University of Alberta

Management Decisions in the Boreal Forest Considering Timber and Carbon Market Incentives

by

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Abstract

This study investigates how carbon management incentives will affect forestry practices in Canada's boreal plains ecozone. Analysis considers changes in forest management decisions over a range of carbon market incentives, regulatory structures, and landscape characteristics. An integrated model is developed for the purposes of this research, capable of incorporating both forest carbon and timber values within an optimal management framework. A key aspect of this modeling approach involves applying the Carbon Budget Model of the Canadian Forest Sector to incorporate a more rigorous and realistic depiction of forest carbon than has previously been captured in economic analyses. By evaluating the carbon management implications of forest landscape characteristics and existing policy frameworks, study results will assist governments and firms in determining which boreal forest regions are candidates for carbon accounting. Conclusions drawn can also contribute to policy discussions concerning the inclusion of forest carbon management within Canada's national climate change strategy.

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Chapter 1: Introduction

In recent years, forest management practices in Canada have been modified to include a broader set of objectives related to the overall ecological integrity of the forested landscape. Encompassed under the heading of sustainable forest management (SFM), this broadened approach considers values such as biodiversity, wildlife habitat and recreational opportunities alongside the traditional management principle of sustained timber yield. However, increased awareness of the effects of greenhouse gas emissions and climate change has also focused attention on the role of forests in the global carbon cycle. By recognizing the potential for forests to sequester carbon, Articles 3.3 and 3.4 of the Kyoto Protocol have helped to generate this interest by creating an opportunity for forest management activities to contribute towards emission reduction targets.

1.1 General Problem & Research Statement

Research has shown that Canada's forest ecosystems have the potential to switch between being net atmospheric carbon sinks and net sources of atmospheric carbon (Kurz and Apps 1999).[1] Forest management practices have the ability to significantly enhance the strength of forest carbon sinks and to delay or reduce emissions from forest carbon sources (Apps *et* al. 2000; Metz *et al.* 2001). Furthermore, the potential to sequester carbon through forest management activities has been identified as a relatively cost-effective means of offsetting emissions from other sources, at least temporarily. Such an

[1] Kurz and Apps (1999) identify forest ecosystem characteristics such as age-class structure, disturbance history and volumes of woody debris as factors which contribute to present and future carbon dynamics.

approach could provide time while more efficient technologies for emission abatement are developed and implemented (van Kooten *et al.* 1997; Metz *et al.* 2001). Given the size of Canada's forested land base, forest carbon management could represent an important component of any Canadian domestic climate change strategy.[2]

As a signatory to the Kyoto Protocol, Canada has the option of whether or not to invoke Article 3.4, concerning human induced activities related to land use, land-use change and forestry, for the first commitment period (2008-2012). The rules related to carbon accounting under Article 3.4 specify that while credits can be claimed for forest management activities that increase the sequestration potential of forests, forestry activities resulting in a net source of emissions must be accounted for as well.[3] If Canada intends to remain within the framework of the Kyoto Protocol, it must carefully assess the potential for forest management activities to generate carbon credits before making this decision. Moreover, the implications of these management practices for the forest landscape must be considered.

A growing number of studies are identifying the alternative silvicultural and forest management methods that could enhance the mitigation potential of managed forests (Hoen and Solberg 1994; Binkley *et al.* 1997; Nabuurs *et al.* 2000; Sampson and Scholes 2000). Modifying forest management decisions to focus on increasing the

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[2] Natural Resources Canada (2006) classifies 35.15% (310.1 million ha) of Canada's land mass as forest land.

[3] Outstanding issues pertaining to Articles 3.3 and 3.4, including land use, land-use change and forestry definitions and the rules for carbon accounting, were agreed upon at Conference of the Parties 7 as part of the Marrakesh Accords (UNFCCC 2002). Details from these proceedings can be located through the United Nations Framework Convention on Climate Change (UNFCCC) website at: http://unfccc.int/methods_and_science/lulucf/items/3063.php.

volume of stored carbon may result in trade-offs with other forest management objectives. Important questions are thus raised concerning how the implementation of forest carbon management will correspond to SFM practices. If forests are to make a contribution to Canada's domestic climate change strategy, it is critical to understand how incentives related to carbon sequestration will affect forest management decisions and forest values.

An additional concern in Canada is the potential impact of carbon management on forest industry. According to Natural Resources Canada (2006), the forestry sector in 2005 generated 2.9% of Canada's GDP, was by far the largest contributor to Canada's trade balance at $31.9 billion, and accounted for 2.1% of Canada's total employment (339,900 direct jobs). Moreover, the forestry sector serves as the main source of income