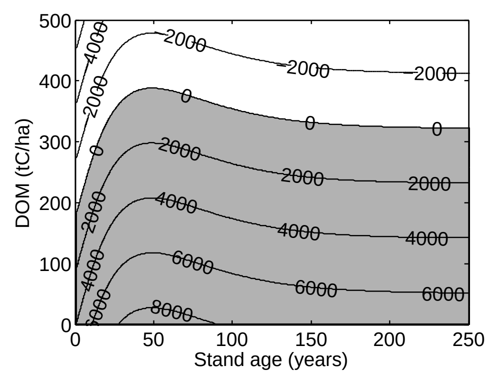
(a) $P^{CO_2} = 0$ CAD/tCO$_2$.



(b) $P^{CO_2} = 2$ CAD/tCO$_2$.



(c) $P^{CO_2} = 10$ CAD/tCO$_2$.



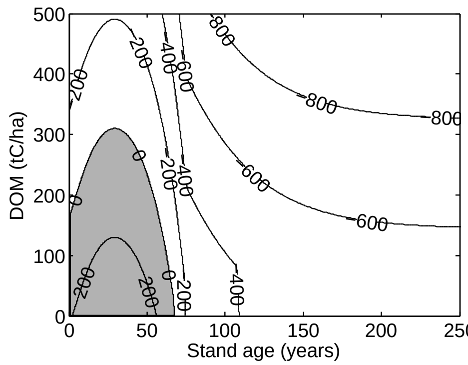
(d) $P^{CO_2} = 40$ CAD/tCO$_2$.

Figure 2.5: Land, timber, and carbon values (CAD/ha) by stand age and carbon stocks in the DOM pool for different carbon prices. The contours indicate combinations of age and DOM states that have the same land, timber, and carbon values. The region where LTCV is positive is shaded grey.

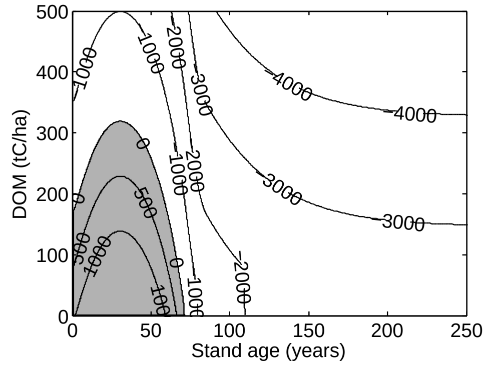
advantageous to the landowner. These contours represent the difference between the LTCVs calculated when $P^{CO_2} = 2$, 10, and 40 CAD/tC and when $P^{CO_2} = 0$. The landowner would find participation in the carbon market to be advantageous when the difference between LTCVs is positive. This occurs when the initial stand is relatively young and has a relatively small DOM pool. The size of the DOM pool where carbon market participation is advantageous is almost always less than the boreal forest average of 340 tC/ha. In other words, given current states of carbon stocks, voluntary participation in the carbon market posited here is unlikely, unless the stand is relatively young with a relatively low stock of carbon in its DOM pool.

In the system modeled here, a forest landowner has the choice at each point in time whether to harvest a stand of a particular age and with a particular stock of DOM carbon, or not. In most cases in this system, the tendency will be for increasing carbon prices to result to delay the optimal age of harvest. A benefit to society of the carbon market would be the additional TEC stored in the forest stand and, therefore, not released to the atmosphere. Fig. 2.7 shows projections of TEC over 1000 years for a stand starting at 50 years of age and 370 tC/ha in DOM stocks under carbon prices of 0 and 10 CAD/tCO_2. The optimal harvest age increases from 73 to 84 years with the 10 CAD/tCO_2 increase in carbon price, so for the 11 years after harvest for the 0 CAD/tCO_2 case, there is substantially more TEC carbon in the 10 than the 0 CAD/tCO_2 projection. There is no difference between the two projections for the first 23 years between the two cases, because both cases are following the same trajectory up to this point in time. On average, the higher carbon price will have more TEC over the projection period, although due to the asynchronous cycles associated with the different rotation ages, there will be points in time where the zero carbon price case has more TEC. If benefits are measured in terms of the additional amount of carbon stored over a time period, the perceived benefits are quite sensitive to initial conditions and the time period used for evaluation. The sensitivity to length of time period given the starting conditions is illustrated in Table 2.2.

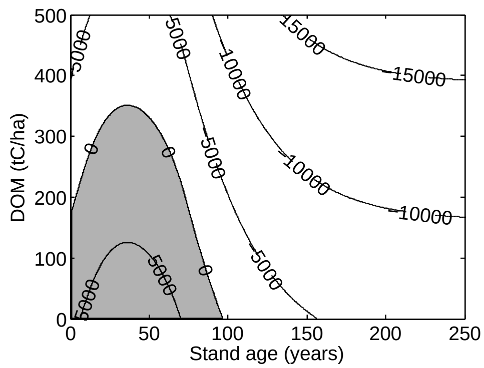
A major difference between this study and those of van Kooten et al. (1995), Spring et al. (2005a,b), Chladná (2007), and Yoshimoto and Marusak (2007) is that I consider carbon stored in biomass and DOM pools, whereas these other studies ignore the biomass pool. In order to evaluate the effect of ignoring the DOM pool, a series of runs with a modified version of the model where the carbon market



(a) $P^{CO_2} = 2$ CAD/tCO_2.



(b) $P^{CO_2} = 10$ CAD/tCO_2.



(c) $P^{CO_2} = 40$ CAD/tCO_2.

Figure 2.6: Change in land, timber, and carbon values (CAD/ha) from $P^{CO_2} = 0$ case by initial state for different carbon prices. The contour lines indicate combinations of age and DOM that have the same change in LTCV from the $P^{CO_2} = 0$ case. The region of state space where this change is positive shaded grey.

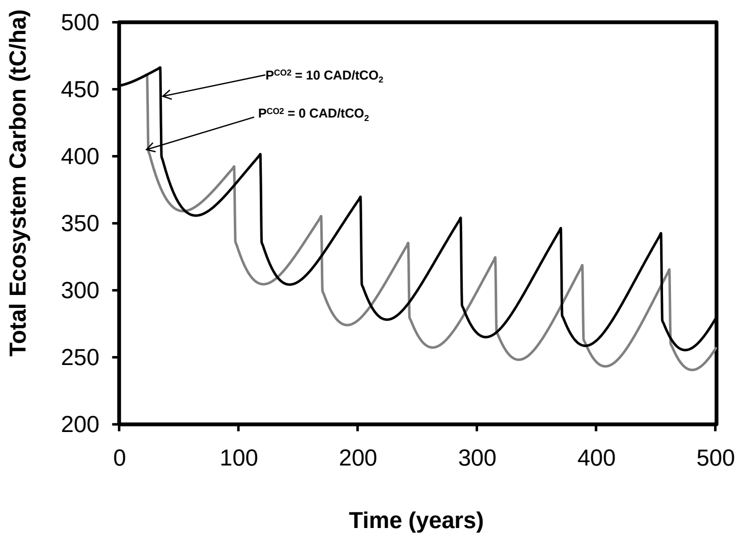


Figure 2.7: Projections of total ecosystem carbon stocks for $P^{CO_2} = 0$ and $P^{CO_2} = 10$ CAD/tCO_2 cases given application of the optimal decision rule and an initial stand age of 50 years and initial DOM stocks of 370 tC/ha.

Table 2.2: Average difference in projection of TEC stocks given optimal policies when $P^{CO_2} = 10$ and $P^{CO_2} = 0$ for different projection periods.

Time (years)	Average difference (tC/ha)
20	0.0
50	20.6
100	8.2
200	18.7
500	17.7
1000	18.8

considered only biomass carbon were conducted. The results are summarized in Table 2.3 and compared with Table 2.1. An obvious result is that the optimal harvest decision is independent of DOM stocks when changes in DOM do not affect the objective function. The optimal rotation age and equilibrium carbon stocks are greater when the DOM pool is not considered. For carbon prices of 5 CAD/tCO_2 or greater, the differences are substantial. This difference occurs because the amount of CO_2 released to the atmosphere through decay is proportional to the stock of carbon in DOM. Maintaining high stocks of DOM is penalized in the approach presented in this paper and is not in the other approaches.

Table 2.3: Summary of harvest age and carbon stock and mean annual increment equilibria for different carbon prices when DOM is not considered. The values for $P^{CO_2} = 30$ are the asymptotic equilibria assuming no harvest.

P^{CO_2} (CAD/tCO_2)	Rotation age (years)	DOM & TEC at age 0 (tC/ha)	DOM at rotation (tC/ha)	TEC at rotation (tC/ha)	MAI (m^3/ha/yr)
0	73	259	187	315	3.76
1	75	264	189	318	3.79
2	76	266	190	321	3.80
5	82	273	197	336	3.84
10	94	290	208	364	3.83
20	173	363	267	459	2.79
30	∞	n/a	320	519	0

2.5 Conclusions

The analysis was conducted considering an isolated timber stand, where prices of timber and carbon storage services were determined exogenously. If a large forest area was participating in this market it would change the timber supply and could affect the prices of timber, which would feed back into the optimal harvest decision. The direction of this effect is not clear, as equilibrium timber production (measured by mean annual increment), increased in this example until carbon prices reached about 10 CAD/tCO_2. When carbon prices are high enough, rotation ages lengthen considerably and mean annual increment declines. In these cases, there would be pressure for both higher timber prices and the possibility of increased substitution of building materials such as concrete and steel for wood. I did not examine any effects of this substitution on national or global carbon accounts.

In this study the formulation of, and results from, a dynamic programming model used to determine the optimal harvest decision for a forest stand used to provide both timber harvest volume and carbon sequestration services is presented. The forest stand is described using two state variables: stand age and the stocks of carbon stored in the DOM pool. To the best of my knowledge, this is the first article to examine the impact of varying DOM on the optimal harvest age. This study provides a basic framework for assessing the economic implications of alternative methods of accounting for carbon stocks in DOM.

The model is used to examine optimal harvest decisions for a lodgepole pine stand in the boreal forest of western Canada. The following main conclusions are drawn from the study:

1. The optimal decision is sensitive to current stocks of carbon in the DOM pool, especially when carbon prices are high and initial DOM stocks are low,

2. For many realistic combinations of the initial stand age and DOM carbon stocks, a non-zero carbon price reduced the value of land, timber, and carbon sequestration services relative to the zero case. To some readers, this may be counter-intuitive as the storage of carbon in forests is often considered to be a benefit. However, because of the decomposition of DOM, forest stands can be a net carbon source for several years after stand initiation (Fig. 2.2). Coupled with a positive discount rate, DOM carbon stocks can represent a significant liability to the landowner, especially if they are required to pay for net carbon emissions in the year that they occur. Because of this, it is quite possible (perhaps even probable) that the economically optimal DOM stocks are smaller than in the initial state (Fig. 2.4a).

3. Compared to the case where changes in carbon stock in only the biomass pool is considered, optimal harvest ages are younger and equilibrium carbon stocks are lower when changes in carbon stocks in the DOM pool are rewarded or penalized.

This study presented the results of an optimal harvesting model for a forest stand where the landowner is paid for net increases in total ecosystem carbon in the stand,

and pays for net decreases, on an annual basis. By approximating a detailed carbon budget simulation model using two carbon pools, I was able to develop a dynamic programming model of the system which captures the important elements of the system for an economic analysis. The Variants of this model to explore alternative forms of carbon markets, including one which accounts for carbon pools in wood products, are presented in Chapters 3 and 4.

This study demonstrates that the optimal management policy can be substantially different between cases where the market considers and ignores carbon in the DOM pool. This raises an interesting issue because the size of the DOM pool is important from a carbon flux standpoint, but is more difficult to measure than biomass.

The analysis was conducted considering an isolated timber stand, where prices of timber and carbon storage services were determined exogenously. If a large forest area was participating in this market it would change the timber supply and could affect the prices of timber, which would feed back into the optimal harvest decision. The direction of this effect is not clear, as equilibrium timber production (measured by mean annual increment), increased in this example until carbon prices reached about 10 CAD/tCO_2. When carbon prices are high enough, rotation ages lengthen considerably and mean annual increment declines. In these cases, there would be pressure for both higher timber prices and the possibility of increased substitution of building materials such as concrete and steel for wood. I do not examine effects of this substitution on national or global carbon accounts.

This paper presents a model used for the determination of the optimal harvest age of a single forest stand in the tradition of Faustmann (1849) and Hartman (1976), with the inclusion of a price and a cost associated with the annual sequestration and emission of CO_2. The general results reported here can be expected to differ from forest-level analyses such as those reported by McCarney (2007) and McCarney et al. (2008) because of the effect of inter-period flow constraints imposed on forest-level models. The results can also be expected to differ from those reported in other stand-level models (*e.g.* van Kooten et al. (1995), Spring et al. (2005a,b), Chladná (2007)) because it is recognized that a forest stand has both carbon sink (the living biomass) and carbon source (the DOM pool) components. The results can also be expected to differ from other analyses because of the particular form of the carbon market assumed in this study. In this analysis, the landowner pays for emissions and gets paid for sequestration in the year of occurrence. Other market structures such as those based on the difference from a business-as-usual baseline or on a contracted amount of carbon storage at a particular point in time could lead to qualitatively different results.

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CHAPTER 3

Optimal harvest decision considering carbon stored in forest and wood products, and associated fossil fuel carbon emissions

3.1 Introduction

In developing incentives and protocols to reduce carbon emissions and increase carbon sequestration, one omission often stands out from the perspective of forest managers and forest product firms. Policy makers omitted wood product carbon, under the assumption that new wood products would simply replace discarded ones with no net change in this carbon pool (IPCC, 1997). However, this is an oversimplification and not a realistic assumption about environmental conditions, because the new wood products do not simply replace the discarded ones. Harvested wood releases its carbon at rates dependent upon its method of processing and its end use: waste wood is usually burned immediately or within a couple of years, paper usually decays in up to 5 years (although landfilling of paper can result in longer-term storage of carbon and eventual release as methane or CO), and lumber decays in up to 100 or more years. Because of this latter fact, forest harvest could result in a net change of carbon if the wood that is harvested is used for long-term products such as building lumber.

Fortunately, there is now broad recognition that this assumption is faulty. As a result of the continuing debate, forward movement on the harvested wood product issue occurred in Copenhagen, including a report that detailed specifics regarding harvested wood product and the approach that countries may take to account for carbon storage in forests and wood products (UNFCCC, 2009). It is likely that a decision on the carbon storage issue will not be based on science alone. Politics are certain to play an important role. For example, in the case of internationally traded wood, what nation should get credit for carbon stored in harvested wood products? Is is the nation in which trees were grown, or the nation in which the wood is used? Which nation, should pay the penalty when products begin to decay and release carbon? These kinds of questions explain part of the reticence in dealing with the stored carbon issue.

To address this faulty assumption (all the carbon contained within trees is released at the moment of harvesting), a number of alternatives have been proposed. One of the proposals which is considered in this study, is the stock change approach. Canada is on record as supporting consistent national accounting for all sources and sinks within a national inventory. This position aligns with the stock change approach (UNFCCC, 2001). Under this approach, flows of wood are tracked, with carbon credits awarded when a country or landowner realizes a net positive change in stocks of harvested wood products. Conversely, a country or landowner that experiences a net loss of stocks of harvested wood products would be penalized. Accounting for stock changes in wood product pool has its challenges. It is hard to imagine how a landowner will retain ownership of wood carbon after a tree is harvested. This does not make sense and yet California climate action registry considers carbon sequestration associated with wood products. In December 2007, the Chicago Climate Exchange (CCX) Committee on Forestry approved new protocols for carbon sequestration associated with long-lived wood products and managed forests. These efforts may help inform international discussions about carbon storage in wood products (CCX, 2007).

The idea of crediting wood products is very controversial. It is seen by some in the scientific community that management regimes that reduce the standing stock of timber, even if they produce sustainable timber harvest over time, will have smaller greenhouse gas (GHG) benefits than regimes that maintain a high volume of standing timber (Liski et al., 2001; Hoover and Stout, 2007). It is seen by some that without harvesting, very old stands will continue to build carbon reserves, particularly in the soil (Luyssaert et al., 2008). They are of the opinion that climate policies should not encourage timber harvest and wood production as a means of reducing GHG emissions.

Despite the controversy, it is important to consider carbon storage in the wood product pool in developing an effective GHG reduction strategy because Canada supports "full carbon accounting that includes the accounting for carbon stored in harvested wood products and the CO_2 emissions and removals associated with harvested wood products". It is also important to consider the wood product pool because it slows down the rate of growth of atmospheric CO_2 concentration. More importantly, wood products are critical to identifying major sources of CO_2 emissions so that policies can be developed to mitigate carbon emissions. Carbon storage in wood products could play an important role in climate change mitigation strategies and yet this role is little understood. Therefore, the main objective of this chapter is to examine the impact of the wood product pool on the optimal behaviour of a landowner, where the landowner is described as an agent who controls both the forest and wood product.

A review of literature shows that harvested wood products can significantly extend the carbon sequestration benefits provided by forests (Dixon et al., 1994; Karjalainen, 1996; Skog and Nicholson, 2000). However, these findings can be misleading as they are only based on stock changes in harvested wood products and do not account for CO_2 emissions and removals associated with harvested wood products.

There is a fairly large body of literature on the biophysical aspect of carbon sequestration in wood products and fossil fuel carbon emissions associated with carbon flows of wood products, but the economic aspect of the problem are still relatively unexplored. In the forest economics literature, van Kooten et al. (1995), assumed that a fraction of harvested timber ("pickling factor") goes into long-term storage in structures and landfills. They used economic analysis to examine the effect of carbon taxes and subsidies on optimal forest rotation age and, consequently, the amount of carbon sequestered in a forest. However, there is no recognition of DOM in the van Kooten analysis. To the best of my knowledge, Gutrich and Howarth (2007) were the first to consider the amount of carbon stored in the DOM and wood product pools in determining the optimal rotation age. However, they did not consider the effect of different initial carbon stocks in the DOM or the wood product pools and they also did not account for fossil fuel carbon emissions associated with wood production cycle.

At the forest level, Hennigar et al. (2008) uses a model II linear programming formulation to simultaneously maximize carbon sequestered in live biomass, DOM and wood products. The results of their study showed that not accounting for wood products underestimates true forest contributions to carbon sequestration. Their wood products analysis did not address alternative CO_2 prices nor account for fossil fuel carbon emissions associated with wood products. The initial DOM and wood product stocks are fixed in their analysis.

Dynamic programming has emerged as a powerful approach to stand level optimization with respect to timber values and carbon sequestration. Spring et al. (2005b) formulated and solved a stochastic dynamic program to maximize the expected net present value of returns from timber production and carbon storage in a forest stand subject to stochastic fire. They modeled the decision problem using stand age as the only state variable: timber production and carbon storage were both treated as functions of stand age. In Spring et al. (2005a), the same authors used stochastic dynamic programming to determine the rotation age considering timber production, water yield, and carbon sequestration under stochastic fire occurrence, again using stand age as the only state variable. Chladná (2007) used dynamic programming to examine the optimal forest stand harvest decision when timber and carbon prices are stochastic. Chladná used stand volume per hectare, timber price, and carbon price as state variables. Yoshimoto and Marusak (2007) optimized timber and carbon values in a forest stand using dynamic programming in a framework where both thinnings and final harvest were considered. In this case, the state variables for the problem were stand age and stand density (number of trees per ha).

In this chapter, a dynamic programming model is developed to find the optimal stand management policy when both timber harvest and carbon sequestration values are considered. The state of the system at any stage can be described in terms of stand age and the quantity of carbon stored in both DOM and wood product pools. The management decisions available to the decision maker are to clearcut a stand of a given age, with a DOM pool of a given size and with a wood product pool of a given size, or to defer the harvest decision. Because a considerable proportion of carbon is stored in DOM relative to the total carbon stored by the stand and wood products have the ability to slow down the rate of CO_2 release back to the atmosphere, consideration of these two carbon pools could be of considerable economic interest. To the best of my knowledge, none of the stand level optimization models that consider timber harvest and carbon sequestration services have examined both the role of variable DOM carbon stock and variable wood product stock in determining the optimal harvest age. A dynamic programming model was developed to:

1. examine the sensitivity of optimal harvest age to amount of carbon stored in the wood product pool and CO_2 prices,
2. examine the sensitivity of net present value to wood product stocks,
3. investigate the impact of fossil fuel carbon emissions on the optimal harvest decision, and
4. investigate the impact of ignoring the wood product pool on the optimal decision to harvest

3.2 The Model

Fig. 3.1 is a schematic representation of the model developed for this study. It describes the flow of materials and energy through the wood product processing chain.

The figure shows that three main activities are involved in GHG emissions from fossil energy use. They include:

1. Stand establishment which involves seed and seedling production, site preparation and planting,
2. Harvesting, which is defined in this model to include road construction, logging and hauling of roundwood to mill, and
3. Processing, which is defined to include milling and transportation of finished product to consumers.

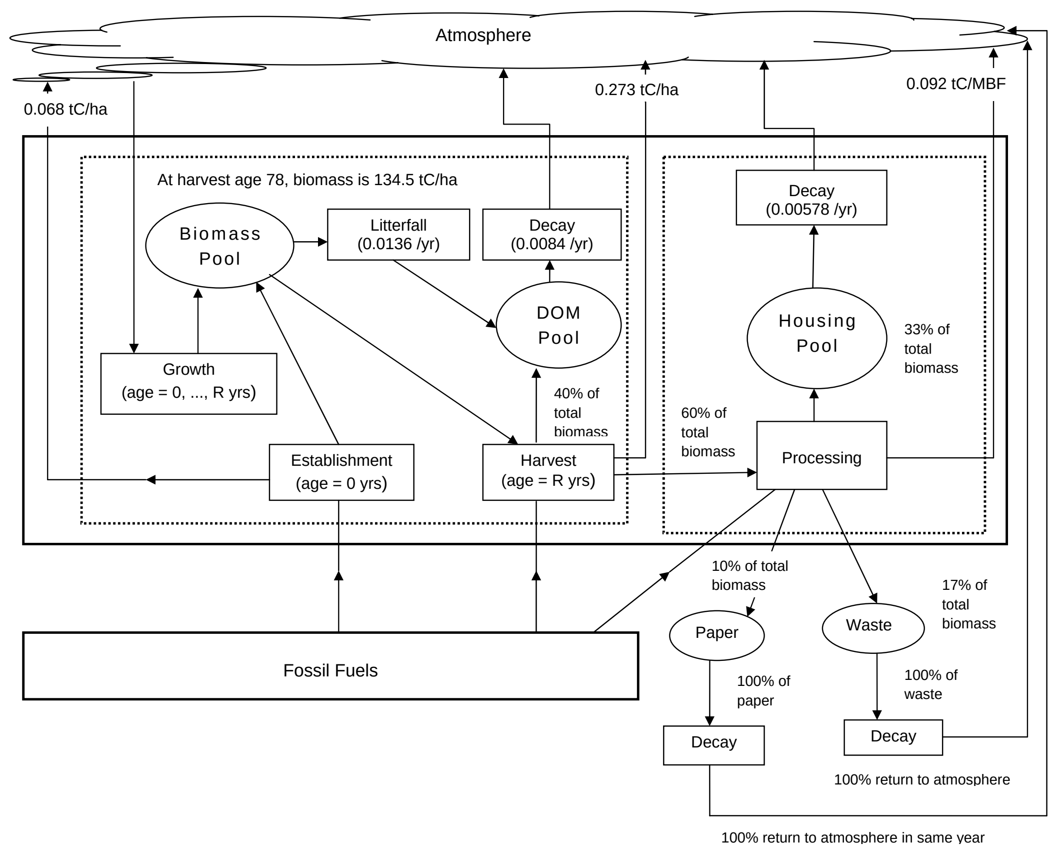


Figure 3.1: Schematic representation of the carbon storage model. The life cycle for wood product begins with the decision to harvest trees and ends with the decay of wood products made from those trees. Big oval boxes represent the pools of carbon in the living biomass, dead organic matter and wood products. The broken boxes represent the industrial forest carbon cycle which includes carbon emissions from forest management, transport, production, consumer use and disposal operations. Arrows represent carbon fluxes into and out of each pool. The cloud represents atmospheric carbon dioxide.

The wood product processing chain begins with stand establishment and ends with the decay of the wood product made from the trees. Using yield information from TIPSY for the lodgepole pine stand, approximately 40% of the total biomass is left behind at harvest and becomes part of the DOM pool. This means that logs removed from harvest represent approximately 60% of the total biomass and hence, carbon available for storage in long-lived products. This study is simplified by dealing with one relatively long-lived product (dimensional lumber for housing) and paper, which is assumed to be a very short-lived product. It is assumed that 100% of stored carbon in paper is emitted in the same year it is manufactured. The portion of the total biomass used for paper production is about 10%. This leaves approximately 50% of the total biomass available for processing lumber for housing. Of the remaining volume, an equivalent of 17% of the total biomass is lost as waste mainly through planing. This means that only 33% of the total biomass ends up in the housing pool.

In addition to carbon lost through decay of wood waste, stand establishment, harvesting and processing of wood product also requires fossil fuel energy.

To maintain credibility of the accounting system, the study boundary is clearly defined to include the flow of wood fibre from the BWBS biogioclimatic zone, in the Dawson Creek Timber Supply Area, in the Prince George Forest Region of British Columbia, and the carbon emissions associated with silviculture, harvest, transportation of wood fibre to the mill, milling, transportation of finished products to market and waste disposal.

This study assumes that a carbon market would develop in which an agent (landowner) with custody of both forest and wood product pool is paid for carbon added to the forest and wood product pools and pays when carbon is released. It is also assumed that the landowner will manage the forest jointly for timber production and carbon sequestration in the forest and wood products in a manner that earns maximum discounted financial return. The forest is managed using an even-aged silvicultural system. Each rotation begins with the establishment of a stand on bare forest land and ends with a clearcut harvest after a number of years of growth. The beginning of a new rotation coincides with the end of the previous rotation. The cycle of establishment, growth, harvest, and establishment is assumed to repeat *ad infinitum.*

3.2.1 Timber yield and costs

The growth and yield data as well as the cost information come from the TIPSY growth and yield simulator (BC MoFR, 2007) developed by the British Columbia Ministry of Forests and Range for use as input to forest management plans. The data used represent a lodgepole pine stand in the BWBS biogeoclimatic zone, in the Dawson Creek Forest District of the Prince George Forest Region of British Columbia, Canada. A medium site class (site index = 16 m at 50 years breast height age) and a planting density of 1600 stems/ha is assumed. The growth and yield data and other costs information generated from TIPSY are presented in Table 3.1. In the interest of saving space, the data in Table 3.1 are reported in decades, although the modelling was done on an annual basis.

The lumber values reported in Table 3.1, represent the total nominal lumber available for making 2×4s, 2×6s, 2×8s and 2×10s. The nominal size of a board varies from the actual size because of planing. The actual lumber size is estimated from the nominal size by using the conversion factors reported in Table 3.1. For example the actual size of a 2×4 is $1.5in \times 3.5in$ ($38mm \times 89mm$). For a one board foot dimensional lumber, the conversion factor is calculated as: $(1.5 \times 3.5 \times 18)/(2 \times 4 \times 18) = 0.66$.

A derived residual value approach (Davis et al., 2001, pp. 418–427) is used to estimate the net value of timber harvest. All costs and prices in this paper are expressed in Canadian dollars (CAD). The residual value is the selling price of the final products (in this case lumber and pulp chips) less the costs of converting standing trees into the final products, expressed in CAD/ha of merchantable timber.

The average lumber price of kiln dried, standard and better, western spruce-pine-fir, 2×4 random length lumber for the period April 1999 to March 2008 was approximately 375 CAD/thousand board feet (MBF) (BC MoFR, 2009). The price of wood chips was assumed to be 70 CAD/bone dry unit (BDU).

The selling price of lumber and chips expressed in terms of wood input at any harvest age (a) is represented by the parameter P_a^w (CAD/MBF) and P_a^x (CAD/BDU) respectively. The total revenue (CAD/ha) at any harvest age is calculated as $[P_a^w L(a) + P_a^x C(a)]$, where L(a) is lumber yield in MBF/ha and C(a) is chip yield in BDU/ha.

Table 3.1: Summary of data generated from TIPSY

	Output						Costs		
Age decades	volume m^3/ha	biomass tC/ha	Chips BDU/ha	Lumber bf/ha	LRF mbf/ha	Conversion factor	Logging CAD/ha	Hauling CAD/ha	Milling CAD/ha
0	0	0	0	0	0	0.00	0	0	0
10	0	1.8	0	0	0	0.00	0	0	0
20	1	13.6	0	13	0.021	0.66	21	5	6
30	26	36.0	6	1,551	0.642	0.66	642	152	485
40	91	62.0	19	12,763	2.100	0.66	2,100	533	2601
50	161	87.0	31	27,004	3.398	0.66	3,398	942	5,031
60	221	107.5	41	40,511	4.263	0.66	4,263	1,293	7,223
70	270	123.8	49	52,803	4.820	0.66	4,820	1,581	9,124
80	310	137.0	56	63,607	5.264	0.66	5,264	1,819	10,743
90	347	149.1	60	73,131	5.589	0.66	5,589	2,032	12,179
100	377	158.8	64	81,130	5.814	0.66	5,814	2,211	13,383
110	399	165.9	68	87,305	5.996	0.66	5,996	2,340	14,283
120	417	171.7	70	92,479	6.231	0.67	6,231	2,446	15,031
130	433	176.8	72	96,931	6.432	0.67	6,432	2,537	15,675
140	448	181.6	74	101,304	6.616	0.67	6,616	2,622	16,292
150	461	185.7	76	105,421	6.783	0.67	6,783	2,700	16,866
160	472	189.2	78	109,041	6.929	0.67	6,929	2,768	17,370
170	483	192.7	79	112,243	7.056	0.67	7,056	2,829	17,816
180	492	195.5	81	115,091	7.169	0.67	7,169	2,883	18,213
190	500	198.1	82	117,638	7.269	0.67	7,269	2,931	18,567
200	508	200.6	83	120,087	7.359	0.67	7,359	2,974	18,898
210	514	202.5	83	122,363	7.439	0.67	7,439	3,013	19,202
220	520	204.4	84	124,424	7.511	0.67	7,511	3,048	19,477
230	526	206.3	85	126,298	7.577	0.67	7,577	3,081	19,727
240	531	207.9	85	128,008	7.636	0.67	7,636	3,110	19,956
250	535	209.1	86	129,573	7.690	0.67	7,690	3,137	20,164

The cost of converting standing trees into end products is the sum of all costs associated with overhead, road construction, harvesting (tree-to-truck), hauling, and milling. Road construction and overhead costs reported by TIPSY for the pine stand were 1,150 and 2,500 CAD/ha respectively.

$F(a)$ in CAD/ha is used to represent the cost (logging, hauling and milling) of converting standing trees of age (a) into end products. Stands are assumed to be reestablished immediately following harvest at a cost of E in CAD/ha.

3.2.2 Carbon pool dynamics

The TIPSY yield table is used as input to CBM-CFS3 in order to generate projections of carbon stored in each of the pools. A highly simplified representation of the carbon pool structure of CBM-CFS3 with just three carbon pools: a wood product pool, a biomass pool representing carbon stored above and below ground in living trees, and a dead organic matter pool representing all other carbon stored in standing dead trees (snags), on the forest floor, and in the soil was created. The label dead organic matter is used even though it is recognized that some of the carbon in this DOM pool is contained in living organisms. It is also assumed that dimensional lumber used in housing is the only wood product since all the carbon stored in paper is assumed to be released in the year of manufacture. Therefore the total carbon stored C_t at any given time t, measured in tC/ha is expressed in Eq. 3.1.

$$C_t = B(a) + D_t + Z_t \tag{3.1}$$

where $B(a)$ represents total carbon sequestered in the living biomass at age a; D_t measures the total carbon sequestered in DOM pool in time t and Z_t represents carbon stored in wood product pool in time t. The mass of carbon in tC/ha, stored in the living trees at age a is generated from CBM-CFS3 and presented in Table 3.1. Timber harvest is assumed to reset the age of the stand, and therefore its biomass, to zero. In this study, total carbon stored (C_t) in tC/ha refers to the sum of the wood product pool and total ecosystem carbon (TEC), where TEC is the sum of DOM and biomass pools.

Three processes are assumed to affect the development of the DOM pool: decay, litterfall, and harvest. DOM is assumed to decay at a rate, α, which represents a fixed proportion of the DOM pool each year. DOM is added to the pool as the proportion of the biomass of the stand that dies naturally each year. This proportion is expressed as the litterfall rate, β.

With no timber harvest, the DOM pool grows according to equation (3.2).

$$D_{t+1} = (1-\alpha)D_t + \beta B(a) \tag{3.2}$$

The decay and litter fall rates were estimated using the method of least squares to find the parameters α and β which result in the closest match to the DOM projections produced from CBM-CFS3 using a pine stand (see Fig. 1.3). The estimated parameters are $\alpha = 0.00841$ and $\beta = 0.01357$. These parameters correspond reasonably well to the CBM-CFS3 projection.

When timber harvest occurs, the merchantable timber volume is removed from the site and processed into lumber and wood chips. The roots, stumps, tops, branches and leaves are assumed to die at the time of harvest and become part of the DOM pool. The mass of carbon removed from the site as merchantable timber volume is calculated as $\gamma V(a)$ where γ is a constant used to convert wood volume to the mass of carbon stored in wood. This study uses $\gamma = 0.2$, which is consistent with a carbon content of wood of approximately 200 kg m^{-3} (Jessome, 1977). With timber harvest, the DOM pool grows according to Eq. 3.3.

$$D_{t+1} = (1-\alpha)D_t + B(a) - \gamma V(a) \tag{3.3}$$

The wood product carbon pool is represented by a single pool with a single annual decay rate of θ. When there is no timber harvest, the dynamics of the carbon in the wood product pool is represented by Eq. 3.4.

$$Z_{t+1} = (1-\theta)Z_t \tag{3.4}$$

With timber harvest, the wood product pool grows according to Eq. 3.5.

$$Z_{t+1} = (1-\theta)Z_t + q\gamma\lambda L(a) \tag{3.5}$$

where θ measures the decay rate for wood product; q is factor that converts the nominal volume into actual volume; λ is the factor that converts nominal lumber volume in thousand board feet into cubic metres of lumber; and $L(a)$ is the lumber volume in thousand board feet at age a.

Lumber is assumed to decay at a rate, θ, which represents a fixed proportion of wood product pool each year. The decay rate was estimated using the method of least squares to find parameter θ which results in the closest match to the estimates of carbon remaining in lumber over time (Kurz et al., 1992). The estimates of carbon remaining over time are presented in Table **??**. The estimated parameter is $\theta = 0.00578$.

Table 3.2: Proportion of original carbon remaining in wood product (lumber) with time

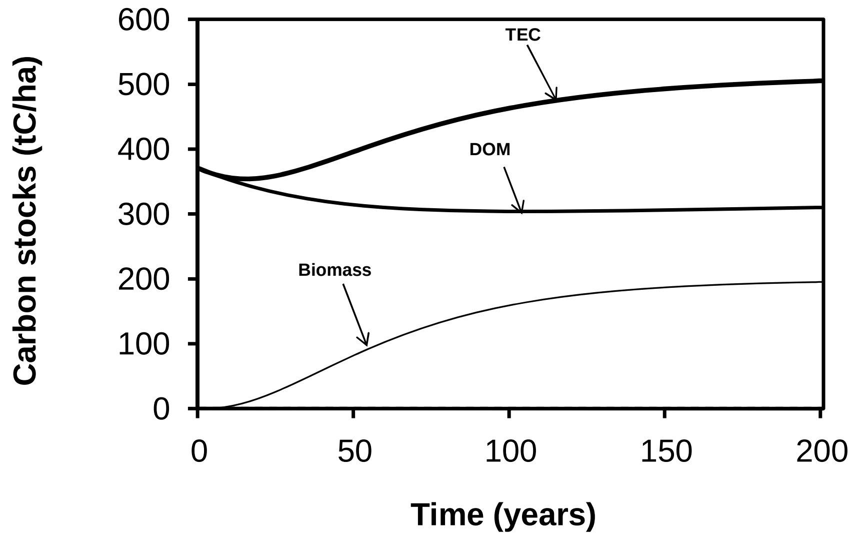
Year	Lumber
0	0.98
20	0.92
40	0.84
60	0.74
80	0.61
100	0.47

Source: (Kurz et al., 1992).

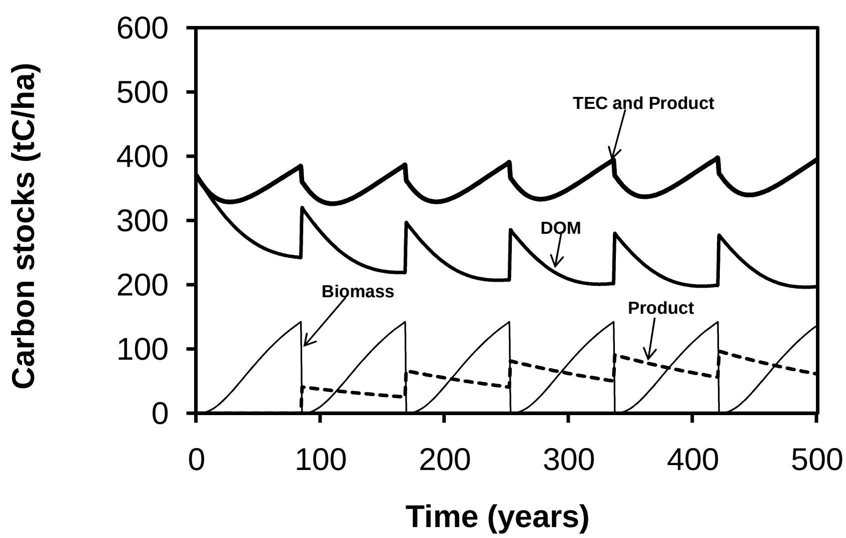
The lumber decay rate, 0.00578 is comparable to other decay rates used in literature. Gutrich and Howarth (2007) estimated the decay rate of softwood lumber as 0.0038. McKenney et al. (2004) assumed a higher decay rate of 0.01 for lumber and other wood products.

Fig. 3.2 shows the development of aggregated carbon pool stocks for a stand that is left unharvested (panel a) and one that is harvested on a 78 year rotation (panel b), given an initial age of 0 years, an initial DOM stock of 370 tC/ha and an initial wood product stock of 0 tC/ha. Panel (a) shows that in the early stages of stand development, the stand is a net source of CO_2 as a result of decay processes (Kurz et al., 1992). As the stand ages, the total carbon stocks increase with increasing biomass, and the decline in DOM stocks slows and reverses as carbon is added to the DOM pool in the form of litterfall, dead branches and natural tree mortality. Panel (b) illustrates what happens after a harvest. The figure shows that if a forest is planted and harvested periodically, carbon is fixed in the living trees during regrowth and put into storage in wood product and DOM carbon pools, which subsequently decays.

To account for fossil fuel carbon emissions, the following assumptions were made.



(a) No timber harvest (No wood product).



(b) Timber harvest on an 78 year rotation.

Figure 3.2: Projections of carbon pool development over time. Panel a)is projection without harvest. Panel b) is the projection with timber harvest on an 78 year rotation.

It was assumed that fossil fuel carbon emissions from stand establishment and harvesting were 0.068 tC/ha and 0.273 tC/ha respectively (Gaboury et al., 2009). At the processing stage which is defined to include milling and transportation of finished product to consumers, fossil fuel carbon emissions was assumed to be 0.0212 tC/MBF for milling (Gower, 2003) and 0.0715 tC/MBF for transportation of finished product to consumers (Karjalainen and Asikainen, 1996).

Some studies have shown that logging and hauling operations are the highest GHG emitters of all forestry-related operations, before the processing of wood products (White et al., 2005; Sonne, 2006). However, with the inclusion of wood products, it can be said that the main drivers of GHG emissions occur during the production of the wood product at the mill and during the transportation of the product to the consumers. It is also assumed that commercial timber is transported by truck to the mill, with an average highway travel time of 3 hours and the final product is transported to consumers by truck, with an average highway distance of 1,000 km.

3.2.3 Carbon valuation

It is assumed that a carbon market exists in which a landowner with custody of both forest and wood product pool is paid for net sequestration of CO_2 and requires payment for net release of CO_2 in the previous year. Net carbon storage is calculated as the change in total carbon stocks (TEC and carbon in wood product pool) between periods $t+1$ and t measured in tC/ha:

$$\Delta C_t = C_{t+1} - C_t \tag{3.6}$$

Carbon is presently not an active tradable commodity with a market price in Canada. The price received per tonne of sequestered CO_2 is the same as the price paid per tonne of released CO_2. A broad range of prices for CO_2 is used in sensitivity analyses. Prices of CO_2 ranging between 0 and 55 CAD per tonne of CO_2 (tCO_2) were examined. The price of permanent carbon credits traded on European Climate Exchange (ECX) between January 2005 and April 2008 ranged from 10 to 45 CAD/tCO_2 (Point Carbon, 2009). Prices for carbon credits traded on the Chicago Climate Exchange (CCX) for the same time period ranged from 1 to 5 CAD/tCO_2 (CCX, 2009). The range of prices used in this study encompass the range of observed prices.

It is conventional to express carbon prices in currency units per tCO_2 and stocks as tonnes of carbon (tC). The practice for reporting is continued here, but for modeling purposes, equivalent prices for carbon (CAD/tC) is defined as $P^C = 3.67P^{C0_2}$ because the molecular weight of CO_2 is approximately 3.67 times the atomic weight of carbon.

3.2.4 Dynamic Programming

The forest management problem modeled here is framed as a discrete backwards recursion dynamic program. The stages represent time, in one year time steps. The forest stand is described by a combination of three state variables, the age of the stand (years), carbon stocks in the DOM pool (tC/ha) and carbon stocks in the wood product pool (tC/ha). There are 251 discrete one-year wide age classes, j, with midpoints $a_j = j,\ j = 0, 1, \ldots, 250$ years. There are 101 DOM classes, i, with midpoints $d_i = 5i,\ i = 0, 1, 2, \ldots, 100$ tC/ha. There are also 101 wood product classes, w, with midpoints $n_w = 5w,\ w = 0, 1, 2, \ldots, 100$ tC/ha. Timber harvest volume and carbon stored in the biomass pool are calculated as a function of stand age.

For each state and each stage the possible decisions are to clearcut the stand immediately or postpone the harvest and let the stand grow for another year. If the landowner chooses to clearcut, immediate timber revenue will be realized. Both the clearcut and the leave decisions will result in a change in total carbon stock and the appropriate carbon credit or debit. If harvesting does occur (i.e., decision, $k = 1$) in stage t, it is assumed that replanting occurs immediately and the stand age is reset to 1 in stage $t + 1$. If harvesting does not occur (i.e., decision, $k = 0$) in stage t, the stand age is incremented by one year in stage $t + 1$.

The net change in carbon stocks, ΔC_{wijk} depends on current wood product class w, current DOM class i, age class j, and harvest decision k. It is the sum of the changes in wood product, DOM and biomass carbon pools.

For the no harvest case:

$$\Delta C_{wij0} = B\left(\left(\min\left(a_j + 1\right), 250\right)\right) + \beta B\left(a_j\right) - \alpha d_i - B\left(a_j\right) - \theta n_w. \tag{3.7}$$

For the harvest case:

$$\Delta C_{wij1} = B\,(1) - \alpha d_i - \gamma V\,(a_j) - \theta n_w + q\gamma\lambda L(a). \tag{3.8}$$

The net harvest revenue for age class j, (H_j) is calculated as

$$H_j = [P_a^w L(a) + P_a^x C(a)] - F(a) - E. \tag{3.9}$$

Establishment costs are included here because it is assumed that reforestation is required, and occurs, immediately after timber harvest.

The stage return or periodic payoff (N_t) is calculated as shown in Eq. 3.10. The payoff is calculated for the midpoints of each wood product class (w), DOM class (i) and stand age (j) and for each of the possible harvest decisions (k). If a stand is not harvested $(k = 0)$, the periodic payoff would be based on ΔC_{wij0} only. If the stand is harvested $(k = 1)$, the payoff is based on ΔC_{wij1}. This payoff is reduced by the total carbon emission charge $(P^C M_T)$, which is the sum of the carbon release charge from stand establishment $P^C M_E$, harvesting $P^C M_H$ and processing $P^C M_R$.

$$N\{w,i,j,k\} = \begin{cases} P^C \Delta C_{wij0} & : \quad k = 0 \\ P^C(\Delta C_{wij1} - M_T) + H_j & : \quad k = 1 \end{cases} \tag{3.10}$$

In this analysis, it is assumed the objective at each stage, is to determine, for each possible combination of stand age, level of carbon in wood product stock and level of carbon in DOM stock, the harvest decision that results in the maximum net present value of land and timber and carbon storage for the remainder of the planning horizon. The stages in this dynamic programming model correspond to the time periods in which decisions are made. It is a finite horizon, deterministic model with time t measured in years.

Because discrete DOM classes and discrete wood product classes are used, the projections from Eqs. 3.2, 3.3, 3.4 and 3.5 are converted to the proportion of the source DOM and wood product class area that move into adjacent target DOM and wood product classes. d^l_{wijk} is used to represent the lower DOM target class, d^u_{wijk} to represent the upper DOM target class, n^l_{wijk} to represent the lower wood product target class, and n^u_{wijk} to represent the upper wood product target class. ρ_{wijk} represents the proportion in the source DOM class and σ_{wijk} represents the proportion in the source wood product class. u is used to represent the proportion that moves into adjacent lower DOM class and adjacent lower wood product class; b to represent the proportion that moves into adjacent upper DOM class and adjacent lower wood product class; e to represent the proportion that moves into adjacent lower DOM class and adjacent upper wood product class; and f to represent the proportion that moves into adjacent upper DOM class and adjacent upper wood product class. Where $u = \sigma_{wijk}\rho_{wijk}$; $b = (1-\rho_{wijk})\sigma_{wijk}$; $e = \rho_{wijk}(1-\sigma_{wijk})$; and $f = (1-\rho_{wijk})(1-\sigma_{wijk})$.

In the notation used here, $\lfloor x \rfloor$ indicates the floor of a real number x, i.e. the largest integer less than or equal to x. The fractional part of x is indicated by $\langle x \rangle$ such that $x = \lfloor x \rfloor + \langle x \rangle$.

$$d^l_{wij0} = \min\left(\lfloor (1-\alpha)\, d_i + \beta B\left(a_j\right) \rfloor, 500\right) \tag{3.11}$$

$$dl_{wij1} = \min\left(\lfloor (1-\alpha)\, d_i + B\left(a_1\right) - \gamma V\left(a_j\right) \rfloor, 500\right) \tag{3.12}$$

$$d^u_{wijk} = \min\left(dl_{wijk} + 5, 500\right) \tag{3.13}$$

$$n^l_{wij0} = \min\left(\lfloor (1-\theta)\, n_w \rfloor, 200\right) \tag{3.14}$$

$$n^l_{wij1} = \min\left(\lfloor (1-\theta)\, n_w + q\gamma\lambda L\left(a_j\right) \rfloor, 200\right) \tag{3.15}$$

$$p^u_{wijk} = \min\left(pl_{wijk} + 2, 200\right) \tag{3.16}$$

$$\rho_{ij0} = \langle (1-\alpha)\, d_i + \beta B\left(a_j\right) \rangle \tag{3.17}$$

$$\rho_{ij1} = \langle (1-\alpha)\, d_i + B\left(a_1\right) - \gamma V\left(a_j\right) \rangle \tag{3.18}$$

$$\sigma_{ij0} = \langle (1-\theta)\, n_w \rangle \tag{3.19}$$

$$\sigma_{ij1} = \langle (1-\theta)\, n_w + q\gamma\lambda L\left(a_j\right) \rangle \tag{3.20}$$

A weighted return is calculated from the target states associated with the harvest decision, k.

For the no harvest decision, $k = 0$,

$$\begin{aligned} W_{wij0} = {} & uR^*_{t+1}\{d^l_{wij0}, \min\left(\left(j+1\right), 250\right)\} + bR^*_{t+1}\{d^u_{wij0}, \min\left(\left(j+1\right), 250\right)\} \\ & + eR^*_{t+1}\{n^l_{wij0}, \min(\left(j+1\right), 250)\} + fR^*_{t+1}\{n^u_{wij0}, \min(\left(j+1\right), 250)\} \end{aligned} \tag{3.21}$$

For the the harvest decision, $k = 1$,

$$W_{wij1} = uR^*_{t+1}\{d^l_{wij1}, 1\} + bR^*_{t+1}\{d^u_{wij1}, 1\} + eR^*_{t+1}\{n^l_{wij1}, 1\} + fR^*_{t+1}\{n^u_{wij1}, 1\} \tag{3.22}$$

The return for the last stage in the problem is initialized to zero,

$$R_T\{w, i, j, k\} = 0. \tag{3.23}$$

This assumption is justified on the basis that T is large (500 years) and the discounted value of R_T for reasonable discount rates for this problem is near zero (e.g. the present value of 1 CAD received 500 years in the future is 2.5×10^{-11} CAD given a 5% discount rate).

The discount factor, $\delta = (1 + r)^{-1}$, represents the relative value of a dollar received one year from now (given an annual discount rate of r) to a dollar today. The discount rate, r, used for the analysis is 5% per annum: for this analysis, $\delta = 0.9528$. This rate is intended to reflect a market rate of time preference.

The recursive objective function for this problem is given in Eq. 3.24.

$$R_t\{w, i, j, k\} = \max_k N\{w, i, j, k\} + \delta W_{wijk}, \ t = T - 1, T - 2, \ldots, 0 \tag{3.24}$$

The recursive objection function selects the harvest decision at each stage for each possible combination of state variables that maximizes the net present value at that stage, assuming that optimal decisions are made in all subsequent stages. It calculates a return for each of the harvest decisions and selects the harvest decision that results in the maximum return as the optimal choice for the state combination in that stage.

Eq. 3.25 below modifies the stage return at time zero for stands of age 0, and represents the soil expectation value for each initial DOM and wood product class. This incorporates establishment costs for time zero. For subsequent stages, establishment costs are incorporated in Eq. 3.10.

$$\forall w, i, j \ : \ R_0\{w, i, j, 0\} \leftarrow R_0\{w, i, j, 0\} - E - P^C M_E \tag{3.25}$$

where M_E, which is the net carbon emissions associated with stand establishment, measured in tC/ha.

3.3 Results and Discussion

In evaluating the economic feasibility of managing for both carbon and timber, a broad spectrum of scenarios have been investigated. A few general trends run throughout a large portion of the results, even though a number of the proposed scenarios differ subtly from one another. First, the sensitivity of optimal harvest age to the amount of carbon stored in the wood product pool and CO_2 prices is examined. Second, the sensitivity of net present value to wood product stocks is examined. Third, the impact of fossil fuel carbon emissions on the optimal harvest decision is investigated. Fourth and finally, the impact of ignoring the wood product pool on the optimal harvest age is also investigated. The results presented in this section were calculated using an implementation of the dynamic programming model programmed in MATLAB (Pratap, 2006).

To determine the impact of carbon stored in wood product pool on optimal harvest policy, two types of results are presented in Fig. 3.3. Panel (a) shows the relationship between the current wood product stocks and the current stand age, and panel (b) shows the relationship between the current DOM stocks and the current stand age. In the interest of saving space, only two model runs with wood product stock held constant at 0 tC/ha and DOM stock held constant at 370 tC/ha are presented in this section. The amount of carbon in the DOM stock was held constant at 370 tC/ha because it is the initialized DOM carbon stock for lodgepole pine in the Dawson Creek Forest District, used in simulating the DOM stocks for this study. This value is close to 344 tC/ha, the (IPCC, 2001) average estimated quantity of soil carbon in the boreal forest of Canada.

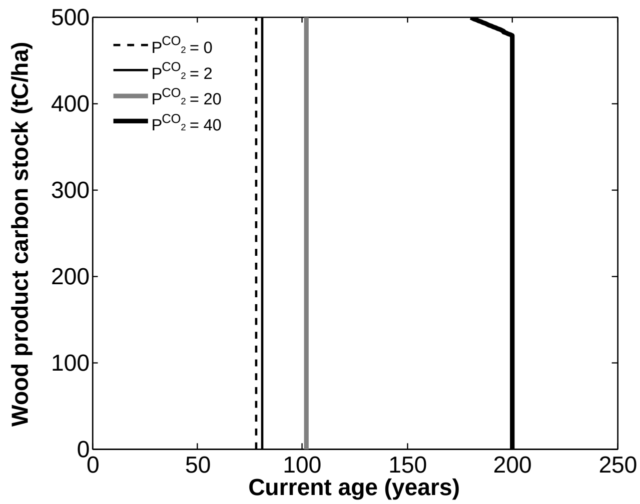
In Fig. 3.3, the decision rule when P^{CO_2} is 0 CAD/tCO_2 corresponds to the case when there is no incentives to manage for carbon: it is always optimal to harvest stands older than the Faustmann rotation age of 78 years, given the data used here. As P^{CO_2} increases, the optimal harvest age increases. When P^{CO_2} is 55 CAD/tCO_2 or greater, the optimal decision is to never harvest. The results show that the optimal harvest policy is sensitive to the wood product stocks at the higher levels when carbon prices are high. This is because the amount of CO_2 released to the atmosphere through decay is higher with higher wood product stocks. Hence, higher financial penalty is associated with higher wood product stocks. Therefore, at higher wood product stocks it is optimal to harvest early to minimize the financial penalties.

The results shown in panel (b) reveals that the optimal harvest policy is sensitive to DOM stocks at the lower levels when P^{CO_2} is 20 CAD/tCO_2. This happens because the amount of CO_2 released to the atmosphere through decay is lower with lower DOM stocks: the marginal gain in CO_2 sequestration from delaying harvest is greater with lower DOM stocks. In chapter 5 of this thesis, an analytical model is used to prove that the optimal harvest age is dependent on the amount of carbon stored in the DOM and wood product pools.

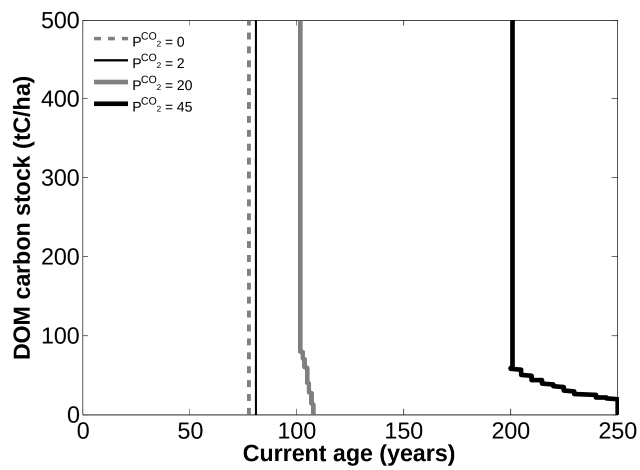
Fig. 3.4 displays a combination of stand age and wood product stocks that have the same value of land, timber and carbon sequestration services (LTCV, hereafter) for the entire state space, when P^{CO_2} is 0, 2, 20, and 55 CAD/tCO_2. In these scenarios, the DOM carbon stock is also held constant at 370 tC/ha. Panel (a) represents the case where $P^{CO_2} = 0$. Because carbon has no value, in this case, the LTCV is independent of the amount of wood product stored. Notice from the results in Fig. 3.4 that the contour lines are not smooth like those presented in chapter 2. This is because unlike Chapter 2, functions were not used to represent the biomass and timber yield curves in this chapter. Instead, tabular data from TIPSY and CMB-CFS3 which show sharp changes in gradient along the curves were used in this chapter.

In general, the results presented in Fig. 3.4 suggest that LTCV declines with increasing P^{CO_2}. Notice that for a landowner or agent who has custody of wood product stocks of about 200 tC/ha and a stand that is 100 years old, his/her LTCV declines from roughly 8,100 CAD/ha when $P^{CO_2} = 0$ CAD/tCO_2 to about 7,800 CAD/ha when $P^{CO_2} = 2$ CAD/tCO_2. It then declines to 3,200 CAD/ha when $P^{CO_2} = 20$ CAD/tCO_2, and finally to 1,800 CAD/ha when P^{CO_2} is increased to 55 CAD/tCO_2. These findings contrast with results from other studies which generally show an increase in financial return when P^{CO_2} is increased. The possible explanation is that there is a carbon emission charge associated with the decay of wood product and DOM decay. The magnitude of this charge becomes negative and large with increasing P^{CO_2}. Hence, for higher P^{CO_2}, the ability of the revenue from timber sale and carbon sequestration revenue to compensate for the carbon emission charge associated with the decay of wood product and DOM decay decreases.

Fig. 3.4 also reveals that LTCV decreases with increasing wood product stocks when the carbon price is positive. This might seem counter-intuitive as more carbon

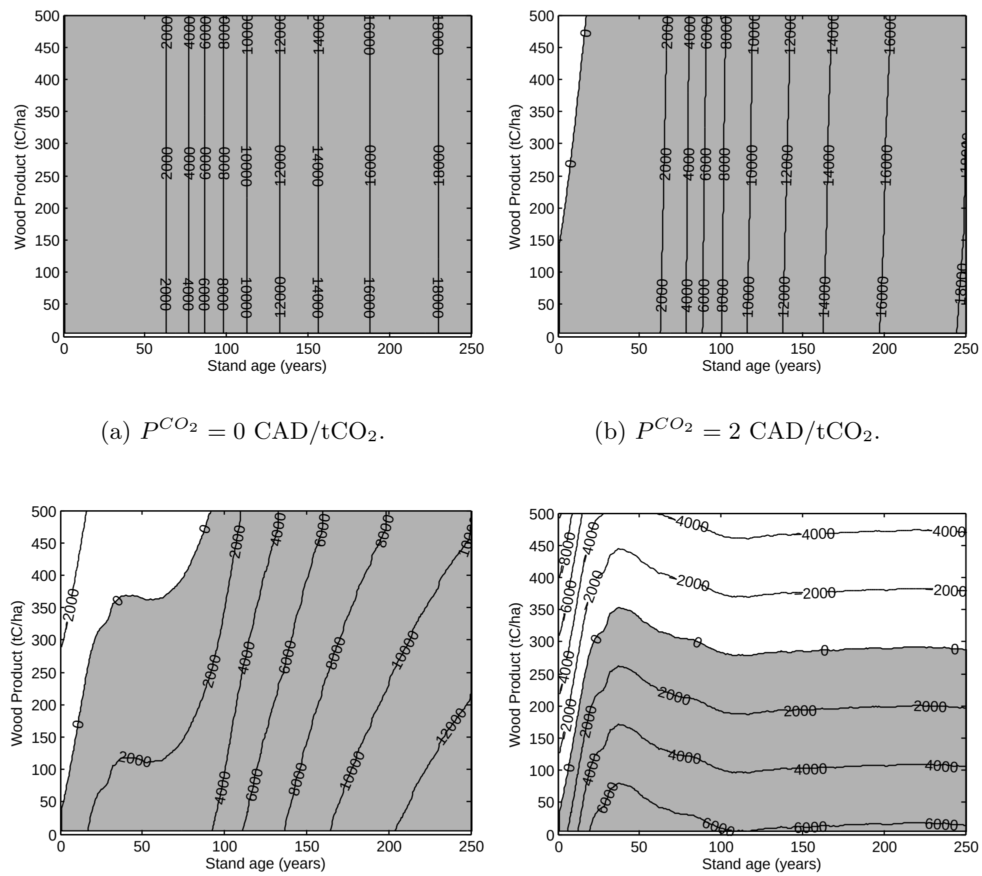


(a) Relationship between current wood product stocks and current age. DOM stock is fixed at 370 tC/ha



(b) Relationship between current DOM stocks and current age. Wood product stock is fixed at 0 tC/ha

Figure 3.3: Optimal harvest policies for different carbon prices. Panel (a) shows the relationship between current wood product stocks and current age and panel (b) shows the relationship between current DOM stocks and current age. The results are based on wood product stock held constant at 0 tC/ha and DOM stock held constant at 370 tC/ha. The region to the right of and above the line corresponding to each carbon price represents the combinations of current age and current wood product or DOM carbon stock for which the optimal decision is to harvest. In the region to the left, the optimal decision is to delay harvest.



(a) $P^{CO_2} = 0$ CAD/tCO$_2$.

(b) $P^{CO_2} = 2$ CAD/tCO$_2$.

(c) $P^{CO_2} = 20$ CAD/tCO$_2$.

(d) $P^{CO_2} = 55$ CAD/tCO$_2$.

Figure 3.4: Land, timber, and carbon values (CAD/ha) by stand age and wood product stocks for different carbon prices. The contours indicate combinations of age and wood product states that have the same land, timber, and carbon values. The region where LTCV is positive is shaded grey. In these scenarios, the DOM carbon stock is held constant at 370 tC/ha.

storage is generally thought of as a good thing. However, a larger stock of wood product will generally release a greater absolute quantity of CO_2 to the atmosphere than a smaller stock. A large stock of decaying wood product is a liability for the decision maker represented in this model.

What differentiates this study from those of van Kooten et al. (1995), Spring et al. (2005a,b), Chladná (2007) and Yoshimoto and Marusak (2007) is that fossil fuel carbon emissions were considered, whereas they ignore fossil fuel carbon emissions. Also wood product and DOM pools are considered in this study whereas they ignore these pools. In order to evaluate the effect of ignoring fossil fuel carbon emissions or wood product or DOM pools, a series of runs with a modified version of the model where the carbon market ignored fossil fuel carbon emissions or wood product or DOM pools were carried out. The results are summarized in Table 3.3.

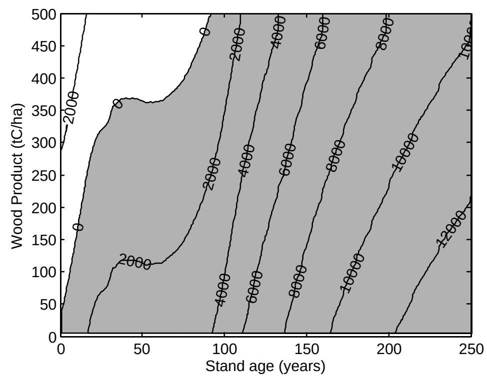
Table 3.3: Summary of optimal harvest ages and carbon stock with or without considering secondary carbon emissions for different carbon prices. TEC refers to total ecosystem carbon, or the sum of DOM and biomass pools.

	Rotation age			
P^{CO_2} (CAD/tCO_2)	No emissions Biomass (years)	No emissions TEC (years)	No emissions TEC and product (years)	With emissions TEC and product (years)
0	78	78	78	78
1	81	81	79	79
2	83	82	81	81
5	89	86	85	85
10	99	90	89	89
20	148	105	99	102
30	∞	133	103	115

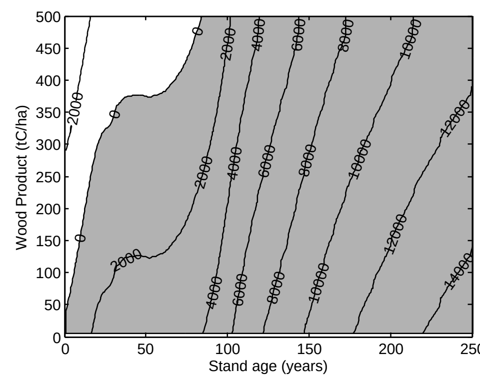
In the range of scenarios that were analyzed, it is clear from the results that fossil fuel carbon emissions have very little impact on the optimal harvest decision except at high prices. In general, the optimal harvest age is older when fossil fuel carbon emissions are considered. The older harvest age is related to the fact that when harvest occurs, fossil fuel carbon emission charge associated with timber harvest reduces the net revenue generated from carbon sequestration. Hence, it is optimal to delay harvest in order to maximize net revenue generated from carbon sequestration.

LTCV as a function of wood product pool and stand age is presented in Fig. 3.5. The results are based on a $P^{CO_2} = 20$ CAD/tCO_2 and DOM stock held constant at 370 tC/ha. The LTCVs show that there is a difference between the scenario that considers fossil fuel carbon emissions and the scenario that ignores fossil fuel carbon emissions. Notice that for a stand age of 100 years and wood product stock of 100 tC/ha, the LTCV is about 3,900 CAD/ha when fossil fuel emissions are considered, compared to 4,800 CAD/ha when fossil fuel emissions are ignored. In this example, the difference is about 700 CAD/ha.

Based on the aforementioned results it can be concluded that when $P^{CO_2} \leq 10$ CAD/tCO_2, carbon emissions have very little or no impact on the optimal behaviour of the landowner but affects the financial returns considerably.



(a) Considers fossil fuel emissions.



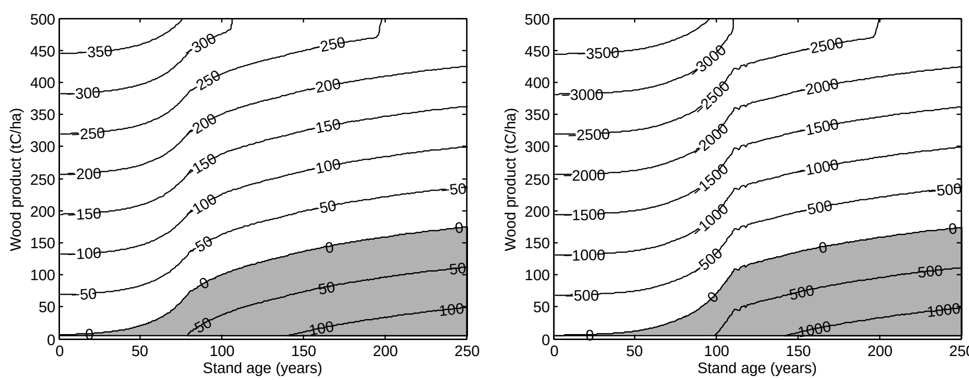
(b) Ignores fossil fuel emissions.

Figure 3.5: Comparison of land, timber, and carbon values (CAD/ha) by stand age and wood product stocks for a scenario when fossil fuel carbon emission is considered with one which ignores fossil fuel carbon emissions. The contours indicate combinations of age and wood product states that have the same land, timber, and carbon values. The region where LTCV is positive is shaded grey. In these scenarios, the initial DOM carbon stock is held constant at 370 tC/ha.

It is also evident from Table 3.3 that wood product carbon has very little or no effect on the optimal harvest decision except at high prices. It can generally be stated that the optimal harvest age is younger in the case when both DOM carbon and the wood product carbon are considered in carbon accounting compared to the case when the wood product carbon is ignored. This happens because the absolute amount of CO_2 released to the atmosphere through decay is greater when both DOM carbon and the wood product carbon are considered. As more CO_2 is released, there is little incentive to delay harvest because the the marginal gain in timber revenue from leaving trees in the stand may not be enough to compensate for the repayment of carbon loss associated with the decay. Harvesting is done early to minimize financial penalty.

Because the optimal harvest decision barely changes when carbon storage in wood product is considered, it can be concluded that it is not worth the extra effort in carbon accounting given that the landowner's behaviour is not likely to change.

Fig. 3.6 highlights the portion of the state space that shows wealth transfer from society to landowners without any noticeable benefit from mitigating the effect of GHG induced climate change when wood product pool is considered. These contours represent the difference between the LTCVs calculated when wood product stocks are considered and when they are ignored for $P^{CO_2} = 2$ and 20 CAD/tCO_2. There is transfer of wealth from society to landowners when the difference in LTCV is greater than zero. Fig. 3.6 shows that wealth is transfered from society to the landowner if he/she owns a stand that is older than 100 years and has custody of wood product that is less than 100 tC/ha.



(a) $P^{CO_2} = 2$ CAD/tCO_2. (b) $P^{CO_2} = 20$ CAD/tCO_2.

Figure 3.6: Change in land, timber, and carbon values (CAD/ha) between the case when wood product pool is considered and the case when wood product pool is ignored for different carbon prices. The region of state space where the change is positive is shaded grey. In these scenarios, the DOM carbon stock is held constant at 370 tC/ha.

Fig. 3.7 shows that a climate policy that encourages timber harvest as illustrated by

78 years harvest cycle and 102 years harvest cycle, will result in a smaller quantity of total carbon storage over a 200 year period, compared to a climate policy that calls for no timber harvest. Over a 200 year period, total carbon storage is about 63,000 tC/ha when the rotation age is 78 years, 70,000 tC/ha when the rotation age is 102 years and 80,000 tC/ha when the decision is not to harvest.

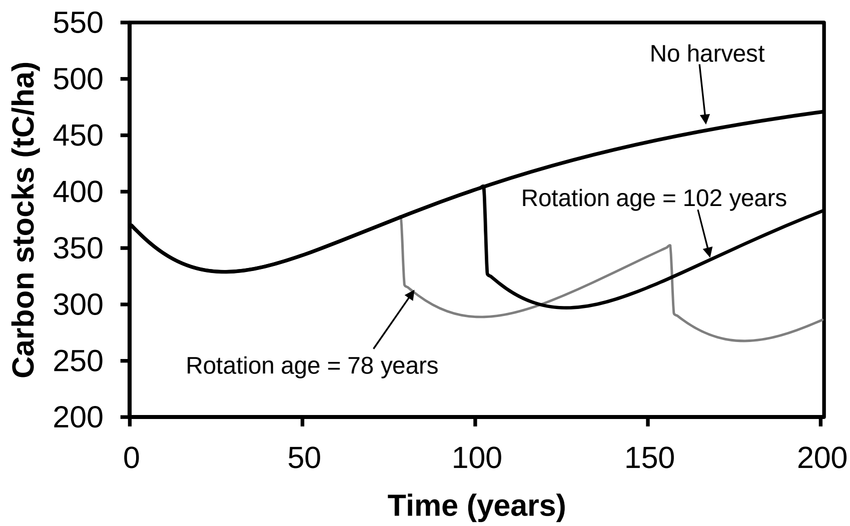


Figure 3.7: Projections of carbon pool development over time for rotation age 78 years, 102 years and no harvest cases given application and initial stand age of 0 years, initial DOM of 370 tC/ha and initial wood product stock of 0 tC/ha.

In addition to readily observable effects on carbon stocks, harvest operations can affect soil and forest floor carbon stores through physical disturbance. Harvesting can lead to overall carbon deficits in the first 20 years as immediate losses of carbon from DOM pool outweigh new growth and litterfall. Also, harvesting in the wet boreal forests with deep peat soils could trigger release of the vast amount of carbon stored in those soils.

This does not mean that harvesting is bad. In fire-prone forest, harvesting that reduces excess fuel loads may reduce the frequency or severity of fire, protecting forest carbon reservoirs into the future. Although it is forest that actually removes carbon from the atmosphere, wood products play an important role by slowing down carbon release back to the atmosphere. Setting public policy will require weighing the advantages of accumulating more carbon in the forest versus the advantages of accumulating it in the housing pool or wood product pool.

3.4 Conclusions

The dynamic programming model proposed in this paper extends the existing literature on the determination of optimal harvest decision for a forest stand that provides both timber harvest volume and carbon sequestration services. The forest stand is described using three state variables: stand age and the stocks of carbon stored in the DOM and wood product pools. To the best of my knowledge, this is the first paper to examine the impact of varying levels of initial wood product stocks and varying levels of initial DOM stocks on the optimal harvest decision. This study provides a basic framework for assessing the economic implications of accounting for carbon stocks in wood product. Some useful results from the analysis include:

1. Optimal harvest age increases with increasing CO_2 price.
2. The optimal harvest decision is sensitive to the current stocks of carbon in the wood product pool, when carbon prices are high and the wood product stocks are high.
3. The economic returns decrease with increasing wood product stocks.
4. Fossil fuel carbon emissions have very little or no impact on the optimal decision to harvest but affects economic returns to carbon management.
5. Wood products have very little or no impact on the optimal decision to harvest but affect economic returns to carbon management.

This study demonstrates that the optimal management policy does not change between cases where the market considers and ignores carbon storage in the wood product pool. It also demonstrates that fossil fuel carbon emissions have little or no impact on the optimal harvest policy. This raises an interesting concern whether it is worth the extra effort and cost to account for carbon stored in wood products and fossil fuel carbon emissions when the landowner's behaviour is not likely to be affected? Policy makers may end up transferring wealth from society to landowners if they allow them to claim credit for carbon stock changes in wood products with no substantial change in behaviour.

The general results reported in this study can be expected to differ from forest-level analyses such as those reported by Hennigar et al. (2008) because of the effect of inter-period flow constraints imposed on forest-level models. The results can also be expected to differ from those reported in other stand-level models (*e.g.* van Kooten et al. (1995), Chladná (2007)) because it is recognized that the dead parts of forest (i.e., DOM and wood product) are a source. The results can also be expected to differ from other analyses because of the particular form of the carbon market assumed in this study. In this analysis, the landowner pays for emissions and gets paid for sequestration in the year of occurrence. Other market structures such as those based on the difference from a business-as-usual baseline or on a contracted amount of carbon storage at a particular point in time could lead to qualitatively different results.

It is important to note that complications to the carbon market considered in this study may come from market leakage and substitution effects, which are both outside the control of the offset system. For instance if the agent considered in this study lowers harvest levels in order to increase forest carbon, but a nearby landowner responds with increase timber harvest, leakage adjustments would have to be made to reduce credictable carbon stocks. Policy makers should be careful in designing a policy that encourages reduction in timber harvest. This is because such a policy may indirectly cause an increase in the use of substitutes such as concrete which emits more GHG in its production cycle.

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CHAPTER 4

Carbon sequestration and the optimal forest harvest decision using alternative baseline policies

4.1 Introduction

Forest landowners can gain financially by selling carbon offset credits to emitters through various voluntary markets, ranging from easements with non-governmental organizations to negotiating directly with carbon dioxide (CO_2) emitters (Rudell et al., 2006). Carbon offset markets are developing and, in the voluntary market, forest carbon offsets are one of the most traded carbon offsets (Hamilton et al., 2007, 2008). However, forest carbon offsets present some unique challenges for technical legitimacy, in particular the issues of additionality.

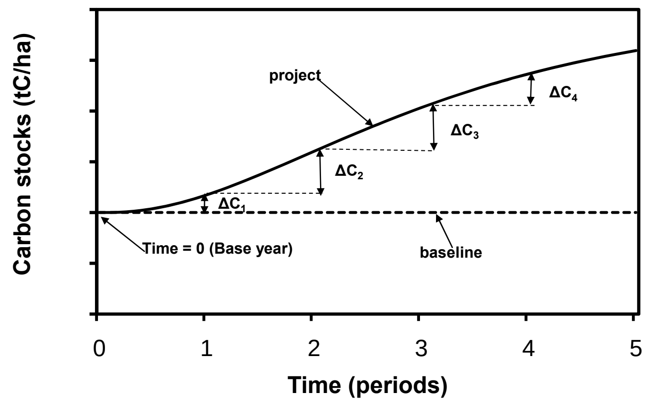
Additionality is key to the credibility of offsetting. Forest carbon offsets must represent new emission reductions or removals because those offsets are intended to compensate for new emissions someplace else. Without additionality, a carbon offset project may actually cause an increase in greenhouse gas (GHG) levels, undermining the purpose (and credibility) of the carbon offset market. Demonstrating additionality can be difficult, sometimes impossible, due to the subjectivity of project baselines.

A baseline is the reference point(s) against which a project's carbon storage or GHG emission reductions are measured. Carbon sequestration levels or emission reductions in excess of the baseline level are considered additional and, thus, available for sale as offsets. Therefore, setting an accurate baseline is important in designing a forest carbon offset project. Two main types of baselines are used in forest carbon projects. The first type is the "base year" baseline also known as the fixed baseline. The fixed baseline approach uses the carbon stocks at the beginning of the project as the baseline throughout the life of the project. Stock changes are calculated by comparing changes of a project's carbon stocks from one reporting period to the next (see panel a of Fig. 4.1). The second type of baseline is the "business-as-usual" (BAU) baseline. With this approach, stock changes are calculated by comparing changes in a project's carbon stocks to the estimated change that would have occurred without the project (see panel b of Fig. 4.1).

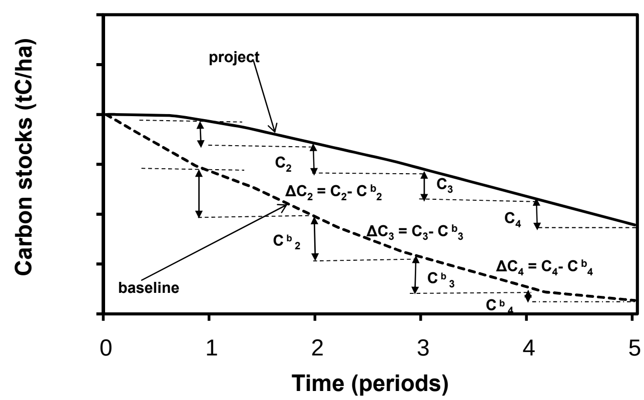
Net change in carbon stocks relative to a baseline is considered additional and in Fig. 4.1 this is defined as $\Delta C_i = C_i - C_i^b$, where C_i is the periodic change in the project's carbon stocks at time i and C_i^b is the periodic change in the baseline carbon stocks at time i. This approach of quantifying offset credits is different from other approaches used in literature. For example, McCarney et al. (2008) defines stock change as the difference between the project's carbon stock and the business-as-usual carbon stock at a particular point in time. In his study, he assumed carbon to be of temporary value, with the excess (deficit) carbon stored in each period, as compared to that period's baseline carbon stock. This does not account for periodic stock changes.

The two main types of baselines used in forest carbon projects are far from perfect. The fixed baseline approach has been criticized on the grounds that it does not consider the amount of sequestration that would have occurred had the project not been implemented, creating uncertainty about whether the project led to any real changes in sequestration levels. The BAU approach is also not free from criticism because it uses a hypothetical projections of sequestration made many years, sometimes decades, into the future. This creates a situation with information assymetry, thus making it possible for a landowner to game the system. Therefore, for most forest offset projects, both approaches lack the ability to assess unequivocally whether, or to what extent, a project's impact is additional (Beane et al., 2008).

In the forest economics literature, most of the stand level optimization models with



(a) Fixed baseline



(b) Business-as-usual baseline

Figure 4.1: Amount of offset credits (tC/ha) generated in hypothetical examples. Panel (a) shows the fixed baseline approach and panel (b) the business-as-usual baseline approach. Under each approach, the "additional" carbon that can be sold as offsets is represented by ΔC_i where i is time in years. The business-as-usual approach requires projecting the amount of carbon that would have been on the project lands had the project not occurred. The fixed baseline approach uses the carbon stocks at time zero (start of project) as the baseline throughout the life of the project (although only increases in carbon stocks net those that have already been sold as offsets are available for sale.)

respect to timber values and carbon sequestration services (van Kooten et al., 1995; Spring et al., 2005a,b; Gutrich and Howarth, 2007) have used the fixed baseline approach to determine optimal harvest age. To the best of my knowledge, none of the stand level optimization models with respect to timber values and carbon sequestration services have used the BAU baseline to determine optimal harvest age. In this paper both fixed and BAU baselines are used to investigate the optimal harvest behaviour of a landowner. This is important because it will assist decision makers in choosing an appropriate baseline, which is key to the credibility of any carbon offset market.

In chapter 2, a fixed baseline was used to demonstrate that the optimal harvest decision is sensitive to current stocks of carbon in the DOM pool, especially when carbon prices are high and initial DOM stocks are low. This paper shows similar results irrespective of the baseline used.

In this paper, a dynamic programming model is also developed to find the optimal stand management policy when both timber harvest and carbon sequestration values are considered. The forest stand being modeled is described in terms of its starting age, current age and initial mass of carbon stored in the DOM pool and current mass of carbon stored in the DOM pool. The management decisions available to the decision maker are to clearcut a stand of a given age and with a DOM pool of a given size, or to defer the harvest decision.

The model is used to:

1. examine the sensitivity of optimal harvest age to stocks of carbon in DOM and carbon prices using different baseline policies,

2. examine the sensitivity of the net present value of forested land to stand age, stocks of carbon DOM, carbon prices and alternative baselines, and

3. investigate the sensitivity of using baselines with different starting conditions.

4.2 Data

4.2.1 Timber yield and cost functions

The timber yield and the cost information used in this paper come from the TIPSY growth and yield simulator (BC MoFR, 2007) developed and used by the British Columbia Ministry of Forests and Range for use as input to forest management plans. The data represents a lodgepole pine stand in the BWBS biogeoclimatic zone, in the Dawson Creek Forest District of the Prince George Forest Region of British Columbia, Canada. A medium site class (site index is 16 m at 50 years breast height age) and a planting density of 1600 stems/ha is assumed.

The tabular representation of the merchantable timber yield table from TIPSY is approximated using a Chapman-Richards growth function, $V(a) = v_1(1 - e^{-v_2 a})^{v_3}$, in which $V(a)$ represents the merchantable timber volume in m^3/ha at age a and v_1, v_2 and v_3 are parameters, which were set at 500.4, 0.027 and 4.003 respectively. These parameters give an acceptable representation of the yield table generated by TIPSY.

A derived residual value approach (Davis et al., 2001, pp. 418–427) is used to estimate the net value of timber harvest. All costs and prices in this paper are expressed in Canadian dollars (CAD). The residual value is the selling price of the final products (in this case lumber and pulp chips) less the costs of converting standing trees into the final products, expressed in CAD/m^3 of merchantable timber.

The average lumber price of kiln dried, standard and better, western spruce-pine-fir, 2×4 random length lumber for the period April 1999 to March 2008 was approximately 375 CAD/thousand board feet (MBF) (BC MoFR, 2009). The price of wood chips was assumed to be 70 CAD/bone dry unit (BDU). At 88 years of age (the volume maximizing harvest age), the pine stand modeled with TIPSY will yield 0.210 MBF of lumber and 0.152 BDU of pulp chips per cubic metre of roundwood input. The base selling price of the final products expressed in equivalent roundwood input terms is 89.40 CAD/m^3. The selling price of final products expressed in terms of wood input is represented by the parameter P^w. The total revenue (CAD/ha) at any harvest age is calculated as $P^w V(a)$.

The cost of converting standing trees into end products is the sum of all costs associated with harvesting, hauling, and milling. Road construction and harvesting costs reported by TIPSY for the pine stand were 1,150 and 5,100 CAD/ha. Log hauling, milling and overhead costs as 4.84, 34.65, and 8.06 CAD/m^3 respectively. The costs reported on a CAD/ha basis are assumed to be closely related to the area harvested; the costs reported as CAD/m^3 are assumed to be more closely related to volume harvested: I use F^a to represent area based costs and F^v to represent volume based costs. The total harvesting and processing costs at any harvest age (CAD/ha) are calculated as $F^a + F^v V(a)$. Based on the costs used here, F^a is set to 6,250 CAD/ha and F^v to 47.55 CAD/m^3. Stands are assumed to be reestablished immediately following harvest at a cost, E, which is set to 1,250 CAD/ha, based on the default parameters used by TIPSY.

4.2.2 Carbon pool dynamics

The TIPSY yield table was used as input to Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) in order to generate projections of carbon stored in each of the pools. A highly simplified representation of the carbon pool structure of CBM-CFS3 with just two carbon pools was created: a biomass pool representing carbon stored above and below ground in living trees, and a dead organic matter pool representing all other carbon stored in standing dead trees (snags), on the forest floor, and in the soil. The label dead organic matter is used even though it is recognized that some of the carbon in this DOM pool is contained in living organisms.

Another Chapman-Richards function is estimated to represent the biomass carbon pool as a function of stand age: $B(a) = b_1(1 - e^{-b_2 a})^{b_3}$, where $B(a)$ is the mass of carbon in tC/ha, stored in the living trees at age a, and b_1, b_2 , and b_3 are coefficients set at 198.6, 0.0253, and 2.64 respectively. This function provides a reasonable representation of the tabulated biomass at different stand ages from CBM-CFS3. Timber harvest is assumed to reset the age of the stand, and therefore its biomass, to zero.

Three processes are assumed to affect the development of the DOM pool: decay, litterfall, and harvest. DOM is assumed to decay at a rate, α, which represents a fixed proportion of the DOM pool each year. DOM is added to the pool as the proportion of the biomass of the stand that dies naturally each year. This proportion is expressed as the litterfall rate, β. With no timber harvest, the DOM pool grows according to Eq. (4.1).

$$D_{t+1} = (1 - \alpha)D_t + \beta B(a) \tag{4.1}$$

The decay and litter fall rates were estimated using the method of least squares to find the parameters α and β used in projections of CBM-CFS3 for the pine stand. The estimated parameters are $\alpha = 0.00841$ and $\beta = 0.01357$.

When timber harvest occurs, the merchantable timber volume is removed from the site and processed into lumber and wood chips. The roots, stumps, tops, branches and leaves are assumed to die at the time of harvest and become part of the DOM pool. The mass of carbon removed from the site as merchantable timber volume is calculated as $\gamma V(a)$ where γ is a constant used to convert wood volume to the mass of carbon stored in wood. $\gamma = 0.2$ is used. This is consistent with a carbon content of wood of approximately 200 kg m^{-3} (Jessome, 1977). With timber harvest, the DOM pool grows according to Eq. 4.2.

$$D_{t+1} = (1 - \alpha)D_t + B(a) - \gamma V(a) \tag{4.2}$$

For the carbon market assumed here, the landowner is paid (pays) for annual changes in a project's TEC stocks in excess (deficit) of the annual change in baseline quantity. The annual change in project's TEC stocks is simply the sum of the changes in biomass and DOM carbon. With no harvest, the change in biomass is given by $\Delta B(a) = [B(a+1) - B(a)] - [B^b(a+1) - B^b(a)]$, where $B^b(a)$ is the mass of carbon stored in the hypothetical projected biomass pool of a given baseline at stand age a. With harvest, the age of the stand is set to 1 for the subsequent year, so the change in biomass becomes $\Delta B(a) = [B(1) - B(a)] - [B^b(a+1) - B^b(a)]$. The change in DOM for no harvest is given by $\Delta D_t = [-\alpha D_t + \beta B(a)] - [D^b_{t+1} - D^b_t]$, where D^b_t is the mass of carbon stored in the hypothetical projected DOM pool of a given baseline at time t. It is $\Delta D_t = [-\alpha D_t + B(a) - \gamma V(a)] - [D^b_{t+1} - D^b_t]$ for the harvest case.

4.2.3 Selection of a BAU baseline for each initial stand age and initial DOM

Two types of hypothetical projections of carbon sequestration levels are assumed for the BAU baseline in this paper, based on the best estimate of how a forest landowner would have managed the forest stand if there were no carbon sequestration incentives. It is assumed that the landowner will either maximize the soil expectation value (SEV) of an infinite stream of forest rotation or will maximize sustained yield timber volume.

In this paper, the two hypothetical projections of carbon sequestration levels are referred to as "Maximum Sustained Yield (MSY) baseline" and "Faustmann baseline". The MSY and the Faustmann baselines are based on TEC stocks derived from a forest that is managed using an even-aged silvicultural system with the objective of maximizing sustained yield timber volume and economic returns respectively.

To derive the a baseline, a three step calculation is followed.

1. First, the rotation age is calculated. In the case of the MSY baseline, the volume maximization sustained yield rotation age is the stand age where the mean annual increment (MAI) is maximized, which is 88 years in this study. For the Faustmann baseline, the optimal economic rotation is the stand age where the marginal return from allowing a stand to grow another year equals the opportunity cost of the capital that would be generated from harvesting the current crop and regenerating the site, thereby maximizing the value of the forest land (Pearse, 1990). This paper used the discrete-time version of the Faustmann formula (Eq. 4.3) to derive the Faustmann baseline.

$$SEV^* = \max_t \left[\frac{P^w V(a) - (F^a + F^v V(a)) - E\,(1+r)^t}{(1+r)^t - 1} \right] \tag{4.3}$$

   For the data used, the optimal economic rotation age is 73.

2. Second, the mass of carbon stored in the living trees is estimated using the biomass function: $B^b(a) = b_1(1 - e^{-b_2 a})^{b_3}$, so that stand age a, runs from initial age to the age where harvest is optimized. The initial age is reset to stand age 1 after harvest and the process is repeated; and

3. Finally, the DOM carbon stocks is then calculated for a combination of starting DOM stocks that runs from 0 to 500 tC/ha. and starting stand age that runs from 0 to 250 years. The mass of carbon stored in the DOM pool is estimated using equations 4.1 and 4.2 where stand age a, runs from initial age to the

age where harvest is optimized. The initial age is reset to stand age 1 after harvest and the process is repeated.

MSY or Faustmann baseline is calculated as the sum of the biomass carbon stocks [$B^b(a)$] and the DOM carbon stocks [D_t^b]. The projection of the TEC stocks for MSY and the Faustmann baselines are presented in Fig. 4.2. Note that the baselines are "wavy" because a single stand is used in this study. A smooth curve will be produced by forest level spectrum.

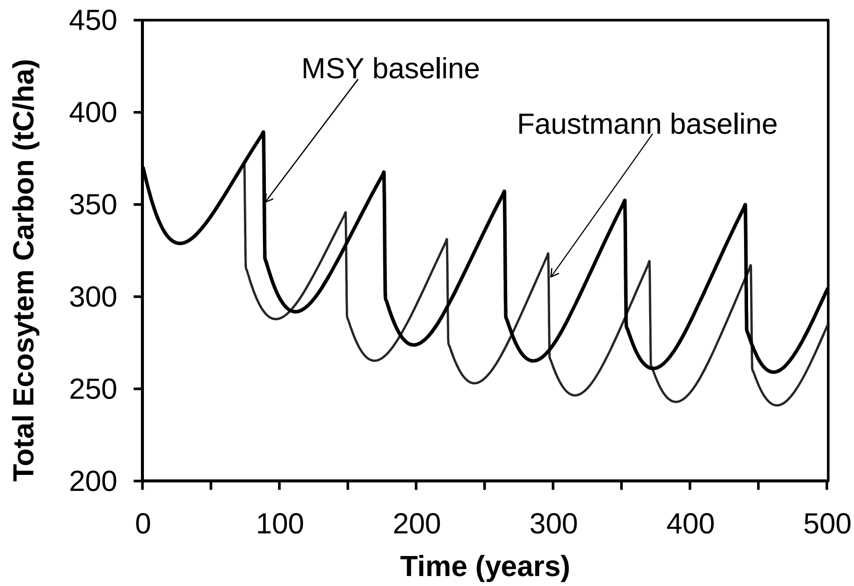


Figure 4.2: Projection of total ecosystem carbon stocks for MSY baseline and the Faustmann baseline cases given an initial stand age of 0 years and initial DOM stocks of 370 tC/ha. There is a different baseline for each of the different starting conditions.

4.2.4 Valuation of carbon

The carbon market described in this paper pays landowners for the annual sequestration of CO_2 in excess of the annual changes in the baseline quantity and requires payment for net annual release of CO_2 in deficit of the annual changes in the baseline quantity. The price received per tonne of sequestered CO_2 is the same as the price paid per tonne of released CO_2. In this paper, a broad range of prices for CO_2 is used in sensitivity analysis. The range of prices chosen encompass the range of observed prices including any discounting that may occur in order to account for the temporary nature of carbon sequestration in forests. It is conventional to express carbon prices in currency units per tCO_2 and stocks as tonnes of carbon (tC). This practice of reporting is continued here, but for modeling purposes, equivalent prices for carbon (CAD/tC) is defined as $P^C = 3.67P^{C0_2}$ because the molecular weight of CO_2 is approximately 3.67 times the atomic weight of C.

4.3 The Model

The basic assumption of the model is that a forest landowner is participating in a carbon market where the landowner is paid for carbon sequestered by the forest and pays when carbon is released. The landowner is assumed to manage the forest jointly for timber production and carbon sequestration in a manner that earns maximum discounted financial return. The forest is managed using an even-aged silvicultural system. Each rotation begins with the establishment of a stand on bare forest land and ends with a clearcut harvest after a number of years of growth. The beginning of a new rotation coincides with the end of the previous rotation. The cycle of establishment, growth, and harvest is assumed to repeat in perpetuity.

The decision problem is represented as a dynamic program, and state variables are used to describe the system at each stage of the decision problem.

4.3.1 Dynamic Programming Model

The model developed here is a discrete backwards recursion dynamic programming model. The stages represent time, in one year time steps. The forest stand is described by a combination of four state variables, the age of the stand (years), the initial stand age (years), carbon stocks in the DOM pool (tC/ha) and the initial carbon stocks in the DOM pool (tC/ha). The initial conditions are necessary to index the baseline. There are 251 discrete one-year wide age classes, j, with midpoints $a_j = j,\ j = 0, 1, \ldots, 250$ years; there are and 501 DOM classes, i, with midpoints $d_i = i,\ i = 0, 1, \ldots, 500$ tC/ha; there are 16 initial age classes, x, with midpoints $a_x = 10x$(tC/ha), $x = 0, 1, 2, \ldots, 15$; and there are 51 initial DOM classes, s, with midpoints $d_s = 10s$(tC/ha), $s = 0, 1, 2, \ldots, 50$. Timber harvest volume and carbon stored in the biomass pool are calculated as a function of stand age.

At each point in time, a decision is made by the landowner whether to clearcut the stand or let the stand grow for another year. Clearcutting yields immediate timber revenue. Both the clearcut and the leave decisions will result in a change in TEC (i.e. change in project's TEC stock less the change in baseline TEC stock) and the appropriate carbon credit or debit. If harvesting does occur (i.e., decision, $k = 1$) in stage t, it is assumed that replanting occurs immediately and the stand age is set to 1 in stage $t+1$. If harvesting does not occur (i.e., decision, $k = 0$) in stage t, the stand age is incremented by one year in stage $t+1$.

The change in total ecosystem carbon, ΔC_{tisxjk} at any given stage t, depends on current DOM class i, initial DOM class s, a current age class j, initial age class x, and harvest decision k. It is the sum of the annual changes in project's DOM stocks less the annual changes in baseline DOM stocks, and the annual changes in biomass stocks less the annual changes in baseline biomass stocks. Where d^b_{tis} is defined as baseline DOM class i given an initial baseline DOM class s in stage t.
For the no harvest case:

$$\begin{aligned} \Delta C_{tisxj0} = {} & B\left(\min\left(\left(a_{xj}+1\right),250\right)\right) + B^b\left(a_{xj}\right) + \beta B\left(a_{xj}\right) + d^b_{tis} \\ & - B^b\left(\min\left(\left(a_{xj}+1\right),250\right)\right) - B\left(a_{xj}\right) - \alpha d_{tis} - \min\left(d^b_{tis}+1,500\right) \end{aligned} \tag{4.4}$$

For the harvest case:

$$\begin{aligned} \Delta C_{tisxj1} = {} & B(1) + B^b\left(a_{xj}\right) + d^b_{tis} - \alpha d_{tis} - \gamma V\left(a_{xj}\right) \\ & - B^b\left(\min\left(\left(a_{xj}+1\right),250\right)\right) - \min\left(d^b_{tis}+1,500\right) \end{aligned} \tag{4.5}$$

The net harvest revenue for initial age x and age class j, (H_{xj}) is calculated as

$$H_{xj} = \left(P^W - F^v\right) V\left(a_{xj}\right) - F^a - E. \tag{4.6}$$

Establishment costs are included here because it is assumed that reforestation is required, and occurs, immediately after timber harvest.

The stage return or periodic payoff (N_t) is calculated as shown in Eq. 4.7. The payoff is calculated for the midpoints of each DOM class (i) given an initial DOM class (s) and stand age (j) given an initial age class (x) and for each of the possible harvest decisions (k). If a stand is not harvested ($k = 0$), the periodic payoff would be based on ΔC_{tisxj0} only. If the stand is harvested ($k = 1$), the payoff includes payments or charges based on ΔC_{tisxj1} as well as the net revenue associated with timber harvesting, processing, and reestablishment.

$$N_t\{s,i,x,j,k\} = \begin{cases} P^C \Delta C_{tisxj0} & : \quad k = 0 \\ P^C \Delta C_{tisxj1} + H_{xj} & : \quad k = 1 \end{cases} \tag{4.7}$$

In this analysis, it is assumed the objective at each stage, is to determine, for each possible combination of stand age given an initial stand age and level of DOM stock given an initial DOM, the harvest decision that results in the maximum net present value of land and timber and carbon storage for the remainder of the planning horizon. The stages in this dynamic programming model correspond to the time periods in which decisions are made. It is a finite horizon, deterministic model with time t measured in years.

Because discrete DOM classes is used, the projections from Eqs. 4.1 and 4.2 are converted to the proportion of the source DOM class area that moves into two adjacent target DOM classes. l_{sixjk} is used to represent the lower target class, and u_{sixjk} to represent the upper. ρ_{tisxjk} is calculated to represent the proportion that moves into the upper class and $\left(1 - \rho_{tisxjk}\right)$ as the proportion that moves into the lower class. In the notation used here, $\lfloor y \rfloor$ indicates the floor of a real number y, i.e. the largest integer less than or equal to y. The fractional part of y is indicated by $\langle y \rangle$ such that $y = \lfloor y \rfloor + \langle y \rangle$.

$$l_{tisxj0} = \min\left(\lfloor (1-\alpha)\, d_{tis} + \beta B\left(a_{xj}\right) \rfloor, 500\right) \tag{4.8}$$

$$l_{tisxj1} = \min\left(\lfloor (1-\alpha)\, d_{tis} + B\left(a_1\right) - \gamma V\left(a_{xj}\right) \rfloor, 500\right) \tag{4.9}$$

$$u_{tisxjk} = \min\left(l_{tisxjk} + 1, 500\right) \tag{4.10}$$

$$\rho_{tisxj0} = \langle (1-\alpha)\, d_{si} + \beta B\left(a_{xj}\right) \rangle \tag{4.11}$$

$$\rho_{tisxj1} = \langle (1-\alpha)\, d_{si} + B\left(a_1\right) - \gamma V\left(a_{xj}\right) \rangle \tag{4.12}$$

A weighted return is calculated from the target states associated with the harvest decision, k. For the no harvest decision, $k = 0$,

$$W_{sixj0} = \left(1 - \rho_{tisxj0}\right) R_{t+1}\{l_{tisxj0}, \min((j+1), 250)\} + \rho_{ij0} R_{t+1}\{u_{ij0}, \min((j+1), 250)\} \tag{4.13}$$

For the the harvest decision, $k = 1$,

$$W_{tisxj1} = \left(1 - \rho_{tisxj1}\right) R_{t+1}\{l_{tisxj1}, 1\} + \rho_{tisxj1} R_{t+1}\{u_{tisxj1}, 1\} \tag{4.14}$$

The return for the last stage in the problem is initialized to zero,

$$R_T\{i, j\} = 0. \tag{4.15}$$

This assumption is justified on the basis that T is large (500 years) and the discounted value of R_T for reasonable discount rates for this problem is near zero (e.g. the present value of 1 CAD received 500 years in the future is 2.5×10^{-11} CAD given a 5% discount rate).

The discount factor, $\delta = (1 + r)^{-1}$, represents the relative value of a dollar received one year from now (given an annual discount rate of r) to a dollar today. The discount rate, r, used for the analysis is 5% per annum: for this analysis, $\delta = 0.9528$. This rate is intended to reflect a market rate of time preference.

The recursive objective function for this problem is given in Eq. 4.16.

$$R_t\{s, i, x, j\} = \max_k N_t\{s, i, x, j, k\} + \delta W_{tisxjk}, \ t = T-1, T-2, \ldots, 0 \tag{4.16}$$

The recursive objection function selects the harvest decision for each possible starting stage and for each possible combination of state variables that maximizes the net present value at each stage, assuming that optimal decisions are made in all subsequent stages. It calculates a return for each of the harvest decisions and selects the harvest decision that results in the maximum return as the optimal choice for the state combination in that stage.

Eq. 4.17 below modifies the stage return at time zero for stands of age 0, and represents the soil expectation value for each initial DOM class. This incorporates establishment costs for time zero. For subsequent stages, establishment costs are incorporated in Eq. 4.7.

$$\forall si \;:\; R_0\{s,i,0\} \leftarrow R_0\{s,i,0\} - E \tag{4.17}$$

4.4 Results and Discussion

The dynamic program presented above is used to determine the optimal harvest policy for a profit-maximizing landowner managing a forest stand for production of wood volume and sequestration of CO_2. The optimal harvest policy is summarized by a decision rule which shows the combinations of stand age and DOM states for which the optimal decision is to harvest, and those combinations for which the optimal decision is to defer harvest. In this paper the change in harvest policy is examined in response to changing prices for CO_2 storage and also according to alternative methods of accounting for DOM. The results presented in this section were calculated using an implementation of the dynamic programming model programmed in MATLAB (Pratap, 2006).

The optimal harvest policies for a number of different carbon prices using alternative baseline policies are presented in Table 4.1. The results show that the baseline policy have very little or no impact on the optimal harvest behaviour of a landowner. This means that the different baselines will have about the same impact of mitigating the effect of GHG induced climate change, although economic returns to the landowner will be different.

In Table 4.1, the decision rule when P^{CO_2} is 0 CAD/tCO_2 corresponds to the case when timber is the only value considered: it is always optimal to harvest stands older than the Faustmann rotation age of 73 years given the data used here. As P^{CO_2} increases, the optimal harvest age also increases. When P^{CO_2} is 35 CAD/tCO_2 or greater, the optimal decision is to never harvest.

A graphical representation of the results in Table 4.1 is presented in Fig. 4.3. The results presented here are based on using the Faustmann baseline only. This is because all alternative baseline scenarios show similar relationships between DOM carbon stocks and current stand age. The results suggest that the optimal decision is sensitive to current stocks of carbon in the DOM pool, especially when carbon prices are high and initial DOM stocks are low. This happens because the amount

Table 4.1: Summary of harvest age for different carbon prices using alternative baseline policies. The results are based on initial stand age of 0 years and initial DOM stocks of 370 tC/ha.

P^{CO_2} (CAD/tCO_2)	Rotation age (Fixed baseline) (years)	Rotation age (Faustmann baseline) (years)	Rotation age (MSY baseline) (years)
0	73	73	73
1	74	75	76
2	75	76	77
5	78	79	79
10	84	84	85
20	101	101	102
30	139	139	139

of CO_2 released to the atmosphere through decomposition is lower with lower DOM stocks: the marginal gain in CO_2 sequestration from delaying harvest is greater with lower DOM stocks.

Fig. 4.4 summarizes the value of land, timber, and carbon sequestration services (LTCV, hereafter) for the entire state space, for carbon prices of 0, 2, 20, and 40 CAD/tC given a Faustmann baseline with initial stand age of 0 years and initial DOM carbon stocks of 370 tC/ha. Panel (a) represents the case where $p^{CO_2} = 0$. Because carbon has no value, in this case, the LTCV is independent of the amount of DOM stored. The results presented in Fig. 4.4 predict that a landowner who begins with a younger stand will benefit when provided with carbon management incentives. As expected, the LTVC generally increases with increasing P^{CO_2} for younger stands. For example, if a landowner who begins with a stand that is 50 years old growing on a piece of land with initial DOM stock of 370 tC/ha is considered, the LTCV is 1,200 CAD/ha when $P^{CO_2} = 0$ CAD/tCO_2. This increases to 1,300 CAD/ha when $P^{CO_2} = 2$ CAD/tCO_2. At a $P^{CO_2} = 20$ CAD/tCO_2, the LTVC is 2,200 CAD/ha and at $P^{CO_2} = 40$ CAD/tCO_2, the LTVC is 4,100 CAD/ha.

The same cannot be said for older stands. The LTCV actually declines with increasing P^{CO_2}. Notice that if a landowner begins with a stand that is 100 years old and initial DOM stock of 370 tC/ha, the LTCV declines from 8,300 CAD/ha when $P^{CO_2} = 0$ CAD/tCO_2 to 7,800 CAD/ha when $P^{CO_2} = 2$ CAD/tCO_2. It then decreases to 3,400 CAD/ha when $P^{CO_2} = 20$ CAD/tCO_2, and finally to 3,300 CAD/ha when P^{CO_2} increases to 40 CAD/tCO_2. These findings contrasts with results from

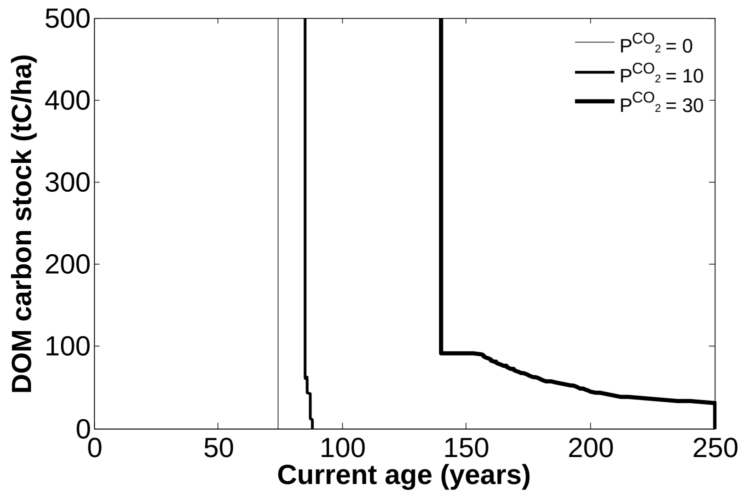
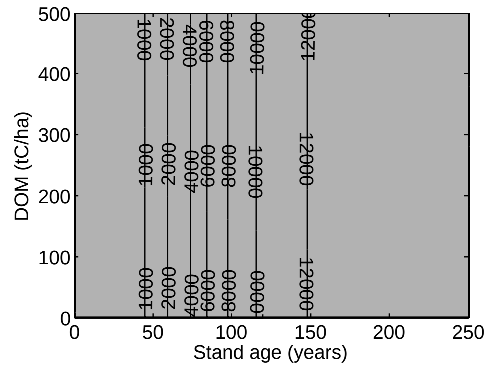
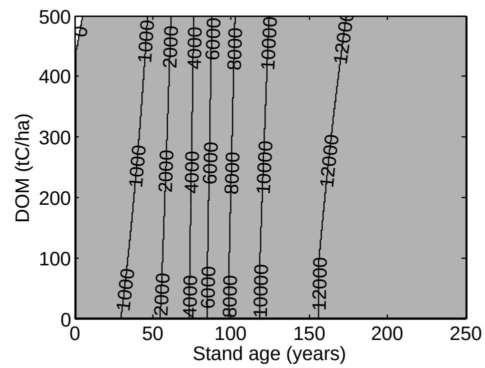


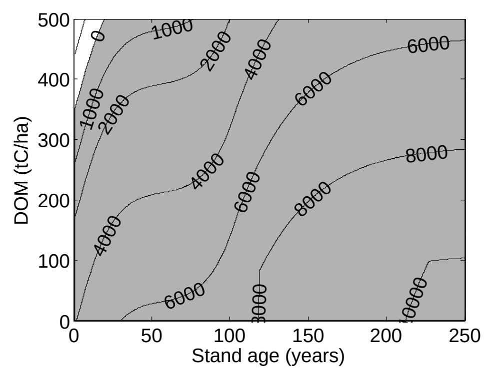
Figure 4.3: Optimal harvest policies for different carbon prices. The region to the right of and above the line corresponding to each carbon price represents the combinations of current age and DOM carbon stock for which the optimal decision is to harvest. In the region to the left of and below the line, the optimal decision is to delay harvest. For carbon prices of 35 CAD/tCO_2 or greater, it is never optimal to harvest. The Faustmann baseline was used in all scenarios presented here



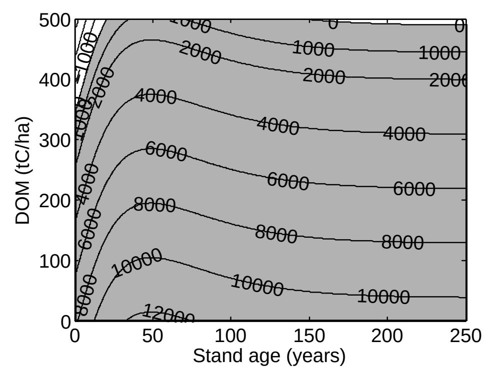
(a) $P^{CO_2} = 0$ CAD/tC.



(b) $P^{CO_2} = 2$ CAD/tC.



(c) $P^{CO_2} = 20$ CAD/tC.



(d) $P^{CO_2} = 40$ CAD/tC.

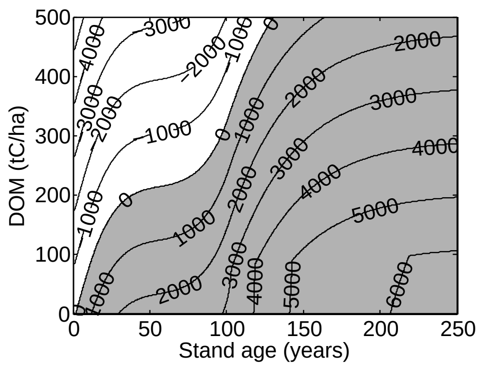
Figure 4.4: Land, timber, and carbon values (CAD/ha) by stand age and carbon stocks in the DOM pool for different carbon prices given a Faustmann baseline with initial stand age of 0 years and initial DOM carbon stocks of 370 tC/ha. The contours indicate combinations of age and DOM states that have the same land, timber, and carbon values. The region where LTCV is positive is shaded grey.

other studies which generally show an increase in financial return with increasing P^{CO_2}. This is because there is a carbon emission charge associated with the decomposition of DOM and carbon sequestration benefit associated with tree growth. Young stands grow faster and store CO_2 at a faster rate. In young stands the carbon benefit may be enough to compensate for the carbon release charge associated with DOM decomposition, resulting in a net CO_2 storage. Hence, financial returns increases with increasing P^{CO_2} in young stands. In older stands, trees show a decline in tree growth and store less CO_2 in the living tree biomass annually. This means that the carbon benefit may not be enough to compensate for the carbon release charge associated with DOM decomposition. And therefore as P^{CO_2} increases, the carbon emission charge also increases, and the financial returns decreases. The same general trend is observed with fixed and MSY baselines.

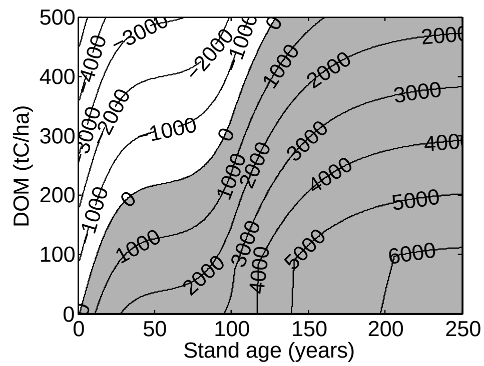
Fig. 4.4 also shows that LTCV decreases with increasing DOM stocks when the carbon price is positive. This might seem counter-intuitive as more carbon storage is generally thought of as a good thing. However, a larger stock of DOM will generally release a greater absolute quantity of CO_2 to the atmosphere than a smaller stock. A large stock of decaying dead organic matter is a liability for the landowner in the type of carbon market presented here.

Fig. 4.5 reveals that given the same starting conditions, the financial return to carbon management is higher when a Faustmann baseline is used compared to a scenario that uses an MSY baseline. For example, consider a baseline with a starting stand age of 0 years and starting DOM of 0 tC/ha, when $P^{CO_2} = 20$ CAD/tCO_2, a stand that is 100 years old and has an initial DOM of 200 tC/ha will produce a LTCV of 1,400 CAD/ha for the Faustmann baseline scenario compared to a LTCV of 1,300 CAD/ha for the MSY baseline scenario. The difference in the results is due to the fact that the MSY baseline has more TEC stocks over time compared to the Faustmann baseline as shown in Fig. 4.2 and therefore the difference between the projects's TEC and the baseline TEC is less for the scenario that uses the MSY baseline, resulting in lower LTCV.

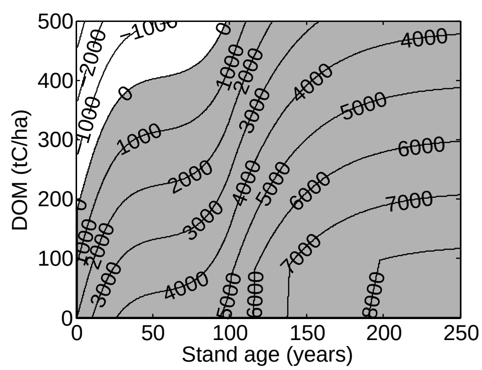
The results presented in Fig. 4.5 show that a landowner may prefer a fixed baseline to either a Faustmann baseline or an MSY baseline when provided with carbon management incentives. With the same starting conditions, the fixed baseline produces the highest LTCV compared to any of the BAU baselines considered. For example, a stand that is 100 years old and has initial DOM of 200 tC/ha and $P^{CO_2} = 20$



(a) MSY baseline



(b) Faustmann baseline

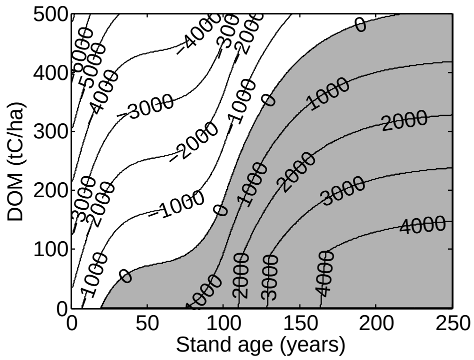


(c) Fixed baseline

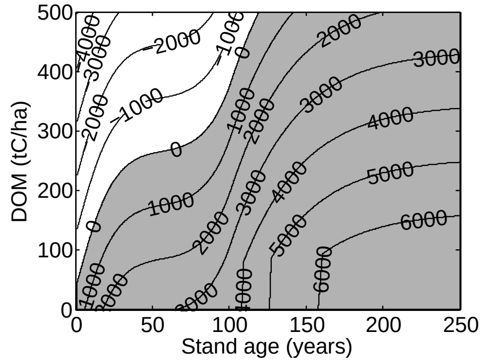
Figure 4.5: Land, timber, and carbon values (CAD/ha) by stand age and carbon stocks in the DOM pool given alternative baselines with initial stand age of 0 years and initial DOM carbon stock of 0 tC/ha. The results are based on $P^{CO_2} = 20$ CAD/tC and the contours indicate combinations of age and DOM states that have the same LTCVs. The region where LTCV is positive is shaded grey.

CAD/tCO_2, the LTCV is 3,500 CAD/ha for the fixed baseline. The difference in the results is due to the different method of carbon accounting. Whereas the periodic change in baseline stocks is zero for the fixed baseline approach, it is not zero in the BAU baseline approach. The result is a larger change in TEC stocks between the project's TEC stocks and the baseline TEC stocks for the fixed baseline scenario. This means that for the same starting conditions the fixed baseline approach will produce a higher LTCV.

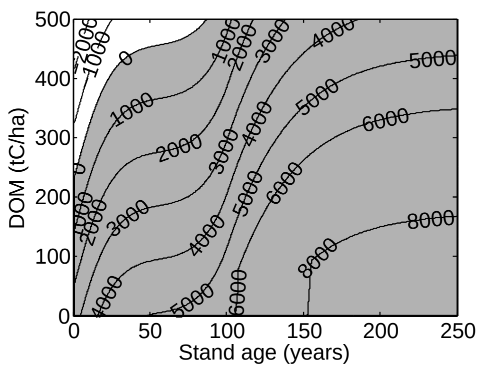
The results presented in Fig. 4.6 suggests that the initial DOM stock of a baseline significantly affects economic returns to carbon management. The model runs presented in Fig. 4.6 are based on $P^{CO_2} = 20$ CAD/tCO_2 and a MSY baseline with different starting conditions. The results show that a landowner is better off if he/she starts with a baseline that has higher initial carbon stocks in the DOM pool. For example if we consider a stand that is 100 years old and has initial DOM of 200 tC/ha and $P^{CO_2} = 20$ CAD/tCO_2, the LTCV is 1,000 CAD/ha if we use an MSY baseline with an initial DOM stock of 0 tC/ha. The LTCV increases to 6,000 CAD/ha if we use an MSY baseline with an initial DOM stock of 500 tC/ha. With the type of carbon market considered here where a carbon credit is calculated as the product of P^{CO_2} and the difference between the annual changes in the project's TEC stocks and the annual changes in the baselines TEC stocks, one will think that a higher initial carbon stocks in the DOM pool will result in lower financial returns, but this is not the case as the reverse is true. Starting with a baseline with a larger stock of DOM will generally release a greater absolute quantity of CO_2 to the atmosphere and therefore increases the absolute difference between the project's TEC stocks and the baseline TEC stocks. The larger the difference between the project's TEC stocks and the baseline TEC stocks, the larger the carbon offset credit and therefore the larger the financial return. Hence, a baseline with a high initial carbon stock in the DOM pool is an asset for the landowner represented in this model. Similar trends in the results were obtained by using a Faustmann baseline. In all model runs, changing the starting conditions or the type of baseline did not impact the optimal harvest policy.



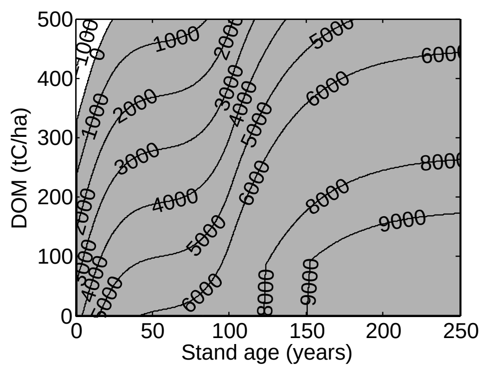
(a) MSY baseline with initial DOM stock of 0 tC/ha and initial age of 50 years.



(b) MSY baseline with initial DOM stock of 200 tC/ha and initial age of 50 years.



(c) MSY baseline with initial DOM stock of 400 tC/ha and initial age of 50 years.



(d) MSY baseline with initial DOM stock of 500 tC/ha and initial age of 50 years.

Figure 4.6: Land, timber, and carbon values (CAD/ha) by stand age and carbon stocks in the DOM pool given a MSY baseline with initial stand age of 50 years and varying initial DOM carbon stocks. The results are based on $P^{CO_2} = 20$ CAD/tC and the contours indicate combinations of age and DOM states that have the same LTCVs. The region where LTCV is positive is shaded grey.

4.5 Conclusions

In this paper a dual product dynamic programming model of timber volume and carbon sequestration services was developed to analyze the impact of different baseline policies on the optimal decision to harvest. To the best of my knowledge, this is the first paper to examine the impact of different project baselines on the optimal harvest age at the stand level. Some useful results from the analysis include:

1. Alternative baselines have little effect on optimal decision but can have a large effect on financial return to landowner. In effect, behaviour changes little, but the size of the transfer of wealth from emitters to landowners is significant.

2. The optimal decision is sensitive to current stocks of carbon in the DOM pool (irrespective of the baseline), especially when carbon prices are high and initial DOM stocks are low, and

3. The starting conditions (i.e. initial DOM) of the baseline imposed on a landowner have a big impact on the financial returns to carbon management. For the type of carbon accounting method considered in this paper, a landowner is better off stating with a baseline with a high DOM stock.

The efficacy of any mitigating project is determined by the extent to which the project activities lead to the GHG reduction benefits that are additional to the established baseline. In this paper it was demonstrated that given the same conditions, alternative baselines have little effect on optimal decision, but can have a large effect on financial returns to landowner. This raises a big concern because although the landowner's behaviour changes little, the size of the transfer of wealth from emitters to landowners is huge.

This means that policy makers should standardize the baseline selection process and ensure that baselines are not set too low for landowners to receive a windfall and be rewarded just for using a particular baseline. In contrast, a baseline should not be set too high to be a disincentive for landowners to participate in the offset carbon market.

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CHAPTER 5

Optimal harvest age considering carbon sequestration in biomass, DOM and wood products pools: comparative static analysis

5.1 Introduction

Concern about increasing concentration of carbon dioxide (CO_2) in the atmosphere has created another objective for forest management: the removal of CO_2 from the atmosphere. Forests may mitigate the effects of greenhouse gas (GHG) induced change, since trees remove substantial amounts of CO_2 from the atmosphere through photosynthesis (IPCC, 2000). About 50% of the dry biomass of a tree is carbon (Salwasser, 2006). Considering the relative size of carbon atoms to CO_2 molecules, this means that the dry weight of one tonne of a tree is involved in sequestering half a tonne of carbon, derived from more than 1.8 tonnes of CO_2 taken from the atmosphere.

The choice of harvest age is the fundamental decision in an even-aged silvicultural system. Harvest age can have significant impact on carbon storage (Harmon and Marks, 2002). Generally, delaying the harvest age allows trees to grow bigger, thereby storing more carbon. Forests managed on a longer harvest cycle accumulate more dead organic matter (DOM) and on the average store more carbon than forests managed on a shorter harvest cycle (Krankina and Harmon, 2006). The choice of harvest age will also affect the stock of carbon stored in wood products. There may be an advantage to choosing a harvest age that provides a larger mean annual increment (MAI), and therefore more lumber production, if the carbon storage potential of wood products is taken into account. The amount of carbon in wood products is reduced if the wood product mix shifts towards products such as pulpwood and fuelwood. Also management practices favouring higher harvesting frequency affects carbon storage in wood products. This is because the choice of harvest age affects harvest volume.

At the stand level, authors such as Hoen (1994), van Kooten et al. (1995), Hoen and Solberg (1997), and Stainback and Alavalapati (2002) have investigated the impact of carbon tax and subsidy schemes on the optimal harvest age for even-aged management. In these models landowners are paid a subsidy for periodic carbon uptake in living biomass and taxed when carbon is released through harvest or decay. The models developed in the above studies are essentially variations on the Hartman (1976) model, which includes non-timber benefits. These models demonstrate that carbon taxes and subsidies will affect the optimal forest harvest age and, consequently, the carbon stored in forests. Other authors have adapted the Hartman model to investigate the impact of carbon price on the optimal harvest age and the amount of sequestered carbon. Englin and Callaway (1995) examined the impact of carbon price on the optimal harvest age of Douglas-fir and concluded that rotation age increases with increasing carbon price. Plantinga and Birdsey (1994) used an analytical model in the framework of Hartman (1976) to show that with carbon benefits only in the analysis, the harvest age was infinite in most cases and with carbon and timber, the harvest age would be between the carbon only and the timber only harvest age. Using eucalyptus plantations in Australia, Enzinger and Jeffs (2000) also showed that with carbon payments the optimal harvest age is longer compared to when the eucalyptus plantations is managed for timber only.

Although these studies have contributed to our understanding of the relationship between optimal harvest age and carbon storage in forests, they are based on relatively simple forest economics models that integrate the net revenues generated by timber harvests and economic benefits of carbon sequestration in live biomass only.

They fail to account for carbon storage in DOM or wood product pools. Carbon storage in the DOM pool represents a substantial proportion of the total carbon stored in forest stands and management decisions such a harvest age can have a substantial effect on soil carbon stocks (Aber et al., 1978; Kaipainen et al., 2004). Chapters 2 of this thesis demonstrates that the optimal management policy can be substantially different between cases where the market considers and ignores carbon in the DOM pool. It is also important to consider the wood product pool because wood products play an important role in climate change mitigation strategies by slowing the rate of increase in atmospheric CO_2 concentration. The carbon in the wood product pool is affected by the choice of harvest age as it directly affects harvest volume. The harvest age also affects the size and distribution of logs in the stand and therefore the product mix (Krankina and Harmon, 2006).

Gutrich and Howarth (2007) build on the the previous work of (Hoen, 1994; van Kooten et al., 1995; Hoen and Solberg, 1997) by developing a simulation model of the economics of timber and carbon management for five different forest types in New Hampshire, USA. Their model includes representation of carbon stored in live biomass, dead and downed wood, soil carbon, and wood products. The results of their study show that harvest ages increase when social benefits of carbon storage are included in a model.

The study presented here builds on the work of previous studies. It incorporates carbon stored in live biomass, DOM, and wood product pools. This study differs from the work of Gutrich and Howarth (2007) because it uses an analytical model to verify the relationship between optimal harvest age and amount of carbon stocks in the DOM and wood product pools. The analytical model is used to find the optimal stand management policy when both timber harvest and carbon sequestration values are considered. The main objectives of this study are:

1. investigate the relationship between the optimal harvest age and stocks of carbon in biomass, DOM and wood product pools, and

2. compare harvest ages under different carbon management policy types.

5.2 The Analytical Model

The analytical model assumes that the landowner's objective is to determine the optimal harvest age, T, that maximizes the net present value (NPV) of timber and carbon sequestration values. To simplify this analysis, it is also assumed that the forest is managed under a single harvest cycle and the cycle of establishment, growth, and harvest is not repeated after the first harvest. This assumption is made because, as shown later in this chapter, the optimal harvest age is dependent on the starting DOM and/or wood product stocks, which means that we can have different harvest ages for the different starting conditions. This makes it difficult to build an analytical model based on multiple rotations.

The parameter of this model considers a timber selling price of P^w (CAD/m^3), a market interest rate of ρ (%), amount of timber growing on a stand at time t as $V(t)$ in m^3 and T as the harvest age in years. $V(t)$ in this study is estimated using the Chapman-Richards growth function, $V(t) = v_1(1 - e^{-v_2 t})^{v_3}$, in which v_1, v_2 and v_3 are parameters, which were set at 500.4, 0.027 and 4.003 respectively. C^a is used to represent area based costs (CAD/ha) and C^v to represent volume based costs (CAD/m^3). The total harvesting and processing costs at harvest age, T is calculated as $C^a + C^v V(T)$. The establishment cost is represented by C^e (CAD/ha).

5.3 Optimal harvest age for a forest stand

What is the optimal harvest age for a forest stand? This question has been debated for more than a century, and numerous competing theories and practices have been developed in attempts to answer it. These theories have used combinations of physical, biological, and economic criteria for determining the optimal harvest age. Economics and other critics argue for economic criteria that maximize discounted net revenue and generally imply shorter rotations (Samuelson, 1976).

In the economics literature, the Faustmann (1849) optimal decision rule for maximizing discounted net revenues is generally accepted as correct. It assumes that the site will stay in forest production in perpetuity so that there is an explicit awareness of the effect that present decisions have on future possibilities. Maximization of net present value (NPV) for a single harvest cycle was proposed by Fisher (1930) as the optimal criterion for forestry harvest age determination. The NPV of a single harvest cycle is maximized when the time productivity of the "timber capital" - the capital value of standing timber is equal to the rate of interest. Fisher's criterion assumes that the landowner will maximize NPV of the forest investment in one harvest cycle but does not account for the NPVs of repeated cycles, whose sum constitutes the value of bare forest land. It is generally accepted that Faustmann's model is more correct than Fisher's model, but close enough for discussion here, due to the difficulties with the possibility of multiple harvest ages as the DOM and/or wood product pool changes.

5.3.1 NPV of a single harvest cycle (timber only)

The net present value of one harvest cycle considering only timber (NPV_t) harvest at age T is presented in equation (5.1). The NPV is simply the discounted returns less the discounted costs.

$$NPV_t = \left(P^w V[T] - C^v V[T] - C^a\right) e^{-\rho T} - C^e \tag{5.1}$$

The first order condition for the optimal harvest age for timber only can be found by differentiating equation (5.1) with respect to harvest age T, and setting the result to zero. The aim here is to maximize the annual economic net yield over a harvest cycle. The results of the maximization is

$$\frac{d}{dt} NPV_t = e^{-\rho T} \left(C^a \rho + (C^v - P^w)\left(\rho V[T] - V'[T]\right)\right) = 0 \tag{5.2}$$

where $V'[T] = dV/dT$. Rearranging the terms yields the first-order necessary condition for an optimum:

$$\left(P^w - C^v\right) V'[T] = \rho \left[\left(P^w - C^v\right) V[T] - C^a\right] \tag{5.3}$$

Equation (5.3) can be interpreted as equating the marginal benefit (left hand side) to the marginal cost (right hand side) of leaving the stand to grow for another year. The marginal benefit of leaving the stand to grow is the additional value from timber growth, $\left(P^w - C^v\right) V'[T]$. The marginal cost, $\rho\left[\left(P^w - C^v\right) V[T] - C^a\right]$, represents the cost of holding the growing stock for an additional year - the amount of interest payments the landowner would get if he/she sells the stand at year t and invests the money at interest rate ρ for one year. The result can be seen intuitively since it implies that the landowner will maintain the trees while they are providing returns above the obtainable interest rate, and harvest them before the yield of the forest investment falls below the market rate. When the marginal benefit of leaving the stand to grow one more year is greater than the marginal cost of doing so, the optimal decision is to leave the stand uncut. On the other hand, when the marginal benefit of leaving the stand to grow another year is less than the cost of doing so, the optimal decision is to harvest the stand.

5.4 Carbon sequestration and harvesting emissions

The total carbon stored $C[t]$ at any given time t, measured in tonnes per hectare is defined in equation (5.4) as the sum of carbon storage in the biomass, DOM and wood product pools.

$$C[t] = B[t] + D[t] + Z[t] \tag{5.4}$$

where $B[t]$ represents total carbon sequestered in tC/ha in the living biomass at stand age t; $D[t]$ measures the total carbon sequestered in DOM pool at time t and $Z[t]$ represents carbon stored in wood product pool at time t.

The objective in the sections that follow is to determine the optimal harvest age, T, that maximizes the NPV of carbon sequestration values in the biomass, DOM and wood product pools and combine the results with the NPV of timber only.

5.4.1 NPV of a single harvest cycle (biomass only)

For the biomass pool, change in carbon storage at any given time is defined as $B'[t]$, where $B'[t] = dB/dt$. The carbon credit at any given moment t is $P^c B'[t]$. Consequently the present value, at the time of harvest will be the sum of the present values of all the instantaneous revenues over harvest age T: $\int_0^T P^c B'[t] e^{-\rho t}\, dt$. where P^c is the price of carbon (CAD/tC). When timber harvest occurs, the merchantable timber volume is removed from the site and processed into lumber and wood chips. The roots, stumps, tops, branches and leaves are assumed to die at the time of harvest and become part of the DOM pool. When harvest occurs, there is a carbon emission charge which is equal to $P^c B[T] e^{-\rho T}$.

The net present value NPV_b of carbon benefits from biomass only (CAD/ha) over a single harvest cycle can then be represented as:

$$NPV_b = -P^c B[T] e^{-\rho T} + \int_0^T P^c B'[t] e^{-\rho t}\, dt. \tag{5.5}$$

5.4.2 NPV of a single harvest cycle (Timber and Biomass)

The net present value NPV_1 of the combined timber and biomass in dollars per hectare over one rotation can then be defined as:

$$NPV_1 = NPV_t + NPV_b \tag{5.6}$$

The optimal rotation age for managing for both timber and biomass can be found by finding the first order conditions of equation (5.6) with respect to T and setting the result equal to zero.

$$\frac{d}{dt} NPV_1 = e^{-\rho T}\left(C^a \rho + (C^v - P^w)\left(\rho V[T] - V'[T]\right)\right) - \rho P^c B[T] e^{-\rho T} = 0 \tag{5.7}$$

Rearranging the terms will yield the first-order necessary condition for an optimum:

$$(P^w - C^v)\, V'[T] = \rho\left[(P^w - C^v)\, V[T] - C^a - P^c B[T]\right] \tag{5.8}$$

Equation (5.8) can be interpreted as equating the marginal benefit (left hand side) to the marginal cost (right hand side) of leaving the stand to grow for another year. The marginal benefit of leaving the stand to grow is the additional value from timber growth, $(P^w - C^v)\, V'[T]$. The marginal cost, $\rho\left[(P^w - C^v)\, V[T] - C^a - P^c B[T]\right]$, represents the cost of holding the growing stock, $\rho\left[(P^w - C^v)\, V[T] - C^a\right]$ adjusted by the interest that could be earned on biomass removed from the forest, $\rho P^c B[T]$.

5.4.3 NPV of a single harvest cycle (DOM only)

Another Chapman-Richards function is estimated to represent the biomass carbon pool as a function of stand age: $B(t) = b_1(1 - e^{-b_2 t})^{b_3}$, where $B(t)$ is the mass of carbon in tC/ha, stored in the living trees at age t, and b_1, b_2 , and b_3 are coefficients set at 198.6, 0.0253, and 2.64 respectively. Three processes are assumed to affect the development of the DOM pool: decay, litterfall, and harvest. DOM is assumed to decay at a rate, α. DOM is added to the pool as the proportion of the biomass of the stand that dies naturally each year. This proportion is expressed as the litterfall rate, β.

At any given moment t, the amount of carbon in the DOM pool $D[t]$ is defined as:

$$D[t] = e^{-t\alpha}\left(D\left[0\right] + \int_0^t e^{\alpha k}\beta B\left[k\right]\, dk\right) \tag{5.9}$$

where $D[0]$ is the initial amount of carbon in the DOM pool, When timber harvest occurs, the merchantable timber volume is removed from the site and processed into lumber and wood chips. The roots, stumps, tops, branches and leaves are assumed to die at the time of harvest and become part of the DOM pool. The mass of carbon removed from the site as merchantable timber volume is calculated as $\gamma V[T]$, where γ is a constant used to convert wood volume to the mass of carbon stored in wood. The net present value NPV_d of carbon benefits from DOM only (CAD/ha) over one harvest cycle can then be represented as:

$$NPV_d = P^c e^{-\rho T}\left(\int_0^T e^{-t\alpha}\left(D\left[0\right] + \int_0^t e^{\alpha k}\beta B\left[k\right]\, dk\right) dt + B[T] - \gamma V[T]\right) \tag{5.10}$$

5.4.4 NPV of a single harvest cycle (Timber, Biomass and DOM)

The net present value NPV_2 of the combined timber, biomass and DOM in dollars per hectare over one rotation can then be defined as:

$$NPV_2 = NPV_1 + NPV_d \tag{5.11}$$

The optimal rotation age for managing for timber, biomass and DOM combined can be found by finding the first order conditions of equation (5.11) with respect to T. The first-order necessary condition becomes:

$$\left(P^w - C^v\right) V'[T] + P^c B'[T] - P^c \gamma V'[T] = \rho\left[\left(P^w - C^v\right) V[T] - C^a\right] - \rho P^c \gamma V[T]$$
$$+\rho P^c \int_0^T e^{-t\alpha}\left(D[0] + \int_0^t \beta B[k] e^{\alpha k}\, dk\right) dt +$$
$$P^c e^{-T\alpha}\left(\int_0^T \beta B(k)\, e^{\alpha k}\, dk - D[0]\right) \tag{5.12}$$

Equation (5.12) can be interpreted as equating the marginal benefit (left hand side) to the marginal cost (right hand side) of leaving the stand to grow for another year. The marginal benefit of leaving the stand to grow is made up of the additional value from timber growth, $(P^w - C^v)V'[T]$), plus the marginal gain in the value of carbon stored in the biomass pool, $P^c B'[T]$, adjusted by the marginal gain in carbon removed from the site as merchantable timber volume, $P^c \gamma V'[T]$. The marginal cost is the forgone interest on timber value, $\rho\left[\left(P^w - C^v\right) V[T] - C^a\right]$, adjusted by the interest that could be earned on carbon removed from the site as merchantable timber volume, $\rho P^c \gamma V[T]$, plus the interest that could be earned on the stock changes in the DOM pool (third term on the right hand side), plus the values of the stock changes in the DOM pool (last term on the right hand side).

Equation (5.12), shows that the optimal harvest age, T depends on the initial stock of carbon in the DOM pool, $D[0]$. This finding is consistent with the results in chapter 2 which suggests that with different initial DOM stocks, the optimal harvest age can be different for the first harvest cycle but an equilibrium harvest age is reached after a number of harvest cycles (refer to Fig. 2.4 in Chapter 2).

5.4.5 NPV of a single harvest cycle(wood product only)

The wood product pools are represented by a single pool with a single annual decay rate of θ. The dynamics of the carbon in the wood product pool is represented by equation. 5.13.

$$Z[t] = Z[0] - \int_0^t \theta Z[x]\,dx. \tag{5.13}$$

where Z[0] is the initial amount of carbon in the wood product pool.

The net present value, NPV_w of carbon benefits from wood product pool only (CAD/ha) over one rotation can then be represented as:

$$NPV_w = P^c \lambda \gamma V[T] e^{-\rho t} + \int_0^T \frac{d(Z[t])}{dt} (P^c e^{-\rho t})\,dt. \tag{5.14}$$

where λ is the constant used to convert timber volume into wood product volume.

5.4.6 NPV of a single harvest cycle (timber and all carbon pools)

The net present value NPV_3 of the combined timber and total carbon storage (biomass, DOM and wood product) in dollars per hectare over one rotation can then be defined as:

$$NPV_3 = NPV_2 + NPV_w \tag{5.15}$$

The optimal rotation age for managing for both timber and carbon values (biomass, DOM and wood product) can be found by finding the first order conditions of equation (5.15) with respect to T. The first-order necessary condition becomes:

$$\begin{aligned}
&(P^w - C^v)\,V'[T] + P^c B'[T] + P^c \gamma \lambda V'[T] - P^c \gamma V'[T] = \\
&\rho\left[(P^w - C^v)\,V[T] - C^a\right] + \rho P^c \gamma \lambda V[T] - \rho P^c \gamma V[T] + P^c e^{-\rho T} \theta Z[0] \\
&+\rho P^c \int_0^T e^{-t\alpha} \left(D[0] + \int_0^t \beta B(k)\, e^{\alpha k}\, dk \right) dt + \\
&P^c e^{-T\alpha} \left(\int_0^T \beta B(k)\, e^{\alpha k}\, dk - D[0] \right)
\end{aligned} \tag{5.16}$$

This condition equation (5.16) can again be interpreted as equating the marginal benefit (left hand side) to the marginal cost (right hand side) of leaving the stand to grow for another year. The marginal benefit of leaving the stand to grow is made up of the additional value from timber growth, $(P^w - F^v)V'[T])$, plus the marginal gain in the value of carbon stored in the biomass pool, $P^cB'[T]$, plus the marginal gain in the value of carbon stored in wood product, $P^c\gamma\lambda V'[T]$, adjusted by the marginal value of the carbon removed from the site as merchantable timber volume,$P^c\gamma V'[T]$. The marginal cost is the forgone interest on timber value, $\rho\left[(P^w - F^v)\, V[T] - C^a\right]$, plus the interest that could be earned on carbon storage in wood product, $\rho P^{-c}\gamma\lambda V\,[T]$, adjusted by the interest that could be earned on the carbon removed from the site as merchantable timber volume, $\rho P^c\gamma V[T]$, plus the initial value of carbon storage in the product pool, $P^ce^{-\rho T}\theta Z\,[0]$, plus the interest that could be earned on the stock changes in the DOM pool (fifth term on the right hand side), plus the values of the stock changes in the DOM pool (last term on the right hand side).

Equation (5.16), shows that the optimal harvest age, T depends on the initial DOM, $(D[0])$ and initial wood product, $(Z[0])$ stocks.

5.5 Results and Discussion (Base case scenario)

The analytical model presented above is used to determine the optimal harvest policy for a profit-maximizing landowner managing a forest stand for production of wood volume and sequestration of CO_2. The main objectives of this study are to determine if the optimal harvest decision is dependent on the DOM and wood product stocks. In addition, the study compares optimal harvest ages for a scenario where carbon sequestration services have value to the landowner and one where carbon sequestration services have no value to the landowner (i.e. $P^c = 0$).

5.5.1 Comparative static analysis

This section compares the optimal harvest age, T for the different management strategies considered in this study. To allow for easy comparison of optimal harvest ages for a scenario where carbon sequestration services have value to the landowner and one where carbon sequestration services have no value to the landowner, the first-order necessary condition for an optimum in the above equations can be rearranged so the ρ occurs on the left hand side of all equations.

Managing for Timber only

The base case scenario for the comparative static analysis is the case where carbon sequestration services have no value to the landowner. For this scenario, equation (5.3) is rewritten as:

$$\rho = \frac{(P^w - C^v)V'[T]}{(P^w - C^v)V[T] - C^a} \tag{5.17}$$

The right hand side of equation (5.17) is referred to as the relative growth rate for the timber only scenario (Clark, 1976). The optimal harvest age as a function of age T for a given forest stand can easily be obtained from the relationship between the discount rate ρ and the relative growth rate. An increase in the relative growth rate, shifts the curve upward and thus lengthens the harvest age T (Clark, 1976).

To simplify the comparison between the scenarios, let $X[T]$ represent the numerator, $(P^w - C^v)V'[T]$ on the right hand side of equation (5.17), and $Y[T]$ represent the denominator, $(P^w - C^v)V[T] - C^a$ on the right hand side of equation (5.17). Therefore equation (5.17) can be rewritten as:

$$\rho = \frac{X[T]}{Y[T]} \tag{5.18}$$

Managing for Timber and Carbon sequestration in Biomass

The static comparative analysis begins by comparing the optimal harvest age when carbon sequestration services have no value to the landowner, and the scenario where carbon sequestration services have value to the landowner, and only the biomass pool is considered. For this scenario, the first-order necessary condition for an optimum, equation (5.8) is rewritten as:

$$\rho = \frac{(P^w - C^v)V'[T]}{(P^w - C^v)V[T] - P^c B[T] - C^a} \tag{5.19}$$

Equation (5.19) can be simplified as:

$$\rho = \frac{X[T]}{Y[T] - P^c B[T]} \tag{5.20}$$

Comparing equations (5.18) and (5.20), it can be said that the denominator of equation (5.20) is smaller, thus increasing the value on the right hand side (relative growth rate) of equation (5.20). An increase in the relative growth rate shifts the curve upward and therefore increases the harvest age. Hence, the optimal harvest age for the scenario that considers timber value and carbon stock changes in the biomass pool, is longer than the harvest age for the scenario that considers timber only.

When the price of carbon, P^c increases, the factor $P^c B[T]$ also increases resulting in a corresponding increase in the relative growth rate. It can therefore be concluded that increasing carbon price results in a longer harvest age.

Managing for Timber and Carbon sequestration in Biomass and DOM

In this section, the optimal harvest age when carbon sequestration services have no value to the landowner is compared to the scenario where carbon sequestration services have value to the landowner, and the carbon accounting method considers carbon stock changes in both the biomass and DOM pools. Under this scenario, equation (5.12) is rearranged and presented as equation (5.21) below:

$$\rho = \frac{X[T] + P^c\left(B'[T] - \gamma V'[T] - e^{-T\alpha}\left(\int_0^T \beta B(k)\, e^{\alpha k}\, dk - D[0]\right)\right)}{Y[T] - P^c\left(\gamma V[T] + \int_0^T e^{-t\alpha}\left(D[0] + \int_0^t \beta B(k)\, e^{\alpha k}\, dk\right) dt\right)} \tag{5.21}$$

From equations (5.18) and (5.21), the direction of the effect of DOM on T is unclear. It is ambiguous to say which of the two right hand sides is bigger. This is because, although $Y[T]$ is reduced by $P^c\gamma V[T]$, it is also increased by the last term in the denominator. Similarly, although $X[T]$ is increased by $P^c B'[T]$, it is also reduced by $P^c\gamma V'[T]$ and the last term in the numerator. It can therefore be concluded from the analytical model that it is ambiguous to tell the effect DOM on T.

From equation (5.21), it is also ambiguous to tell the effect of increasing carbon price, P^c on harvest age, T. This finding contrasts with results of previous studies that suggest that including carbon sequestration benefits will necessarily increase the optimal harvest age (Hoen, 1994; Englin and Callaway, 1995; Hoen and Solberg, 1997; Stainback and Alavalapati, 2002).

Equation (5.21) also shows that the optimal harvest age depends on the starting DOM stock, $D[0]$. Increasing $D[0]$ has the effect of decreasing the relative growth rate and therefore decreasing the harvest age. This is because an increase in $D[0]$ decreases the numerator, and increases the denominator at the same time. This finding is consistent with the findings in Chapter 2 of this thesis, which shows that the optimal harvest age is older if a landowner begins with a lower initial DOM stock.

Managing for Timber and Carbon storage in Biomass, DOM and Harvested Wood Product

Finally, a comparison is made between the optimal harvest age for the case where carbon sequestration services have no value to the landowner, and the scenario where carbon sequestration services have value to the landowner. Here, the carbon accounting method considers stock changes in all three major carbon pools (biomass, DOM and harvested wood product pools). In this scenario, equation (5.16) is rewritten as:

$$\rho = \frac{X[T] + P^c\left(B'[T] + \gamma\lambda V'[T] - \gamma V'[T] - e^{-T\theta}P^c\theta Z[0]\right)}{Y[T] + P^c\left(\gamma\lambda V[T] - \gamma V[T] + \int_0^T e^{-t\alpha}\left(D[0] + \int_0^t \beta B(k)\, e^{\alpha k}\, dk\right) dt\right)} + \frac{-P^c e^{-T\alpha}\left(\int_0^T \beta B(k)\, e^{\alpha k}\, dk - D[0]\right)}{Y[T] + P^c\left(\gamma\lambda V[T] - \gamma V[T] + \int_0^T e^{-t\alpha}\left(D[0] + \int_0^t \beta B(k)\, e^{\alpha k}\, dk\right) dt\right)} \tag{5.22}$$

By comparing the right hand side of equation (5.18) to the right hand side of equation (5.22), it unclear to say which of the two right hand sides is bigger and therefore which of the two management scenarios will produce a longer harvest age. It is also ambiguous the tell from equation (5.22), the effect of increasing P^c on the optimal harvest age, T.

From equation (5.22), it can be said that the optimal harvest age is dependent on both the starting DOM stock, $D[0]$ and the starting wood product stock, $Z[0]$. Equation (5.22) reveals that increasing $Z[0]$, causes the right hand side (i.e., relative growth rate) to decrease, thus causing the optimal harvest age T, to decrease. This finding is consistent with the results in Chapter 3 of this thesis. This is because the amount of CO_2 released to the atmosphere through decay is higher with higher wood product stocks. Hence, higher financial penalty is associated with higher wood product stocks. Therefore, at higher wood product stocks it is optimal to harvest early to minimize the financial penalties.

Equation (5.22) again confirms that the optimal harvest age depends on the starting DOM stock $D[0]$. Increasing $D[0]$ has the effect of decreasing the relative growth rate and therefore decreasing the harvest age. This finding is consistent with the findings in Chapter 2 of this thesis, which shows that the optimal harvest age is older if a landowner begins with a lower initial DOM stock. This happens because the amount of CO_2 released to the atmosphere through decay is lower with lower DOM stocks: the marginal gain in CO_2 sequestration from delaying harvest is greater with lower DOM stocks.

5.5.2 Empirical example

The results derived above are applied to the determination of the harvest age of a lodgepole pine stand in the BWBS biogeoclimatic zone, in the Dawson Creek Forest District of the Prince George Forest Region of British Columbia, Canada. The timber yield and the cost information used in this study come from the TIPSY growth and yield simulator (BC MoFR, 2007) developed and used by the British Columbia Ministry of Forests and Range for use as input to forest management plans.

All costs and prices in this section are expressed in Canadian dollars (CAD). A derived residual value approach (Davis et al., 2001, pp. 418–427) is used to estimate the net value of timber harvest. The residual value is the selling price of the final products (in this case lumber and pulp chips) less the costs of converting standing trees into the final products, expressed in CAD/m^3 of merchantable timber.

The average lumber price of kiln dried, standard and better, western spruce-pine-fir, 2×4 random length lumber for the period April 1999 to March 2008 was approximately 375 CAD/thousand board feet (MBF) (BC MoFR, 2009). The price of wood chips was assumed to be 70 CAD/bone dry unit (BDU), with chip recovery factor as 0.152 BDU per cubic metre and lumber recovery factor as 0.210 MBF per cubic metre. The base selling price of the final products expressed in equivalent roundwood input terms was calculated as 89.40 CAD/m^3.

The cost of converting standing trees into end products is the sum of all costs associated with harvesting, hauling, and milling. Road construction and harvesting costs reported by TIPSY for the pine stand were 1,150 and 5,100 CAD/ha. Log hauling, milling and overhead costs as 4.84, 34.65, and 8.06 CAD/m^3 respectively. Based on the costs used here, C^a was set to 6,250 CAD/ha and C^v to 47.55 CAD/m^3. The established cost, C^e, is set to 1,250 CAD/ha, based on the default parameters used by TIPSY.

The price of permanent carbon credits traded on European Climate Exchange (ECX) between January 2005 and April 2008 ranged from 10 to 45 CAD/tCO_2 (Point Carbon, 2009). Prices for carbon credits traded on the Chicago Climate Exchange (CCX) for the same time period ranged from 1 to 5 CAD/tCO_2 (CCX, 2009). For the purpose of this study the base carbon price was set as 10 CAD/tCO_2.

Before employing an empirical method to compare harvest ages between the different management strategies, it is necessary to compare the harvest ages for a stand managed exclusively for timber management under single harvest cycle and one managed on a multiple harvest cycle provided by Faustmann's model. The marginal growth rate for the multiple harvest cycle is defined by the right hand side of equation (5.23) as shown below (Clark, 1976):

$$\frac{\rho}{1-e^{-\rho T}} = \frac{(P^w - C^v)V'[T]}{(P^w - C^v)V[T] - C^a - C^e} \tag{5.23}$$

Comparing the right hand side of equation (5.17) to the right hand side of equation (5.23), it can be said that the right hand side of equation (5.23) is bigger because of the establishment cost, C^e. Therefore the Faustmann's model is expected to have a longer rotation age. However, comparison of the left hand side shows that the Faustmann's model introduces an additional factor $1 - e^{-\rho T}$ in the denominator. Because $1 - e^{-\rho T} < 1$, the left hand side of equation (5.23) is bigger. A higher discount rate means that the optimal harvest age will be younger for the Faustmann's model compared to the Fisher's model (equation 5.17). Generally, when the soil expectation value (SEV) is positive, the harvest age for the multiple harvest cycle is expected to be shorter than the harvest age for the single cycle. The reverse is true for a negative SEV.

Harvest age as a function of stand age T for a forest stand can also be obtained numerically by using the graph in figure 5.1. The family of curves in figure 5.1 were generated using equations 5.17 and 5.23.

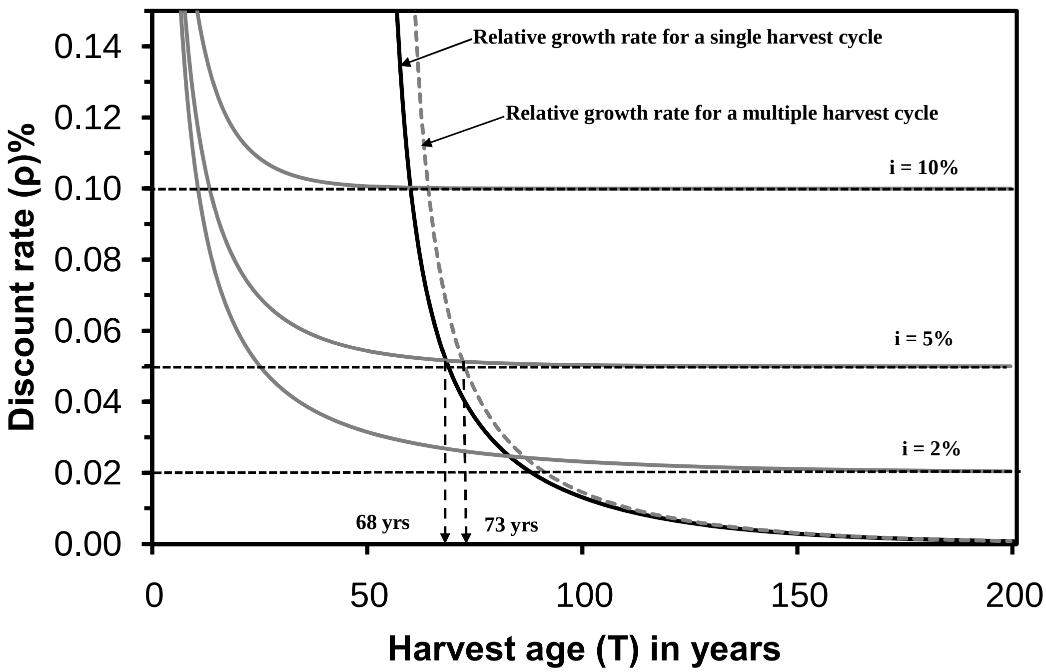
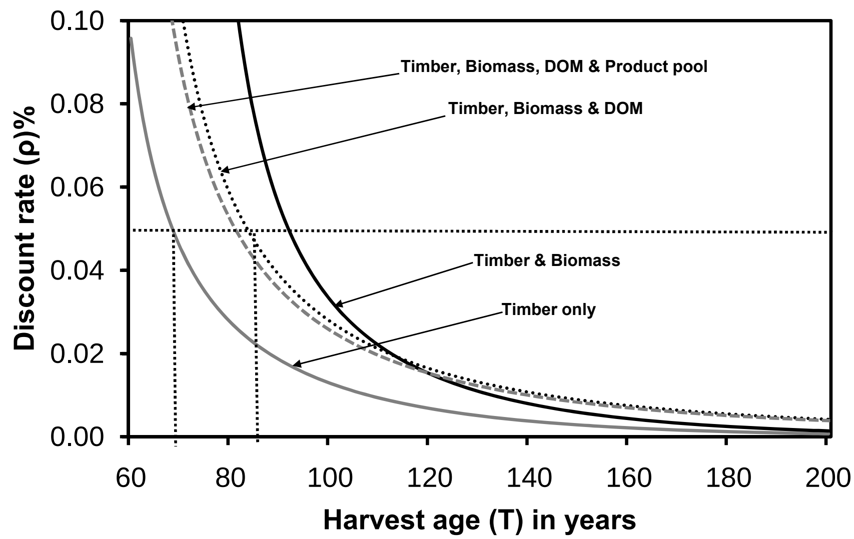


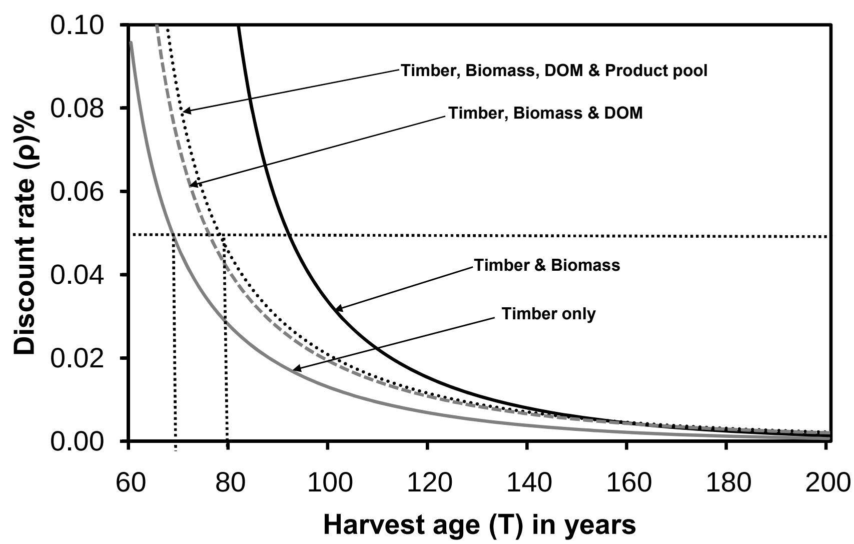
Figure 5.1: Graphical determination of harvest age. i is the annual discount rate. For a discount rate of 5%, the harvset age is 68 years for the single rotation and 73 years for the multiple model

The optimal harvest age is the age where the left hand side of equations 5.17 and 5.23, equals the right hand side. The results displayed in figure 5.1 show that for a discount rate of 5%, the harvset age is 68 years for the Fisher's model and 73 years for the Faustmann's model. The results are close enough for the discussion in this study.

The results show an inverse relationship between annual discount rate and harvest age. It can be seen that the harvest age is shorter when the annual discount rate increases. This is because when the annual discount rate is increased, the cost of leaving the stand to grow another year becomes more expensive, hence the landowner is better off harvesting the stand early, and investing in an alternative investment that will yield better returns. A rise in interest rate also acts to reduce the present



(a) Initial DOM stock = 25t C/ha and Initial stand age = 0yrs



(b) Initial DOM stock = 370 tC/ha and Initial stand age = 0yrs

Figure 5.2: A graphical representation of the relationship between discount rate and harvest age for different carbon management strategies. For an annual discount rate of 5% and a carbon price of 36.67 CAD/tC, panel (a) shows that the harvest age is 68 years when the stand is managed exclusively for timber and 84 years when the stand is managed for timber and carbon, and panel(b) shows that the harvest age is 68 years when the stand is managed exclusively for timber and 80 years when the stand is managed for timber and carbon.

value of the stand because the income stream is being more heavily discounted. Figure 5.1 shows that for an annual discount rate of 5% the harvest age is 68 years when the stand is managed exclusively for timber on a single harvest cycle and 73 years on a multiple harvest cycle.

To compare harvest ages under different carbon management strategies using numerical analysis, a number of scenarios has been investigated, based on different starting DOM carbon stocks and carbon price. Some of the results are summarized in figure 5.2. As a reference point, the base case scenario deals with carbon management strategy in which carbon sequestration services have no value to the landowner. Discussion of the results is limited to $P^c = 36.67$ CAD/tC (which is equivalent to 10 CAD/tCO_2), and only two starting conditions of DOM carbon stocks, since similar patterns were observed with other starting conditions and carbon prices. Also, changing the starting conditions for the wood product pool produced similar results. Panel (a) of figure 5.2 shows the results of the case where the initial stand age is 0 years and the initial DOM stock is 25 tC/ha and panel (b) shows the results of the scenario where the initial stand age is 0 years and the initial DOM stock is 370 tC/ha.

In the range of the scenarios that were analyzed, the empirical analysis generally show that for any given annual discount rate, the carbon management strategy produces a longer rotation age compared to the base case scenario. For example at an annual discount rate of 5% and a carbon price of 10 CAD/tCO_2, panel (a) shows that the harvest age is 68 years when the stand is managed exclusively for timber and 84 years when the stand is managed for timber and carbon, and the carbon accounting method considers for stock changes in the biomass and DOM pools.

The empirical analysis also reveal that the harvest age is dependent on the carbon stocks in the DOM and wood product pools. This is because as revealed in figure 5.2, for any given annual discount rate, the harvest age is different for the different carbon accounting methods. Figure 5.2 also reveal that the optimal harvest age is younger in the case when both DOM carbon and the wood product carbon are considered in carbon accounting compared to the case when the wood product carbon is ignored. This happens because the absolute amount of CO_2 released to the atmosphere through decay is greater when both DOM carbon and the wood product carbon are considered. As more CO_2 is released, there is little incentive to delay harvest because the the marginal gain in timber revenue from leaving trees in the stand may not be enough to compensate for the repayment of carbon loss associated with the decay. Harvesting is done early to minimize financial penalty.

Furthermore, it is interesting to observe from figure 5.2 that the harvest age depends on the starting DOM carbon stock. Panel (a) shows that the harvest age is about 84 years when the stand is managed for timber, biomass and DOM carbon stocks, and the initial DOM stock at 25 tC/ha. On the other hand, panel (b) shows that the harvest age is about 80 years when the stand is managed for timber, biomass and DOM carbon stocks, and the initial DOM stock at 370 tC/ha. This happens because with a lower starting DOM stock, the amount of CO_2 released to the atmosphere through decay is lower: the marginal gain in CO_2 sequestration from delaying harvest is greater with lower DOM stocks. This important finding is also another justification for using a single harvest cycle in this analytical model of carbon sequestration as opposed a multiple harvest cycles.

Finally, figure 5.2 shows that, generally for a given discount rate, the harvest age is longer when the DOM and the wood product carbon stocks are ignored compared to when they are considered in the carbon accounting method. This finding further supports the results in Chapter 2 and 3 of this thesis that show that the optimal harvest age is older when the DOM and wood product pools are ignored. It is interesting to note that the trends displayed in figure (5.2), however, are not consistent over the full range of annual discount rates. Panel (a) of figure (5.2) shows that when the annual discount rate is below 2% and the initial DOM stock is 25 tC/ha, the accounting method that considers all three carbon pools and the method that ignores only the wood product pool, shift upwards compared to the curve that considers only the biomass pool. In other words the harvest age is younger when the two carbon pools (DOM and wood product) are ignored. This is interesting because it contradicts the findings in Chapters 2 and 3 of this thesis.

5.6 Conclusions

In this study an analytical model of carbon sequestration in biomass, DOM and wood product pools used to determine the optimal harvest decision for a forest stand that provides both timber harvest volume and carbon sequestration services is presented. To the best of my knowledge, this is the first study of its kind to use an analytical model to examine the impact of DOM and wood product carbon stocks on the optimal decision to harvest.

The model is used to examine optimal harvest decisions for a lodgepole pine stand in the boreal forest of western Canada. The following main conclusions is drawn from the study:

1. The harvest age is dependent on the initial DOM and initial wood product stocks,

2. For the analytical model presented in this study, the optimal harvest age is older for a case that that considers only carbon stock changes in the biomass pools, compared to the case where the stand is managed exclusively for timber production,

3. The analytical method also reveal that increasing carbon price has an ambiguous effect on the optimal harvest age if the carbon accounting method considers stock changes in the DOM pool.

4. Based on the parameters used in the numerical examples, it was shown that for a given annual discount rate, the harvest age is older for the scenario where carbon sequestration services have value to the landowner compared to the case where carbon sequestration services have no value to the landowner. In general, the oldest harvest age is the case that ignored both the DOM and wood product pools and the youngest is the case that considered all three carbon pools. However, this is not consistent over the full range of annual discount rates, particularly at low discount rates.

The general results reported here can be expected to differ from those reported in other stand-level models (*e.g.* van Kooten et al. (1995), Hoen and Solberg (1997), Stainback and Alavalapati (2002)) because it is recognized that a forest stand has both carbon sink (the living biomass) and carbon source (the DOM and wood product pools) components. The results can also be expected to differ from other analyses because of the way stock changes are calculated. For example, McCarney et al. (2008) calculates stock change as the difference between the project's carbon stock and the "business-as-usual" (BAU) carbon stock at a particular point in time. The BAU carbon stocks is the estimated amount of carbon stocks that would have occurred without a project. Here, stock changes are calculated as the periodic change in the project's carbon stocks at a given time, less the periodic changes in the baseline carbon stocks. This study only considered a fixed baseline in calculating carbon stock changes. This is because with a fixed baseline, the periodic change in the baseline stocks is zero and that makes the mathematics easy to solve. With a BAU baseline, the "spikes" in the baseline carbon stocks makes it impractical to compare different management options with different harvest ages.

Finally, it is probable that a global initiative to deal with climate change will utilize some form of carbon credit and an associated recognition for carbon sequestration activities. This means that valuable directions for further study should include extending the model presented here to include the impact of factors such as fertilization, site preparation and tree improvement on optimal harvest age, if the landowner's objective is the maximize NPV from timber and carbon.

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CHAPTER 6

Discussion and Conclusions

This thesis presents four studies related to the economics of carbon sequestration. In the first study (Chapter 2), the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) is approximated using two carbon pools (biomass and DOM) to develop a dynamic programming model of the system which captures the important elements of the system for an economic analysis. The state of the system is described using stand age and the stocks of carbon stored in the DOM pool. The dynamic programming model is used to determine the optimal harvest decision for a forest stand that provides both timber harvest volume and carbon sequestration services. The results of the study show that the optimal decision is sensitive to current stocks of carbon in the DOM pool, especially when carbon prices are high and initial DOM stocks are low. The study also reveals that the optimal management policy can be substantially different between cases where the market considers and ignores carbon in the DOM pool. This raises an interesting issue because the size of the DOM pool is important from a carbon flux standpoint, but is much more difficult to measure than biomass.

The second study (Chapter 3) uses a dynamic programming model with three state variables: stand age and the stocks of carbon stored in the DOM and wood product pools to determine the optimal harvest decision for a forest stand that provides both timber harvest volume and carbon sequestration services. The results show that the optimal harvest decision is sensitive to the current stocks of carbon in the wood product pool, when carbon prices are high and the initial wood product stocks are high. The results from this chapter also reveal that the optimal management policy have little or no impact between cases where the market considers and ignores carbon in the wood product pool or between cases where the market considers and ignores fossil fuel carbon emissions. This raises an interesting concern whether it is worth the extra effort and cost to account for carbon stored in wood products and fossil fuel carbon emissions when the optimal harvest behaviour of the landowner is not likely to change substantially. Policy makers may end up transfering wealth from society to landowners if they allow landowners to account for carbon stored in wood product or fossil carbon emissions with no gain in carbon sequestration

In the third study (Chapter 4), a dynamic programming model that considers four state variables is used to demonstrate that alternative baselines have very little effect on optimal decision but can have a effect on financial return to landowner. In effect, behaviour changes little but the size of the transfer of wealth from emitters to landowners is siginificant.

In the last and final study (Chapter 5), an analytical model is used to demonstrate that the optimal harvest decision is dependent on the initial DOM and wood product stocks. This supports the findings in the first three papers. Based on the parameters used in a numerical analysis, I showed that for a given annual discount rate, the harvest age is older for a case where carbon sequestration services have value to the landowner compared to a case where carbon sequestration services have no value to the landowner.

This thesis contributes to the understanding of the economics of forest carbon sequestration at the stand level. The first study builds on the work of van Kooten et al. (1995) by incorporating DOM or soil carbon pool. While Gutrich and Howarth (2007) did include DOM and soil carbon pools in their model, they assumed a fixed initial stock of DOM. The first study extends the Gutrich and Howarth (2007) approach by solving simultaneously for a range of initial DOM stocks. The second study extends the existing literature on the economics of carbon sequestration at the stand level, by demonstrating that accounting for fossil fuel carbon emissions or carbon stored in wood products have little or no impact on the optimal harvest policy. To the best of my knowledge, the third study is the first of its kind to examine the impact of alternative baselines on the optimal harvest age at the stand level. This study reveals that the alternative baselines have little effect on optimal decision but can have a large effect on financial return to landowners. This study will assist policy makers in designing a credible carbon offset project.

All four studies ware carried out using an isolated timber stand, where prices of timber and carbon storage services were determined exogenously. If a large forest area was participating in the carbon market desribed in these studies it would change the timber supply and could affect the prices of timber, which would feed back into the optimal harvest decision. These studies also assume that all prices remain constant, leakage associated with carbon sequestration is not accounted for in any of the studies. If carbon sequestration projects lead to widespread extending of harvest age, it is likely that prices could rise initially if landowners withhold substantial timber from markets. Over the long term, prices could fall if rotations are extended, or they could rise if carbon prices are high enough to cause forest land to be set aside permanently. These considerations are important and could be built into these studies to provide valuable information for policy makers.

There is substantial room for further research. The dynamic programming models presented in this thesis are all deterministic. It would be worthwhile exploring stochastic optimization techniques for application to these models.

Finally, this research did not consider the use of biofuels to replace fossil fuel use nor did it consider the use of wood product in place of other products that generate higher GHG emissions for their manufacture. These are mechanisms by which mitigation benefits may be achieved. Future research could look at optimized timber and carbon values in a forest stand using dynamic programming in a framework where these mitigation benefits are considered.

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APPENDIX A

Appendix to Chapter 2

```
clear all
tic
%% Program control parameters
maxStage=500
maxDOM=500
maxAge=250
nState=(maxDOM+1) * (maxAge+1)

discount_rate = 0.05
discount_factor = 1/(1 + discount_rate)
% logprice  =   15.58 % $/m^3 Lumber Price is 250 CAD/MBF
logprice  =   41.83 % $/m^3 Lumber Price is 375 CAD/MBF
% logprice  =   68.08 % $/m^3 Lumber Price is 500 CAD/MBF
logcost   = 6250% $/ha % (Road:1150 CAD/ha; TTT:5100 CAD/ha)
% (Milling: 34.65 CAD/m3; Haul: 4.84 CAD/m3; Overhead: 8.06 CAD/m3)
estabcost =  1250; % $/ha
%estabcost =  0; % $/ha
co2_c_ratio = (12 + (16 * 2)) / 12;
p_co2 = 10; % $1/Mg CO_2
p_c = p_co2 * co2_c_ratio % $/Mg C

decay = 0.008412 % decay rate for DOM
litterfall = 0.01357 % biomass to DOM conversion rate
wood_C_ratio = 0.2 % (Mg C) / (m^3 merchantable volume)
```

```
%% Function coefficients
% biomass coefficients
b1 = 198.6
b2 = 0.0253
b3 = 2.64
% merchantable volume
v1 = 500.4
v2 = 0.027
v3 = 4.003

%% Save the run control information for later use

save runcontrol.mat maxStage maxDOM maxAge nState discount_rate discount_factor ...
    logprice logcost estabcost co2_c_ratio p_co2 p_c decay litterfall ...
    wood_C_ratio b1 b2 b3 v1 v2 v3

%% State payoff calculations
netRevenueHarvest = zeros(nState,1);
netRevenueNoHarvest = zeros(nState,1);

toAgeHarvest=1;

toStateNoHarvest=zeros(nState,2);
toStateHarvest=zeros(nState,2);

propStateNoHarvest=zeros(nState,2);
propStateHarvest=zeros(nState,2);

for startDOM=0;
 for startAge=0;
for iState=1:nState

  if (mod(iState,10000) == 0)  %print current state to indicate model is running
    iState;
  end

  [age,DOM]=getAgeDOM(iState,maxAge,maxDOM)

  mv = merchvol(age,v1,v2,v3);
```

```
  bm = biomass(age,b1,b2,b3);
  bm1 = biomass(age+1,b1,b2,b3);

  netTimberRevenueHarvest =logprice * mv  - logcost - estabcost;

  deltaBmNoHarvest = bm1 - bm;
  deltaBmHarvest = -bm;

  deltaDOMNoHarvest = (-decay * DOM) + (litterfall * bm);
%   deltaDOMHarvest = deltaDOMNoHarvest + bm - (wood_C_ratio * mv);
  deltaDOMHarvest = (-decay * DOM) + bm - (wood_C_ratio * mv);

%   deltaDOMNoHarvest = 0;
%   deltaDOMHarvest = 0;

  carbonRevenueNoHarvest = p_c * (deltaBmNoHarvest + deltaDOMNoHarvest);
  carbonRevenueHarvest = p_c * (deltaBmHarvest + deltaDOMHarvest);

  netRevenueHarvest(iState,1) = netTimberRevenueHarvest + carbonRevenueHarvest;
  netRevenueNoHarvest(iState,1) = carbonRevenueNoHarvest;

  toAgeNoHarvest=min(age+1,maxAge);

  toDOMNoHarvest=min(DOM+deltaBmNoHarvest+deltaDOMNoHarvest,maxDOM);
  toDOMNoHarvest_lower=fix(toDOMNoHarvest);
  toDOMNoHarvest_upper=min(toDOMNoHarvest_lower+1,maxDOM);

  toStateNoHarvest(iState,1)=stateIndex(toAgeNoHarvest,toDOMNoHarvest_lower,maxAge);
  toStateNoHarvest(iState,2)=stateIndex(toAgeNoHarvest,toDOMNoHarvest_upper,maxAge);

  toDOMHarvest=max(min(DOM+deltaBmHarvest+deltaDOMHarvest,maxDOM),0);
  toDOMHarvest_lower=fix(toDOMHarvest);
  toDOMHarvest_upper=min(toDOMHarvest_lower+1,maxDOM);

  toStateHarvest(iState,1)=stateIndex(toAgeHarvest,toDOMHarvest_lower,maxAge);
  toStateHarvest(iState,2)=stateIndex(toAgeHarvest,toDOMHarvest_upper,maxAge);

  t=rem(toDOMNoHarvest,1);
  propStateNoHarvest(iState,1)=1-t;
```

```
  propStateNoHarvest(iState,2)=t;

  t=rem(toDOMHarvest,1);
  propStateHarvest(iState,1)=1-t;
  propStateHarvest(iState,2)=t;

   end
  end
end
iState;

%%%%% The Dynamic Program
return0=zeros(nState,1);
decision0=zeros(nState,1);
nStage=maxStage
for iStage=nStage:-1:0
    return1=return0;
    decision1=decision0;
    for iState=1:nState
        if (mod(iState,10000) == 0)
            [iStage,iState]
        end
        return_harvest = netRevenueHarvest(iState,1) + ...
            discount_factor * ...
            (propStateHarvest(iState,1) * return1(toStateHarvest(iState,1),1)+ ...
             propStateHarvest(iState,2) * return1(toStateHarvest(iState,2),1));
        return_noharvest = netRevenueNoHarvest(iState,1) + ...
            discount_factor * ...
            (propStateNoHarvest(iState,1) * return1(toStateNoHarvest(iState,1),1) + ...
             propStateNoHarvest(iState,2) * return1(toStateNoHarvest(iState,2),1)) ;
        if (return_harvest > return_noharvest)
            return0(iState)=return_harvest;
            decision0(iState)=1;
        else
            return0(iState)=return_noharvest;
            decision0(iState)=0;
        end
    end
end
```

```
decsionRule=zeros(maxAge+1,maxDOM+1);
 return0=return0-estabcost;
returnMatrix=zeros(maxAge+1,maxDOM+1);
for iState=1:nState
      [age,DOM]=getAgeDOM(iState,maxAge,maxDOM);
      decisionRule(age+1,DOM+1)=decision0(iState);
      returnMatrix(age+1,DOM+1)=return0(iState);
end

%% Save the model solution
save solution.mat decisionRule returnMatrix

%% Plot Decision Rule
figure(1)
mesh(decisionRule')
shading faceted;
view([0 90])
xlabel('Stand age (years)')
ylabel('DOM (tC/ha)')
title('Decision Rule')

%% Plot Return
figure(2);
levels =[-2000 -4000 -6000];
[C,h]=contour(returnMatrix',levels);
clabel(C,h);
hold all
levels =[0 2000 4000 6000 8000 10000 12000];
[C,h]=contourf(returnMatrix',levels);
clabel(C,h);
set(h,'ShowText','on','TextStep',get(h,'LevelStep')*2);
colormap cool;
xlabel('Stand age (years)')
ylabel('DOM (tC/ha)')
axis([0 250 0 500])
title('NPV ($/ha) countour by initial state')

save price10.mat decisionRule returnMatrix;
```

```
%% Solution
 decisionRule(age+1,DOM+1)=decision0(iState)
toc

%%%The following functions are needed to run the dynamic programming model:

%% merch volume
function mv = merchvol(age,v1,v2,v3)
  mv = v1 * (1-exp(-v2 * age))^v3;
end

%% biomass
function bm = biomass(age,b1,b2,b3)
  bm = b1 * (1-exp(-b2 * age))^b3;
end

function[age, DOM] = getAgeDOM(index,maxAge,maxDOM)
  age=mod(index - 1, maxAge+1);
  DOM=fix((index - 1) / (maxAge + 1));
end

%% state index
function si = stateIndex(age,DOM,maxAge)
  si=(age + 1) + (maxAge + 1) * DOM;
end
```

APPENDIX B

Appendix to Chapter 3

```
clear all
tic
%% Program control parameters
maxStage=500;

%Lumber
minLumber=0;
maxLumber=500;
incLumber=5;
nLumber=(maxLumber-minLumber)/incLumber+1;

%DOM
minDOM=0;
maxDOM=500;
incDOM=5;
nDOM=(maxDOM-minDOM)/incDOM+1;

minAge=0;
maxAge=250;
incAge=1;
nAge=(maxAge-minAge)/incAge+1;

nState=(nDOM) * (nAge) * (nLumber);

discount_rate = 0.05;
```

```
discount_factor = 1/(1 + discount_rate);
lumberprice = 375; %Lumber Price is 375 CAD/MBF
chipprice = 70; %Chip price of 70 CAD/BDU
overhead = 2500; %CAD/ha
road = 1150; %CAD/ha
% logprice  =   41.83; % CAD/m3 Lumber Price is 375 CAD/MBF
% logcost   = 6250;% CAD/ha % (Road:1150 CAD/ha; TTT:5100 CAD/ha)
% % (Milling: 34.65 CAD/m3; Haul: 4.84 CAD/m3; Overhead: 8.06 CAD/m3)
estabcost =  1250; % CAD/ha
co2_c_ratio = (12 + (16 * 2)) / 12;
p_co2 = 10; % $/Mg CO_2
p_c = p_co2 * co2_c_ratio; % $/Mg C

decaydom = 0.008412; % (%/year)decay rate for DOM
decaylumber =0.0057825; % (%/year)decay rate for Lumber
%in building
litterfall = 0.01357; % biomass to DOM conversion rate
wood_C_ratio = 0.2; % t C/(m^3 merchantable volume)
% nominal_to_actuallumber = 0.67; %Proportion of actual
%lumber to nominal lumber
mbf_to_cubicmeters = 2.359737216; %Conversion Factor from
%thousand board feet to m3

%% Switches:
emissionswitch =1; % 1 when emissions are considered and 0
%when ignored
domswitch = 1; % 1 when dom carbon stocks are considered
%and 0 when ignored
bmswitch = 1; % 1 when biomass carbon stocks are considered
%and 0 when ignored
productswitch = 1; % 1 when wood product carbon stocks are
%considered and 0 when ignored

%Carbon Emissions Parameters
EM_Regen = 0.068; %tC/ha (Seed & Seedling Production, Site Prep,
%Planting and Survey)

Em_Harvesting = 0.273;%tC/ha (Hauling, Roads, Timber
%Harvesting and Machinery Transportation)
```

```
Em_sawmill = 0.021; %tC/MBF(tonnes of C emission per
%MBF during milling)

Em_transportation = 0.0715; %tC/MBF(tonnes of C emission
%per MBF for long distance haul of 1000 km)

Em_pulp = 0.08;%1.554; %tC/tC 0.08

Em_Waste = 0.06; %tC/tC (Percentage of carbon emission from waste)
%% Merch Volume (m3/ha) from TIPSY
%yield function in cubic metres per hectare by year.... element 1
%coresponds to age 1, element 250 to age 250
yield=[0 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0 0 0 0 0 0 ...
1 1 2 3 3 7 11 15 18 22 26 32 38 45 51 56 62 68 76 84 ...
91 98 105 112 119 126 133 140 147 154 161 167 174 180 186 192 ...
198 204 210 215 221 226 231 236 241 246 251 256 261 265 270 274 ...
279 283 287 291 295 299 303 307 310 314 318 322 326 329 333 337 ...
340 343 347 350 353 357 360 363 366 369 372 375 377 380 383 385 ...
387 389 391 393 395 397 399 401 403 405 407 409 411 412 414 416 ...
417 419 421 422 424 425 427 429 430 432 433 434 436 437 439 440 ...
442 443 445 446 448 449 450 452 453 454 456 457 458 460 461 462 ...
463 464 466 467 468 469 470 471 472 474 475 476 477 478 479 480 ...
481 482 483 484 485 486 487 487 488 489 490 491 492 493 494 494 ...
495 496 497 498 499 499 500 501 502 502 503 504 505 505 506 507 ...
508 508 509 510 510 511 512 512 513 514 514 515 515 516 517 517 ...
518 518 519 520 520 521 521 522 522 523 524 524 525 525 526 526 ...
527 527 528 528 529 529 530 530 531 531 532 532 533 533 533 534 ...
534 535 ];

%% Biomass (tC/ha) from CBM-CFS3
%biomass yield function in tonnes per hectare by year.... element 1
%coresponds to age 1, element 250 to age 250
biomass_cbm=[0 0 0.1  0.1  0.2  0.3  0.4  0.6  0.8 1.1 1.4  1.8 ...
2.3 2.9 3.6 4.4 5.5 6.6  8.1 9.7 11.6 13.6 15.8  18.3 20.7 23.3 ...
25.9 28.4 30.5  32.4 34.2 36.0 38.7 41.2 43.7 46.2 48.6 ...
51.4 54.1 56.7 59.4 62.0 64.6 67.1 69.7  72.2 74.7 77.2 79.7 ...
82.1 84.6 87.0 89.2 91.3 93.4 95.6  97.7 99.6 101.6 103.6 ...
105.5 107.5 109.1 110.8 112.5 114.2 115.8  117.4 119.0 120.6 ...
```

```
122.2 123.8 125.2 126.6 128.0 129.3 130.7 132.0 133.2 134.5 135.7 ...
137.0 138.2 139.5 140.7 142.0 143.2 144.4 145.6   146.7 147.9 ...
149.1 150.1 151.2 152.2 153.2 154.3 155.2 156.1 157.0 157.9 158.8 ...
159.6 160.3 161.1 161.9 162.7 163.3 164.0 164.6 165.2  165.9 ...
166.5 167.2 167.8 168.5 169.1 169.6 170.1 170.6 171.1 171.7 172.2 ...
172.7 173.2 173.7 174.2 174.7 175.2 175.8 176.3 176.8 177.2 177.7 ...
178.1 178.6 179.0 179.5 180.0 180.5 181.1 181.6 182.0 182.3 182.7 ...
183.1 183.5 183.9 184.4 184.8 185.3 185.7 186.1 186.5 186.9 187.2 ...
187.6 187.9 188.3 188.6 188.9 189.2 189.6 190.0 190.3 190.7 191.1 ...
191.4 191.7 192.1 192.4 192.7 192.9 193.2 193.5 193.7 194.0 194.3 ...
194.6 194.9 195.2 195.5 195.8 196.1 196.3 196.6 196.8 197.1 197.3 ...
197.6 197.8 198.1 198.3 198.6 198.8 199.1 199.3 199.6 199.9 200.1 ...
200.4 200.6 200.8 201.0 201.2 201.4 201.6 201.7 201.9 202.1 202.3 ...
202.5 202.7 202.9 203.1 203.3 203.5 203.6 203.8 204.0 204.2 204.4 ...
204.6 204.8 205.0 205.2 205.3 205.5 205.7 205.9 206.1 206.3 206.4 ...
206.5 206.7 206.8 206.9 207.1 207.3 207.5 207.7 207.9 208.0 208.1 ...
208.2 208.4 208.5 208.6 208.8 208.9 209.0 209.1];

%% Lumber (MBF/ha) from TIPSY
%Lumber function in MBF/ha by years.... element 1 coresponds to age 1,
%element 250 to age 250
lumber2x4=[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 ...
0 0.004  0.013 0.022 0.030 0.039 0.048 0.283 0.545 0.803 1.057 ...
1.306 1.551 2.488 3.474 4.442 5.391 6.321 7.233 8.266 9.791 11.284 ...
12.747 14.179 15.582 16.955 18.300 19.657 21.035 22.384 ...
23.704 24.997 26.262 27.501 28.714 29.901 31.050 32.108 ...
33.143 34.158 35.151 36.123  37.076 38.009 38.923 39.819 ...
40.696 41.556 42.340 43.071 43.787 44.489 45.178 45.853 ...
46.514 47.163 47.800 48.424 49.036 49.637 50.226 50.805  ...
51.372 51.886 52.353 52.811 53.261 53.703 54.137 54.563 ...
54.982 55.393 55.797 56.193 56.583 56.966 57.342 57.712 ...
58.075 58.433 58.784 59.129  59.469 59.803 60.181 60.601 ...
61.013 61.418 61.817 62.210 62.596 62.977 63.351 63.719 ...
64.081 64.438 64.790 65.136 65.476 65.812 66.142 66.467 ...
66.788 67.104 67.415 67.721 68.023 68.321 68.614 68.903 ...
69.188 69.469 69.746 70.019 70.288 70.553 70.790 70.898 ...
71.004 71.109 71.212 71.314 71.415 71.514 71.612 71.709 ...
71.804 71.898 71.991 72.083 72.173 72.262 72.351 72.438 ...
72.523 72.608 72.692 72.775 72.857 72.937 73.017 73.096 ...
```

```
73.173 73.250 73.326 73.401 73.475 73.548 73.620 73.692 ...
73.762 73.832 73.901 73.969 74.037 74.103 74.169 74.234 ...
74.298 74.362 74.425 74.487 74.549 74.609 74.669 74.729 ...
74.788 74.846 74.903 74.960 75.017 75.072 75.127 75.182 ...
75.236 75.290 75.362 75.433 75.503 75.573 75.642 75.710 ...
75.778 75.844 75.911 75.976 76.041 76.105 76.168 76.231 ...
76.294 76.355 76.416 76.477 76.537 76.596 76.654 76.713 ...
76.770 76.827 76.884 76.940 76.995 77.050 77.104 77.158 ...
77.211 77.264 77.316 77.368 77.420 77.471 77.521 77.571 ...
77.621 77.670 77.718 77.766 77.814 77.862 77.908 77.955 ...
78.001 78.047 78.092 78.137 78.181 78.226 78.269 78.313 ...
78.356 78.398 78.441];

%% Chips (BDU/ha) from TIPSY
%Chips function in BDU/ha by years.... element 1 coresponds to age 1,
%element 250 to age 250
chips=[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 ...
0 0 0 0 0 1 2 3 4 5 6 7 9 10 11 13 14 15 17 18 ...
19 21 22 23 24 26 27 28 29 30 31 32 33 34 ...
35 36 37 38 39 40 41 42 43 44 45 46 46 47 48 49 49 ...
50 51 51 52 53 53 54 55 55 56 56 57 57 58 58 59 59 ...
60 60 60 61 61 62 62 63 63 63 64 64 64 65 65 65 66 ...
66 66 67 67 67 68 68 68 68 69 69 69 69 70 70 70 70 ...
71 71 71 71 71 72 72 72 72 72 73 73 73 73 73 74 74 ...
74  74 74 75 75 75 75 75 76 76 76 76 76 76 77 77 77 ...
77 77 77 78 78 78 78 78 78 79 79 79 79 79 79 79 80 ...
80 80 80 80 80 80 80 81 81 81 81 81 81 81 81 81 82 ...
82 82 82 82 82 82 82 82 82 82 83 83 83 83 83 83 83 ...
83 83 83 83 83 83 83 84 84 84 84 84 84 84 84 84 84 ...
84 84 84 84 84 84 85 85 85 85 85 85 85 85 85 85 85 ...
85 85 85 85 85 85 85 85 86 86];

%%
nominal_to_actuallumber =[0 0  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 ...
0.65625 0.65625 0.65625 0.65625 0.65625 0.65625 0.65625 0.65625 ...
0.65625 0.65625 0.65625 0.65625 0.65625 0.65625 0.65625 0.65625 ...
0.65625 0.65625 0.65625378 0.656269139 0.656280434 0.656289176 ...
0.656294017 0.656300058 0.656303359 0.656307952 0.656405024 ...
0.656590904 0.656750044 0.656886701 0.657005143 0.657108669 ...
```

```
0.657200809 0.657282371 0.657355918 0.657464413 0.657763976 ...
0.658034324 0.658278539 0.658499416 0.658702887 0.658887787 ...
0.659058626 0.659216124 0.659360945 0.659496277 0.659621885 ...
0.65983448 0.660090446 0.660328901 0.660551765 0.660759598 ...
0.660954983 0.661138034 0.661310477 0.661473021 0.661626053 ...
0.661771582 0.661908679 0.662038547 0.662161863 0.662279632 ...
0.662420852 0.66258035 0.662732373 0.662877556 0.663015585 ...
0.663147369 0.663273309 0.663393889 0.663510122 0.663620662 ...
0.66372662 0.663828847 0.663926913 0.664021016 0.664111738 ...
0.664199114 0.664282913 0.664364064 0.664442294 0.664517697 ...
0.664590504 0.66463869 0.664664741 0.664689421 0.66471366 ...
0.664737274 0.664759853 0.664781952 0.664803653 0.664824153 ...
0.664844719 0.664864191 0.664883497 0.664902227 0.664920173 ...
0.664938083 0.664955114 0.664971655 0.664988406 0.665004251 ...
0.66501961 0.665034735 0.66504955 0.665063748 0.665077709 ...
0.66509162 0.665105239 0.665118042 0.665130868 0.665143193 ...
0.665155634 0.665167585 0.665179056 0.665201232 0.665276156 ...
0.665349452 0.665421209 0.665491128 0.665559578 0.665626527 ...
0.665691884 0.665756076 0.665818569 0.665880118 0.665939965 ...
0.665998809 0.666056343 0.666112818 0.66616796 0.666222026 ...
0.666275097 0.666327191 0.666377809 0.666427973 0.666476921 ...
0.66652499 0.666572364 0.666618478 0.66666407 0.666708504 ...
0.666752226 0.666794963 0.666837233 0.666878916 0.666919407 ...
0.66695946 0.666998802 0.667037383 0.667075343 0.667112467 ...
0.667149431 0.667185257 0.667220606 0.667255375 0.667289997 ...
0.667323614 0.667356713 0.667389409 0.667421628 0.667453024 ...
0.667484453 0.667514833 0.667545074 0.667574604 0.667603929 ...
0.667632658 0.667661264 0.667689083 0.66771659 0.667743815 ...
0.667770271 0.667796718 0.667822779 0.667849263 0.667875665 ...
0.667901473 0.667927056 0.667952152 0.667977127 0.668001643 ...
0.668025764 0.668049382 0.66807304 0.668096042 0.668118938 ...
0.668141476 0.668163626 0.668185536 0.668207194 0.668228264 ...
0.668249404 0.66827006 0.668290585 0.66831084 0.668330659 ...
0.668350155 0.668369587 0.668388751 0.668407796 0.668426675 ...
0.668445048 0.668463106 0.668481261 0.668498952 0.668516389 ...
0.668533782 0.668550862 0.668567803 0.668584593 0.668601283 ...
0.668617291 0.66863354 0.668649358 0.668665083 0.668680765 ...
0.668696208 0.668711462 0.668726479 0.668741322 0.66875603 ...
0.668770359 0.668784895 0.668798909 0.668813132 0.668827076 ...
```

```
0.668840712 0.668854265 0.668867775 0.668881075 0.668894102];

treetotruck=[0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 6 ...
21 36 51 65 79 169 267 364 458 551 642  788  934   1077  ...
1216 1352 1484 1622 1787 1946 2100 2248 2392 2531 2666 ...
2798 2929 3054 3174 3288 3398 3504 3605 3702 3796 ...
3883 3966 4046 4122 4194 4263 4330 4393 4453 4510 ...
4565 4617 4665 4711 4767 4820 4872 4922 4970 5017 ...
5062 5105 5147 5187 5226 5264 5302 5339 5374 5409 ...
5442 5473 5504 5534 5562 5589 5616 5637  5658 5679 ...
5700 5722 5743 5764 5785 5806 5828 5849 5870 5891 ...
5934  5955 5976 5997 6019 6040 6061 6082  6103 6125 ...
6146 6167 6188 6210  6231 6253 6274 6295 6315 6335 ...
6355 6375 6394  6413 6432 6450 6468 6486 6504 6523 ...
6543 6561  6580 6598 6616 6634 6652 6669 6686 6703 ...
6719  6736 6752 6768 6783 6799 6814 6829 6844 6859 ...
6873 6887 6901 6915 6929 6942 6956 6969 6982  6995 ...
7007 7020 7032 7044 7056 7068 7080 7092  7103 7115 ...
7126 7137 7148 7158 7169 7180 7190  7200 7211 7221 ...
7231 7240 7250 7260 7269 7279  7288 7297 7306 7315 ...
7324 7333 7341 7350 7359  7367 7375 7384 7392 7400 ...
7408 7416 7423 7431  7439 7446 7454 7461 7469 7476 ...
7483 7490 7497  7504 7511 7518 7525 7531 7538 7545 ...
7551 7558  7564 7570 7577 7583 7589 7595 7601 7607 ...
7613  7619 7625 7630 7636 7642 7647 7653 7658 7664 ...
7669 7675 7680 7685 7690];

%Hauling cost (CAD/ha) From TIPSY
haul = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 5  8 12 ...
15 18 40 63 86 108 130 152 188 225 261 296 331 365 401 ...
446 490 533  576  618  658  698  739 781 823  863 903  942  ...
980  1017 1054 1089 1125 1160 1194 1228 1261 1293 ...
1324 1355 1385 1415 1444 1472 1501 1528 1555 1581 ...
1607 1633 1657 1682 1706 1729 1752 1775 1797 1819 ...
1841  1864 1886    1908 1930 1951 1972 1992 2012 2032 ...
2052 2071 2089 2108 2126 2143 2161 2178 2195 2211 ...
2228 2242  2255 2268    2280 2293 2305 2317 2329 2340 ...
2351 2363 2374 2384 2395 2406 2416 2426 2436 2446 ...
2456 2465 2475  2484 2493  2502 2511 2520 2529 2537 ...
```

```
2546 2554 2562 2571 2579 2588 2597 2606 2614 2622 ...
2631 2639 2647 2655  2663 2670  2678 2685 2693 2700 ...
2707 2715 2722 2729 2735 2742 2749 2755 2762 2768 ...
2775 2781 2787 2794 2800  2806 2812  2817 2823 2829 ...
2835 2840 2846 2851 2857 2862 2867 2872 2878 2883 ...
2888 2893 2898 2903 2907 2912  2917 2922  2926 2931 ...
2935 2940 2944 2949 2953 2957 2962 2966 2970 2974 ...
2978 2982 2986 2990 2994 2998 3002  3006 3009  3013 ...
3017 3020 3024 3028 3031 3035 3038 3042 3045 3048 ...
3052 3055 3058 3062 3065 3068 3071 3074  3077 3081  ...
3084 3087 3090 3093 3096 3098 3101 3104 3107 3110 ...
3113 3115 3118 3121 3124 3126 3129 3132 3134 3137];

%Milling cost (CAD/ha) From TIPSY
milling = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 2 6 11 15 ...
20 24 106 185 262 338 412 485 682 881 1073 1259 1441 1619 ...
1814 2083 2345 2601 2851    3095 3334 3568 3811 4066 ...
4315 4559 4798 5031 5260 5483 5702 5919 6148 6373 ...
6592 6807 7017 7223 7424 7622  7815 8004 8190 8380 ...
8572 8759 8943 9124 9300 9474 9643 9810 9973 10133 ...
10290 10444 10595 10743 10894 11048 11198 11346 11491 11634 ...
11774 11911 12046 12179 12309 12437 12562 12686 12807 12926 ...
13044 13159 13272 13383 13493 13593 13684 13774 13862 13949 ...
14035 14119 14202 14283 14363 14442 14520 14597 14672 14746 ...
14819 14891 14962 15031 15100 15168 15234 15300 15365 15429 ...
15492 15553 15615 15675 15734 15793 15850 15909 15975 16040 ...
16105 16168 16231 16292 16353 16413 16473 16531 16589 16646 ...
16702 16757 16812 16866 16920 16972 17024 17076 17126 17176 ...
17226 17275 17323 17370 17417 17464 17510 17555 17600 17644 ...
17688 17731 17774 17816 17858 17899 17940 17980 18020 18059 ...
18098 18137 18175 18213 18250 18287 18323 18359 18394 18430 ...
18465 18499 18533 18567 18600 18633 18666 18700 18734 18767 ...
18801 18833 18866 18898 18930 18961 18992 19023 19054 19084 ...
19114 19144 19173 19202 19231 19259 19287 19315 19343 19370 ...
19397 19424 19451 19477 19503 19529 19555 19580 19605 19630 ...
19655 19679 19703 19727 19751 19775 19798 19821 19844 19867 ...
19889 19912 19934 19956 19977 19999 20020 20041 20062 20083 ...
20104 20124 20144 20164];
```

```
%% Function coefficients:
% biomass coefficients
b1 = 198.6;
b2 = 0.0253;
b3 = 2.64;
% merchantable volume coefficients
v1 = 500.4;
v2 = 0.027;
v3 = 4.003;


%% Save the run control information for later use
save runcontrol.mat maxStage minLumber incLumber nLumber ...
maxLumber minDOM incDOM nDOM maxDOM nAge minAge incAge ...
maxAge nState discount_rate discount_factor estabcost ...
co2_c_ratio p_co2 p_c decaydom decaylumber litterfall  ...
nominal_to_actuallumber wood_C_ratio  mbf_to_cubicmeters ...
b1 b2 b3 v1 v2 v3 l1 l2 l3 p1 p2 p3 emissionswitch productswitch ...
domswitch  bmswitch milling haul treetotruck chips lumber_all ...
biomass_cbm EM_Regen Em_Harvesting Em_Waste lumberprice ...
chipprice overhead road mbf_to_cubicmeters

%% State payoff calculations
netRevenueHarvest = zeros(nState,1);
netRevenueNoHarvest = zeros(nState,1);

toAgeHarvest=1;

toStateNoHarvest=zeros(nState,4);
toStateHarvest=zeros(nState,4);

propStateNoHarvest=zeros(nState,4);
propStateHarvest=zeros(nState,4);

for iState=1:nState
    if (mod(iState,10000) == 0)  %print current state to indicate model
    %is running
        iState;
    end
```

```
    [age DOM Lumber]= getAgeDOMLumber(iState,nAge,nDOM,nLumber,...
        incAge,incDOM,incLumber)
    temp_index=age+1;

    mv=yield(temp_index);
    bm=biomass_cbm(temp_index);
    bm1=biomass_cbm(temp_index+1);
    sv=lumber_all(temp_index);
    pv=chips(temp_index);

    hl=haul(temp_index);
    ml=milling(temp_index);
    ttt=treetotruck(temp_index);

    k = nominal_to_actuallumber(temp_index);

    netTimberRevenueHarvest =(lumberprice * sv + chipprice * pv)  - ...
        ml - ttt - hl - road - overhead - estabcost;

%Carbon Emissions for Forest Product Chain:

        % Carbon Emissions
        actual_lumber = sv * k; % Dimensional lumber after planning etc
        waste = sv * (1-k);

        Waste_percent = 0.06; %tC/tC (Percentage of carbon emission from waste)

        CE_Silviculture = 0.068;%(tC)Carbon Emissions from Silvi. Operations
        %(Seed & Seedling Production, Site Prep, Planting and Survey)

        CE_harvesting = 0.273;%tC/ha (Hauling, Roads, Timber Harvesting
        %and Machinery Transportation)

        %CE_processing = Em_processing * actual_lumber * productswitch; %
        CE_sawmill = Em_sawmill * sv * productswitch; %

        CE_pulp = Em_pulp * pv * productswitch; %
```

```
        CE_transportation = Em_transportation * actual_lumber * productswitch;

        CE_processing = CE_sawmill + CE_transportation;

        CE_Waste = Waste_percent * waste * productswitch;
        % Total carbon emissions from waste

        CE_Total = CE_Silviculture + CE_harvesting + CE_processing ...
        + CE_Waste + CE_pulp;

        %% STOCK CHANGES:
            %%  Change in Biomass:
            deltaBmNoHarvest = (bm1 - bm);
            deltaBmHarvest = -bm;

            %% Change in DOM
            deltaDOMNoHarvest = (-decaydom * DOM) + (litterfall * bm);
            deltaDOMHarvest = deltaDOMNoHarvest + bm - (wood_C_ratio * mv);

            %% Change in Lumber Considering Carbon Emissions:
            deltaLumberNoHarvest = (-decaylumber * Lumber);

            deltaLumberHarvest = deltaLumberNoHarvest + ...
                (wood_C_ratio * k * sv * mbf_to_cubicmeters);

   %% Payoffs:
      TotalcarbonemissionCharge = p_c * (emissionswitch * CE_Total);
      SilvicultureemissionCharge = p_c * (emissionswitch*CE_Silviculture);

      carbonRevenueNoHarvest = p_c*((deltaBmNoHarvest*bmswitch) + ...
      (deltaDOMNoHarvest*domswitch) + (deltaLumberNoHarvest*productswitch));

      carbonRevenueHarvest = p_c*((deltaBmHarvest*bmswitch) + ....
      (deltaDOMHarvest*domswitch) + (deltaLumberHarvest*productswitch));

      %Total Revenue from product sale and carbon sequestration
       netRevenueHarvest(iState,1) = netTimberRevenueHarvest + ...
       carbonRevenueHarvest - (TotalcarbonemissionCharge);
```

```
    netRevenueNoHarvest(iState,1) = carbonRevenueNoHarvest ;

    %% Create harvest transition matrix
    toAgeNoHarvest=min(age+1,maxAge);

    toDOMNoHarvest=min(DOM+deltaBmNoHarvest+deltaDOMNoHarvest,maxDOM);
    toDOMNoHarvest_lower=fix(toDOMNoHarvest/incDOM)*incDOM;
    toDOMNoHarvest_upper=min(toDOMNoHarvest_lower+incDOM,maxDOM);
    toLumberNoHarvest=min(Lumber+deltaLumberNoHarvest,maxLumber);
    toLumberNoHarvest_lower=fix(toLumberNoHarvest/incLumber)*incLumber;
    toLumberNoHarvest_upper=min(toLumberNoHarvest_lower + ...
    incLumber,maxLumber);

    toStateNoHarvest(iState,1)=stateIndex(toAgeNoHarvest,
        toDOMNoHarvest_lower,toLumberNoHarvest_lower,nAge,nDOM,
        incAge,incDOM,incLumber);

    toStateNoHarvest(iState,2)=stateIndex(toAgeNoHarvest,
        toDOMNoHarvest_lower,toLumberNoHarvest_upper,nAge,nDOM,
        incAge,incDOM,incLumber);

    toStateNoHarvest(iState,3)=stateIndex(toAgeNoHarvest,
        toDOMNoHarvest_upper,toLumberNoHarvest_lower,nAge,nDOM,
        incAge,incDOM,incLumber);

    toStateNoHarvest(iState,4)=stateIndex(toAgeNoHarvest,
         toDOMNoHarvest_upper,toLumberNoHarvest_upper,nAge,nDOM,
         incAge,incDOM,incLumber);
%----------------------------
    toDOMHarvest=max(min(DOM+deltaBmHarvest+deltaDOMHarvest,maxDOM),0);
    toDOMHarvest_lower=fix(toDOMHarvest/incDOM)*incDOM;
    toDOMHarvest_upper=min(toDOMHarvest_lower+incDOM,maxDOM);
    toLumberHarvest=max(min(Lumber+deltaLumberHarvest,maxLumber),0);
    toLumberHarvest_lower=fix(toLumberHarvest/incLumber)*incLumber;
    toLumberHarvest_upper=min(toLumberHarvest_lower+incLumber,maxLumber);

    toStateHarvest(iState,1)=stateIndex(toAgeHarvest,
        toDOMHarvest_lower,toLumberHarvest_lower,nAge,nDOM,
        incAge,incDOM,incLumber);
```

```
        toStateHarvest(iState,2)=stateIndex(toAgeHarvest,
            toDOMHarvest_lower,toLumberHarvest_upper,nAge,
            nDOM,incAge,incDOM,incLumber);

        toStateHarvest(iState,3)=stateIndex(toAgeHarvest,
            toDOMHarvest_upper,toLumberHarvest_lower,nAge,
            nDOM,incAge,incDOM,incLumber);

        toStateHarvest(iState,4)=stateIndex(toAgeHarvest,
            toDOMHarvest_upper,toLumberHarvest_upper,nAge,
            nDOM,incAge,incDOM,incLumber);
   %-------------------------------
            d=rem(toDOMNoHarvest,incDOM)/incDOM;
            p=rem(toLumberNoHarvest,incLumber)/incLumber;
            propStateNoHarvest(iState,1)=(1-d)*(1-p);
            propStateNoHarvest(iState,2)=p*(1-d);
            propStateNoHarvest(iState,3)=d*(1-p);
            propStateNoHarvest(iState,4)=d*p;

            d=rem(toDOMHarvest,incDOM)/incDOM;
            p=rem(toLumberHarvest,incLumber)/incLumber;
            propStateHarvest(iState,1)=(1-d)*(1-p);
            propStateHarvest(iState,2)=p*(1-d);
            propStateHarvest(iState,3)=d*(1-p);
            propStateHarvest(iState,4)=d*p;
end
iState
%--------------------------------------
%%% The Dynamic Program
return0=zeros(nState,1);
decision0=zeros(nState,1);
nStage=maxStage
for iStage=nStage:-1:0
    return1=return0;
    decision1=decision0;
    for iState=1:nState
        if (mod(iState,10000) == 0)
            [iStage,iState]
```

```
        end

%iState=round(iState);
    return_harvest = netRevenueHarvest(iState,1) + discount_factor * ...
      propStateHarvest(iState,1)*return1(round(toStateHarvest(iState,1)),1) + ...
      propStateHarvest(iState,2)*return1(round(toStateHarvest(iState,2)),1)+ ...
      propStateHarvest(iState,3)*return1(round(toStateHarvest(iState,3)),1)+ ...
      propStateHarvest(iState,4)*return1(round(toStateHarvest(iState,4)),1));

 return_noharvest = netRevenueNoHarvest(iState,1)+ discount_factor * ...
  (propStateNoHarvest(iState,1)*return1(round(toStateNoHarvest(iState,1)),1)+ ...
   propStateNoHarvest(iState,2)*return1(round(toStateNoHarvest(iState,2)),1) + ...
   propStateNoHarvest(iState,3)*return1(round(toStateNoHarvest(iState,3)),1) + ...
   propStateNoHarvest(iState,4)*return1(round(toStateNoHarvest(iState,4)),1));

        if (return_harvest > return_noharvest)
            return0(iState)=return_harvest;
            decision0(iState)=1;
        else
            return0(iState)=return_noharvest;
            decision0(iState)=0;
        end
    end
end
decisionRule=zeros(nAge,nDOM,nLumber);
return0=return0-estabcost - SilvicultureemissionCharge;
returnMatrix=zeros(nAge,nDOM,nLumber);
for iState=1:nState
  [age DOM Lumber]= getAgeDOMLumber(iState,nAge,nDOM,nLumber,...
     incAge,incDOM,incLumber);
  decisionRule(age+1,DOM/incDOM+1,Lumber/incLumber+1)=decision0(iState);
  returnMatrix(age+1,DOM/incDOM+1,Lumber/incLumber+1)=return0(iState);
end

% Save the model solution
save solution.mat decisionRule returnMatrix;
save price10E.mat decisionRule returnMatrix;

%% Plot Decision Rule
```

```
graph=squeeze(decisionRule(:,:,1));
figure(1)
mesh(graph');
shading interp;
view([0 90])
xlabel('Stand Age (years)')
ylabel('DOM (tC/ha)')
title('Decision Rule')
set(gca,'YTickLabel',{'0';'100';'200';'300';'400';'500';'600'})

graph=squeeze(decisionRule(:,:,20));
figure(2)
mesh(graph');
shading interp;
view([0 90])
xlabel('Stand Age (years)')
ylabel('DOM (tC/ha)')
title('Decision Rule')
set(gca,'YTickLabel',{'0';'100';'200';'300';'400';'500';'600'})

graph=squeeze(decisionRule(:,:,40));
figure(3)
mesh(graph');
shading interp;
view([0 90])
xlabel('Stand Age (years)')
ylabel('DOM (tC/ha)')
title('Decision Rule')
set(gca,'YTickLabel',{'0';'100';'200';'300';'400';'500';'600'})

graph=squeeze(decisionRule(:,:,60));
figure(4)
mesh(graph');
shading interp;
view([0 90])
xlabel('Stand Age (years)')
ylabel('DOM (tC/ha)')
title('Decision Rule')
set(gca,'YTickLabel',{'0';'100';'200';'300';'400';'500';'600'})
```

```
graph=squeeze(decisionRule(:,:,80));
figure(5)
mesh(graph');
shading interp;
view([0 90])
xlabel('Stand Age (years)')
ylabel('DOM (tC/ha)')
title('Decision Rule')
set(gca,'YTickLabel',{'0';'100';'200';'300';'400';'500';'600'})

graph=squeeze(decisionRule(:,:,100));
figure(6)
mesh(graph');
shading interp;
view([0 90])
xlabel('Stand Age (years)')
ylabel('DOM (tC/ha)')
title('Decision Rule')
set(gca,'YTickLabel',{'0';'100';'200';'300';'400';'500';'600'})

graph=squeeze(decisionRule(:,1,:));
figure(7)
mesh(graph');
shading interp;
view([0 90])
xlabel('Stand Age (years)')
ylabel('Wood product (tC/ha)')
title('Decision Rule')
set(gca,'YTickLabel',{'0';'100';'200';'300';'400';'500';'600'})

graph=squeeze(decisionRule(:,20,:));
figure(8)
mesh(graph');
shading interp;
view([0 90])
xlabel('Stand Age (years)')
ylabel('Wood product (tC/ha)')
title('Decision Rule')
```

```
set(gca,'YTickLabel',{'0';'100';'200';'300';'400';'500';'600'})

graph=squeeze(decisionRule(:,40,:));
figure(9)
mesh(graph');
shading interp;
view([0 90])
xlabel('Stand Age (years)')
ylabel('Wood product (tC/ha)')
title('Decision Rule')
set(gca,'YTickLabel',{'0';'100';'200';'300';'400';'500';'600'})

graph=squeeze(decisionRule(:,60,:));
figure(10)
mesh(graph');
shading interp;
view([0 90])
xlabel('Stand Age (years)')
ylabel('Wood product (tC/ha)')
title('Decision Rule')
set(gca,'YTickLabel',{'0';'100';'200';'300';'400';'500';'600'})

graph=squeeze(decisionRule(:,80,:));
figure(11)
mesh(graph');
shading interp;
view([0 90])
xlabel('Stand Age (years)')
ylabel('Wood product (tC/ha)')
title('Decision Rule')
set(gca,'YTickLabel',{'0';'100';'200';'300';'400';'500';'600'})
%
graph=squeeze(decisionRule(:,100,:));
figure(12)
mesh(graph');
shading interp;
view([0 90])
xlabel('Stand Age (years)')
ylabel('Wood product (tC/ha)')
```

```
title('Decision Rule')
set(gca,'YTickLabel',{'0';'100';'200';'300';'400';'500';'600'})
%-----------------------------------

bob=squeeze(returnMatrix(:,:,1));
figure(13)
levels =[-2000 -4000 -6000 -8000 -10000];
[C,h]=contour(bob');
clabel(C,h);
hold all
levels =[0 2000 4000 6000 8000 10000 12000 14000 16000 18000];
bob=squeeze(returnMatrix(:,:,30));
[C,h]=contourf(bob',levels);
clabel(C,h);
set(h,'ShowText','on','TextStep',get(h,'LevelStep')*2);
colormap cool;
xlabel('Stand age (years)')
ylabel('DOM (tC/ha)')
axis([0 250 0 100])
title('NPV ($/ha) countour by initial state')
set(gca,'YTickLabel',{'0';'50';'100';'150';'200';'250';'300';'350';'400';'450';'500'})

bob=squeeze(returnMatrix(:,:,20));
figure(14)
levels =[-2000 -4000 -6000 -8000 -10000];
[C,h]=contour(bob');
clabel(C,h);
hold all
levels =[0 2000 4000 6000 8000 10000 12000 14000 16000 18000];
bob=squeeze(returnMatrix(:,:,30));
[C,h]=contourf(bob',levels);
clabel(C,h);
set(h,'ShowText','on','TextStep',get(h,'LevelStep')*2);
colormap cool;
xlabel('Stand age (years)')
ylabel('DOM (tC/ha)')
axis([0 250 0 100])
title('NPV ($/ha) countour by initial state')
set(gca,'YTickLabel',{'0';'50';'100';'150';'200';'250';'300';'350';'400';'450';'500'})
```

```
bob=squeeze(returnMatrix(:,:,40));
figure(15)
levels =[-2000 -4000 -6000 -8000 -10000];
[C,h]=contour(bob');
clabel(C,h);
hold all
levels =[0 2000 4000 6000 8000 10000 12000 14000 16000 18000];
bob=squeeze(returnMatrix(:,:,30));
[C,h]=contourf(bob',levels);
clabel(C,h);
set(h,'ShowText','on','TextStep',get(h,'LevelStep')*2);
colormap cool;
xlabel('Stand age (years)')
ylabel('DOM (tC/ha)')
axis([0 250 0 100])
title('NPV ($/ha) countour by initial state')
set(gca,'YTickLabel',{'0';'50';'100';'150';'200';'250';'300';'350';'400';'450';'500'})

bob=squeeze(returnMatrix(:,:,60));
figure(16)
levels =[-2000 -4000 -6000 -8000 -10000];
[C,h]=contour(bob');
clabel(C,h);
hold all
levels =[0 2000 4000 6000 8000 10000 12000 14000 16000 18000];
bob=squeeze(returnMatrix(:,:,30));
[C,h]=contourf(bob',levels);
clabel(C,h);
set(h,'ShowText','on','TextStep',get(h,'LevelStep')*2);
colormap cool;
xlabel('Stand age (years)')
ylabel('DOM (tC/ha)')
axis([0 250 0 100])
title('NPV ($/ha) countour by initial state')
set(gca,'YTickLabel',{'0';'50';'100';'150';'200';'250';'300';'350';'400';'450';'500'})

bob=squeeze(returnMatrix(:,:,80));
figure(17)
```

```
levels =[-2000 -4000 -6000 -8000 -10000];
[C,h]=contour(bob');
clabel(C,h);
hold all
levels =[0 2000 4000 6000 8000 10000 12000 14000 16000 18000];
bob=squeeze(returnMatrix(:,:,30));
[C,h]=contourf(bob',levels);
clabel(C,h);
set(h,'ShowText','on','TextStep',get(h,'LevelStep')*2);
colormap cool;
xlabel('Stand age (years)')
ylabel('DOM (tC/ha)')
axis([0 250 0 100])
title('NPV ($/ha) countour by initial state')
set(gca,'YTickLabel',{'0';'50';'100';'150';'200';'250';'300';'350';'400';'450';'500'})

bob=squeeze(returnMatrix(:,:,100));
figure(18)
levels =[-2000 -4000 -6000 -8000 -10000];
[C,h]=contour(bob');
clabel(C,h);
hold all
levels =[0 2000 4000 6000 8000 10000 12000 14000 16000 18000];
bob=squeeze(returnMatrix(:,:,30));
[C,h]=contourf(bob',levels);
clabel(C,h);
set(h,'ShowText','on','TextStep',get(h,'LevelStep')*2);
colormap cool;
xlabel('Stand age (years)')
ylabel('DOM (tC/ha)')
axis([0 250 0 100])
title('NPV ($/ha) countour by initial state')
set(gca,'YTickLabel',{'0';'50';'100';'150';'200';'250';'300';'350';'400';'450';'500'})

bob=squeeze(returnMatrix(:,1,:));
figure(19)
levels =[-2000 -4000 -6000 -8000 -10000];
[C,h]=contour((bob'),levels);
clabel(C,h);
```

```
hold all
levels =[0 2000 4000 6000 8000 10000 12000 14000 16000 18000];
bob=squeeze(returnMatrix(:,30,:));
[C,h]=contourf(bob',levels);
clabel(C,h);
set(h,'ShowText','on','TextStep',get(h,'LevelStep')*2);
colormap cool;
xlabel('Stand age (years)')
ylabel('Wood Product (tC/ha)')
axis([0 250 0 100])
title('NPV ($/ha) countour by initial state')
set(gca,'YTickLabel',{'0';'50';'100';'150';'200';'250';'300';'350';'400';'450';'500'})

bob=squeeze(returnMatrix(:,20,:));
figure(20)
levels =[-2000 -4000 -6000 -8000 -10000];
[C,h]=contour((bob'),levels);
clabel(C,h);
hold all
levels =[0 2000 4000 6000 8000 10000 12000 14000 16000 18000];
bob=squeeze(returnMatrix(:,30,:));
[C,h]=contourf(bob',levels);
clabel(C,h);
set(h,'ShowText','on','TextStep',get(h,'LevelStep')*2);
colormap cool;
xlabel('Stand age (years)')
ylabel('Wood Product (tC/ha)')
axis([0 250 0 100])
title('NPV ($/ha) countour by initial state')
set(gca,'YTickLabel',{'0';'50';'100';'150';'200';'250';'300';'350';'400';'450';'500'})

bob=squeeze(returnMatrix(:,40,:));
figure(21)
levels =[-2000 -4000 -6000 -8000 -10000];
[C,h]=contour((bob'),levels);
clabel(C,h);
hold all
levels =[0 2000 4000 6000 8000 10000 12000 14000 16000 18000];
bob=squeeze(returnMatrix(:,30,:));
```

```
[C,h]=contourf(bob',levels);
clabel(C,h);
set(h,'ShowText','on','TextStep',get(h,'LevelStep')*2);
colormap cool;
xlabel('Stand age (years)')
ylabel('Wood Product (tC/ha)')
axis([0 250 0 100])
title('NPV ($/ha) countour by initial state')
set(gca,'YTickLabel',{'0';'50';'100';'150';'200';'250';'300';'350';'400';'450';'500'})

bob=squeeze(returnMatrix(:,60,:));
figure(22)
levels =[-2000 -4000 -6000 -8000 -10000];
[C,h]=contour((bob'),levels);
clabel(C,h);
hold all
levels =[0 2000 4000 6000 8000 10000 12000 14000 16000 18000];
bob=squeeze(returnMatrix(:,30,:));
[C,h]=contourf(bob',levels);
clabel(C,h);
set(h,'ShowText','on','TextStep',get(h,'LevelStep')*2);
colormap cool;
xlabel('Stand age (years)')
ylabel('Wood Product (tC/ha)')
axis([0 250 0 100])
title('NPV ($/ha) countour by initial state')
set(gca,'YTickLabel',{'0';'50';'100';'150';'200';'250';'300';'350';'400';'450';'500'})

bob=squeeze(returnMatrix(:,80,:));
figure(23)
levels =[-2000 -4000 -6000 -8000 -10000];
[C,h]=contour((bob'),levels);
clabel(C,h);
hold all
levels =[0 2000 4000 6000 8000 10000 12000 14000 16000 18000];
bob=squeeze(returnMatrix(:,30,:));
[C,h]=contourf(bob',levels);
clabel(C,h);
set(h,'ShowText','on','TextStep',get(h,'LevelStep')*2);
```

```
colormap cool;
xlabel('Stand age (years)')
ylabel('Wood Product (tC/ha)')
axis([0 250 0 100])
title('NPV ($/ha) countour by initial state')
set(gca,'YTickLabel',{'0';'50';'100';'150';'200';'250';'300';'350';'400';'450';'500'})

bob=squeeze(returnMatrix(:,100,:));
figure(24)
levels =[-2000 -4000 -6000 -8000 -10000];
[C,h]=contour((bob'),levels);
clabel(C,h);
hold all
levels =[0 2000 4000 6000 8000 10000 12000 14000 16000 18000];
bob=squeeze(returnMatrix(:,30,:));
[C,h]=contourf(bob',levels);
clabel(C,h);
set(h,'ShowText','on','TextStep',get(h,'LevelStep')*2);
colormap cool;
xlabel('Stand age (years)')
ylabel('Wood Product (tC/ha)')
axis([0 250 0 100])
title('NPV ($/ha) countour by initial state')
set(gca,'YTickLabel',{'0';'50';'100';'150';'200';'250';'300';'350';'400';'450';'500'})

% Solution
decisionRule(age+1,DOM/incDOM+1,Lumber/incLumber+1)=decision0(iState)
toc

%%The following functions are needed to run the dynamic programming model:

%% merch volume
function mv = merchvol(age,v1,v2,v3)
  mv = v1 * (1-exp(-v2 * age))^v3;
end

%% biomass
function bm = biomass(age,b1,b2,b3)
  bm = b1 * (1-exp(-b2 * age))^b3;
```

```
end

%% Calculates Lumber, DOM, and Age given the state index
function [age DOM Lumber]=getAgeDOMLumber(index,nAge, nDOM,
nLumber, incAge, incDOM, incLumber)

age = (mod(index-1, nAge))*incAge;
Lumber = (fix((index-1)/(nAge*nDOM)))*incLumber;

bob=index-(Lumber/incLumber)*nAge*nDOM;
DOM = (fix((bob-1)/nAge))*incDOM;
end

%% state index
function si = stateIndex(age,DOM,Lumber,nAge,nDOM,incAge,incDOM,incLumber)
  si=(Lumber/incLumber)*nDOM*nAge+(DOM/incDOM)*nAge+age/incAge+1;
end
```

APPENDIX C

Appendix to Chapter 4

```
clear all
tic

%% Program control parameters
maxStage=500;

minDOM=0;
maxDOM=500;
incDOM=1;
nDOM=(maxDOM-minDOM)/incDOM+1;

minAge=0;
maxAge=250;
incAge=1;
nAge=(maxAge-minAge)/incAge+1;

nState= nDOM * nAge;
%%
discount_rate = 0.05;
discount_factor = 1/(1 + discount_rate);
% logprice  =   15.58 % $/m^3 Lumber Price is 250 CAD/MBF
logprice  =   41.83; % $/m^3 Lumber Price is 375 CAD/MBF
% logprice  =   68.08 % $/m^3 Lumber Price is 500 CAD/MBF
logcost   = 6250;% $/ha % (Road:1150 CAD/ha; TTT:5100 CAD/ha)
% (Milling: 34.65 CAD/m3; Haul: 4.84 CAD/m3; Overhead: 8.06 CAD/m3)
```

```
estabcost =  1250; % $/ha
co2_c_ratio = (12 + (16 * 2)) / 12;
p_co2 = 20; % $/Mg CO_2
p_c = p_co2 * co2_c_ratio; % $/Mg C

decay = 0.008412; % decay rate for DOM
litterfall = 0.01357; % biomass to DOM conversion rate
wood_C_ratio = 0.2; % (Mg C) / (m^3 merchantable volume)
Rental_Rate = p_c * discount_rate;
%% Function coefficients
% biomass coefficients
b1 = 198.6;
b2 = 0.0253;
b3 = 2.64;
% merchantable volume
v1 = 500.4;
v2 = 0.027;
v3 = 4.003;

%% Save the run control information for later use
save runcontrol.mat maxStage minDOM incDOM nDOM maxDOM minAge ...
incAge nAge maxAge nState discount_rate discount_factor logprice ...
logcost estabcost co2_c_ratio p_co2 Rental_Rate p_c decay ...
litterfall wood_C_ratio b1 b2 b3 v1 v2 v3

%% State payoff calculations
netRevenueHarvest = zeros(nState,1);
netRevenueNoHarvest = zeros(nState,1);

toAgeHarvest=1;

toStateNoHarvest=zeros(nState,2);
toStateHarvest=zeros(nState,2);

propStateNoHarvest=zeros(nState,2);
propStateHarvest=zeros(nState,2);
%%
Rotation_MSY = baselineMSY(v1,v2,v3); %MAXIMUM SUSTAIN YIELD ROTATION AGE
Rotation_Faustmann=baselineFaustmann(v1,v2,v3); %FAUSTMANN ROTATION AGE
```

```
%%
previous_bmbaseline=0;
previousDOM=-1;
for startDOM = 0:10:maxDOM;

    for startAge= 0:10:maxAge;
        baselineDOM=zeros(maxStage+1,1);
        baselineBiomass=zeros(maxStage+1,1);
        baselineAge=zeros(maxStage+1,1);
        baselineTEC=zeros(maxStage+1,1);
        baselineMV=zeros(maxStage+1,1);

        iDOM=floor(startDOM/incDOM)+1;
        iAge=floor(startAge/incAge)+1;

        for iStage=1:maxStage+1
            if (iStage==1)
                baselineDOM(iStage)=(iDOM-1)*incDOM;
                age=iAge-1;
                baselineAge(iStage)=age;
                baselineBiomass(iStage)=biomass(age,b1,b2,b3);
                baselineMV(iStage)=merchvol(age,b1,b2,b3);
            else
                prevDOM=baselineDOM(iStage-1);
                prevBiomass=baselineBiomass(iStage-1);
                prevMV=baselineMV(iStage-1);
                baselineDOM(iStage)=(1-decay)*prevDOM + ...
                    litterfall * prevBiomass;

%                 if (baselineAge(iStage-1) >= Rotation_Faustmann)
%                     age=1;
                if (baselineAge(iStage-1) >= Rotation_MSY)
                    age=1;

                    baselineDOM(iStage)=baselineDOM(iStage) + ...
                        prevMV - (prevMV * wood_C_ratio);
                else
                    age=baselineAge(iStage-1)+1;
```

```
        end
        baselineAge(iStage)=age;
        baselineBiomass(iStage)=biomass(age,b1,b2,b3);
        baselineMV(iStage)=merchvol(age,b1,b2,b3);
    end
end

baselineTEC=baselineBiomass+baselineDOM;
plot(baselineTEC)
deltaBaselineTEC=baselineTEC-circshift(baselineTEC,1);
deltaBaselineTEC(1)=0;
plot(deltaBaselineTEC)

deltaTECNoHarvest=zeros(nState,1);
deltaTECHarvest=zeros(nState,1);
for iState=1:nState

    if (mod(iState,10000) == 0)  %print current state to
    %indicate model is running
        iState;
    end

    [age,DOM]=getAgeDOMNew(iState,minAge, incAge, maxAge, ...
    minDOM, incDOM, maxDOM)

    mv = merchvol(age,v1,v2,v3);
    bm = biomass(age,b1,b2,b3);
    bm1 = biomass(age+1,b1,b2,b3);

    netTimberRevenueHarvest =logprice * mv  - logcost - estabcost;

    %% DELTA BIOMASS:
    %No Harvest
    deltaBmNoHarvest = bm1 - bm;
    %Harvest
    deltaBmHarvest = -bm;

    %% DELTA DEAD ORGANIC MATTER:
```

```
%No Harvest
deltaDOMNoHarvest = (-decay * DOM) + (litterfall * bm);
%Harvest
deltaDOMHarvest = deltaDOMNoHarvest + bm - (wood_C_ratio * mv);
%% DELTA Total Ecosystem Carbon:
%No Harvest
deltaTECNoHarvest(iState) = deltaBmNoHarvest + deltaDOMNoHarvest;
%Harvest
deltaTECHarvest(iState) = deltaBmHarvest + deltaDOMHarvest;

%% BASELINE:
%% Maximum Sustained Yield Rotation
newAge=newAgeMSY(age,startAge,Rotation_MSY);
mv_baseline=mvbaselineMSY(age, startAge, v1,v2,v3,Rotation_MSY);
bm_baseline=bmbaselineMSY(age, startAge, b1,b2,b3,Rotation_MSY);
DOMB=DOMbaselineMSYNew(startDOM, previousDOM, age, startAge, ...
b1,b2,b3,v1,v2,v3,Rotation_MSY);

%% Faustmann Rotation
 % newAge=newAgeFaustmann(age,startAge,Rotation_Faustmann);
 % mv_baseline=mvbaselineFaustmann(age, startAge, ...
 % v1,v2,v3,Rotation_Faustmann);
 % bm_baseline=bmbaselineFaustmann(age, startAge, ...
 % b1,b2,b3,Rotation_Faustmann);

% DOMB=DOMbaselineFaustmannNew(startDOM, previousDOM, ...
% age, startAge, b1,b2,b3,v1,v2,v3,Rotation_Faustmann);

%% DELTA BASELINE:
% Delta Biomass baseline:
delta_bmbaseline=bm_baseline-previous_bmbaseline;

% Delta DOM baseline:
if previousDOM==-1
    %      previousDOM=0;
    previousDOM=startDOM;
 end

 delta_DOMbaseline=DOMB-previousDOM;
```

```
        % Delta TEC Baseline:
        deltaTECBaseline = delta_bmbaseline + delta_DOMbaseline

        previousDOM=DOMB;
        previous_bmbaseline=bm_baseline;

        %% Revenue:
        %Carbon Revenue
        %carbonRevenueNoHarvest = p_c * (deltaTECNoHarvest-deltaTECBaseline);
        %carbonRevenueHarvest = p_c * (deltaTECHarvest-deltaTECBaseline);

        %Total Revenue from product sale and carbon sequestration
        netRevenueHarvest(iState,1) = netTimberRevenueHarvest;
        netRevenueNoHarvest(iState,1) = 0;

        toAgeNoHarvest=min(age+1,maxAge);
%---------------
        toDOMNoHarvest=min(DOM+deltaBmNoHarvest+deltaDOMNoHarvest,maxDOM);
        toDOMNoHarvest_lower=fix(toDOMNoHarvest/incDOM)*incDOM;
        toDOMNoHarvest_upper=min(toDOMNoHarvest_lower+incDOM,maxDOM);
%---------------
        toStateNoHarvest(iState,1)=stateIndexNew(toAgeNoHarvest,
        toDOMNoHarvest_lower,minAge, incAge, maxAge, minDOM, incDOM, maxDOM);

        toStateNoHarvest(iState,2)=stateIndexNew(toAgeNoHarvest,
        toDOMNoHarvest_upper,minAge, incAge, maxAge, minDOM, incDOM, maxDOM);
%---------------
        toDOMHarvest=max(min(DOM+deltaBmHarvest+deltaDOMHarvest,maxDOM),0);
        toDOMHarvest_lower=fix(toDOMHarvest/incDOM)*incDOM;
        toDOMHarvest_upper=min(toDOMHarvest_lower+incDOM,maxDOM);
%---------------
        toStateHarvest(iState,1)=stateIndexNew(toAgeHarvest,
        toDOMHarvest_lower,minAge, incAge, maxAge, minDOM, incDOM, maxDOM);

        toStateHarvest(iState,2)=stateIndexNew(toAgeHarvest,
        toDOMHarvest_upper,minAge, incAge, maxAge, minDOM, incDOM, maxDOM);
 %---------------
        %   t=rem(toDOMNoHarvest,1);
```

```
            t=rem(toDOMNoHarvest,incDOM)/incDOM;
            propStateNoHarvest(iState,1)=1-t;
            propStateNoHarvest(iState,2)=t;

            %   t=rem(toDOMHarvest,1);
            t=rem(toDOMHarvest,incDOM)/incDOM;
            propStateHarvest(iState,1)=1-t;
            propStateHarvest(iState,2)=t;
        end
        iState;
       %---------------
        %%% The Dynamic Program
        return0=zeros(nState,1);
        decision0=zeros(nState,1);
        nStage=maxStage
        for iStage=nStage:-1:0
            return1=return0;
            decision1=decision0;
            for iState=1:nState

                carbonRevenueHarvest=p_c*(deltaTECHarvest(iState) ...
                -deltaBaselineTEC(iStage+1));
                carbonRevenueNoHarvest=p_c*(deltaTECNoHarvest(iState)...
                -deltaBaselineTEC(iStage+1));

                if (mod(iState,10000) == 0)
                    [iStage,iState]
                end
return_harvest = netRevenueHarvest(iState,1) + carbonRevenueHarvest + ...
      discount_factor * (propStateHarvest(iState,1) * ...
      return1(toStateHarvest(iState,1),1) + ...
      propStateHarvest(iState,2) * ...
      return1(toStateHarvest(iState,2),1));

return_noharvest = netRevenueNoHarvest(iState,1) + carbonRevenueNoHarvest + ...
      discount_factor * (propStateNoHarvest(iState,1) * ...
      return1(toStateNoHarvest(iState,1),1) + ...
      propStateNoHarvest(iState,2) * ...
      return1(toStateNoHarvest(iState,2),1));
```

```
                if (return_harvest > return_noharvest)
                    return0(iState)=return_harvest;
                    decision0(iState)=1;
                else
                    return0(iState)=return_noharvest;
                    decision0(iState)=0;
                end
            end
        end

        decisionRule=zeros(nAge,nDOM);
        return0=return0-estabcost;
        returnMatrix=zeros(nAge,nDOM);

        for iState=1:nState
            [age,DOM]=getAgeDOMNew(iState,minAge, incAge, maxAge, ...
            minDOM, incDOM, maxDOM);

            decisionRule(age+1,DOM/incDOM+1)=decision0(iState);
            returnMatrix(age+1,DOM/incDOM+1)=return0(iState);
        end

        %% Save the model solution
        fileName=strcat('SDF0',int2str(startDOM),'SAF0',int2str(startAge));
        save (fileName, 'decisionRule','returnMatrix');

    end
end
%------------------------------------

%% Plot Decision Rule
figure(1)
mesh(decisionRule')
shading flat
view([0 90])
xlabel('Stand Age (years)')
ylabel('DOM (tC/ha)')
title('Decision Rule')
```

```
%% Plot Return
figure(2);
levels =[-1000 -2000 -3000 -4000 -5000 -6000 -7000 -8000];
[C,h]=contour(returnMatrix',levels);
clabel(C,h);
hold all
levels =[0 1000 2000 3000 4000 5000 6000 8000 9000 10000];
[C,h]=contourf(returnMatrix',levels);
clabel(C,h);
set(h,'ShowText','on','TextStep',get(h,'LevelStep')*2);
colormap cool;
xlabel('Stand age (years)')
ylabel('DOM (tC/ha)')
axis([0 250 0 500])
title('NPV ($/ha) countour by initial state')

%% Solution
decisionRule(age+1,DOM/incDOM+1)=decision0(iState)
toc

%%%The following functions are needed to run the dynamic programming model:

%% merch volume
function mv = merchvol(age,v1,v2,v3)
  mv = v1 * (1-exp(-v2 * age))^v3;
end
%----------
%% biomass
function bm = biomass(age,b1,b2,b3)
  bm = b1 * (1-exp(-b2 * age))^b3;
end
%----------
function bm_baseline=bmbaselineMSY(age, startAge,b1,b2,b3,Rotation_MSY);
    newAge=newAgeMSY(age,startAge,Rotation_MSY);
    if (newAge==Rotation_MSY)
        newAge=1;
    else
        newAge=newAge+1;
```

```
    end
    bm_baseline = biomass(newAge,b1,b2,b3);
end

function Rotation_Faustmann=baselineFaustmann(v1,v2,v3)
    v1 = 500.4;
    v2 = 0.027;
    v3 = 4.003;
    discount_rate = 0.05;
    logprice  =   41.83; % $/m^3
    logcost   = 6250; % $/ha 11500
    estabcost = 1250; % $/ha

i=1;
    for age=0:250

        mv = merchvol(age,v1,v2,v3);

        Current_Revenue(i)=(logprice * mv)/(((1+discount_rate)^i)-1);
        Current_Logcost(i)=logcost/(((1+discount_rate)^i)-1);

         Current_Estabcost(i)=estabcost*(1+discount_rate)^i/
         (((1+discount_rate)^i)-1);

netTimberRevenueHarvest(i) = Current_Revenue(i)-Current_Logcost(i) ...
     - Current_Estabcost(i);
i=i+1;
     end

    [value,index]=(max(netTimberRevenueHarvest));
    Rotation_Faustmann=index
%----------
function[age, DOM] = getAgeDOMNew(index, minAge, incAge, ...
maxAge, minDOM, incDOM, maxDOM);

    age=minAge + incAge*(mod(index-1, (maxAge-minAge)/incAge+1));
    DOM=minDOM + incDOM* fix ( (index-1) / ((maxAge-minAge)/incAge+1));
end
%----------
```

```
function newAge=newAgeFaustmann(age,startAge,Rotation_Faustmann);

if (startAge<Rotation_Faustmann)
    if (startAge+age)<=Rotation_Faustmann
        newAge=startAge+age;
    else

    temp=mod((startAge+age), Rotation_Faustmann);
        if (temp==0)
newAge=(startAge+age)-(fix((startAge+age)/Rotation_Faustmann)-1)*
Rotation_Faustmann;
        else
            newAge=temp;
        end
    end
else
    if (age<Rotation_Faustmann)
        newAge=age+1;
    else
        newAge=mod(age, Rotation_Faustmann)+1;
     end
end
end
%----------

function newAge=newAgeMSY(age,startAge,Rotation_MSY)
if (startAge<Rotation_MSY)
    newAge=mod((startAge+age), Rotation_MSY+1);
else
    newAge=mod(age, Rotation_MSY+1);
end
end
%----------
function newAge=newAgeFaustmann(age,startAge,Rotation_Faustmann);
if (startAge<Rotation_Faustmann)
    if (startAge+age)<=Rotation_Faustmann
        newAge=startAge+age;
    else
 temp=mod((startAge+age), Rotation_Faustmann);
```

```
        if (temp==0)
        newAge=(startAge+age)-(fix((startAge+age)/Rotation_Faustmann)-1)*
        Rotation_Faustmann;
        else
            newAge=temp;
        end
    end
else
    if (age<Rotation_Faustmann)
        newAge=age+1;
    else
        newAge=mod(age, Rotation_Faustmann)+1;
     end
     end
end
%----------
function newAge=newAgeMSY(age,startAge,Rotation_MSY)
if (startAge<Rotation_MSY)
    newAge=mod((startAge+age), Rotation_MSY+1);
else
    newAge=mod(age, Rotation_MSY+1);
end
end
%----------
function mv_baseline=mvbaselineMSY(age, startAge, v1,v2,v3,Rotation_MSY);
    newAge=newAgeMSY(age,startAge,Rotation_MSY);
    mv_baseline = merchvol(newAge,v1,v2,v3);
end
%----------
function mv_baseline=mvbaselineFaustmann(age, startAge,...
 v1,v2,v3,Rotation_Faustmann);
    newAge=newAgeFaustmann(age,startAge,Rotation_Faustmann);
    mv_baseline = merchvol(newAge,v1,v2,v3);
end
%----------
function bm_baseline=bmbaselineMSY(age, startAge, b1,b2,b3,Rotation_MSY);
    newAge=newAgeMSY(age,startAge,Rotation_MSY);
    if (newAge==Rotation_MSY)
        newAge=1;
```

```
    else
        newAge=newAge+1;
    end
    bm_baseline = biomass(newAge,b1,b2,b3);
end
%----------
function bm_baseline=bmbaselineFaustmann(age, startAge,...
 b1,b2,b3,Rotation_Faustmann);
    newAge=newAgeFaustmann(age,startAge,Rotation_Faustmann);
    if (newAge==Rotation_Faustmann)
        newAge=1;
    else
        newAge=newAge+1;
    end
    bm_baseline = biomass(newAge,b1,b2,b3);
end
%----------
 function DOMB=DOMbaselineMSYNew(startDOM, previousDOM,...
 age, startAge, b1,b2,b3,v1,v2,v3,Rotation_MSY);

    decay = 0.008412; % decay rate for DOM
    litterfall = 0.01357; % biomass to DOM conversion rate
    wood_C_ratio = 0.2; % (Mg C) / (m^3 merchantable volume)

    bm_baseline=bmbaselineMSY(age, startAge, b1,b2,b3,Rotation_MSY);
    mv_baseline=mvbaselineMSY(age, startAge, v1,v2,v3,Rotation_MSY);

    newAge=newAgeMSY(age,startAge, Rotation_MSY);

    if(previousDOM==-1)
        BiotoDOM=0; %Biomass to DOM when harvesting occurs in time ZERO
        if startAge>=Rotation_MSY %When the initial stand is older than the
        %rotation age

     BiotoDOM = biomass(startAge,b1,b2,b3)- ...
            wood_C_ratio*merchvol(startAge,v1,v2,v3);
        end

   DOMB=startDOM + BiotoDOM;
```

```
    %When newAge is not a multiple of Rotation Age
    else if ((age+startAge)<Rotation_MSY);
        DOMB=previousDOM*(1-decay)+ bm_baseline*litterfall;

    % When newAge is a multiply of Rotation Age
        else
            if (newAge==Rotation_MSY)
                bm_baseline_previous=biomass(Rotation_MSY,b1,b2,b3);
               mv_baseline_previous=mvbaselineMSY(age-1, startAge,...
               v1,v2,v3,Rotation_MSY);

             temp=(bm_baseline_previous-wood_C_ratio*mv_baseline_previous);
             DOMB=previousDOM*(1-decay)+ bm_baseline*litterfall + ...
             (bm_baseline_previous-wood_C_ratio*mv_baseline_previous);
            else
                DOMB=previousDOM*(1-decay)+ bm_baseline*litterfall;
            end
        end
   end
end
%----------
 function DOMB=DOMbaselineFaustmannNew(startDOM, previousDOM, age, ...
  startAge, b1,b2,b3,v1,v2,v3,Rotation_Faustmann);

    decay = 0.008412; % decay rate for DOM
    litterfall = 0.01357; % biomass to DOM conversion rate
    wood_C_ratio = 0.2; % (Mg C) / (m^3 merchantable volume)

    bm_baseline=bmbaselineFaustmann(age, startAge, b1,b2,b3,Rotation_Faustmann);
    mv_baseline=mvbaselineFaustmann(age, startAge, v1,v2,v3,Rotation_Faustmann);

    newAge=newAgeFaustmann(age,startAge, Rotation_Faustmann);

    if(previousDOM==-1)
        BiotoDOM=0; %Biomass to DOM when harvesting occurs in time ZERO
        if startAge>=Rotation_Faustmann %When the initial stand is older
        %than the rotation age
```

```
  BiotoDOM=biomass(startAge,b1,b2,b3)- wood_C_ratio*merchvol(startAge,v1,v2,v3);
        end

        DOMB=startDOM + BiotoDOM;

   %When newAge is not a multiple of Rotation Age
    else
        if ((age+startAge)<Rotation_Faustmann)

            DOMB=previousDOM*(1-decay)+ bm_baseline*litterfall;

            % When newAge is a multiply of Rotation Age
        else
            if (newAge==Rotation_Faustmann)
                bm_baseline_previous=biomass(Rotation_Faustmann,b1,b2,b3);

                mv_baseline_previous=mvbaselineFaustmann(age-1, ...
                startAge, v1,v2,v3,Rotation_Faustmann);

             temp=(bm_baseline_previous-wood_C_ratio*mv_baseline_previous);
             DOMB=previousDOM*(1-decay)+ bm_baseline*litterfall + ...
             (bm_baseline_previous-wood_C_ratio*mv_baseline_previous);
            else
                DOMB=previousDOM*(1-decay)+ bm_baseline*litterfall;
            end
        end
   end
end
```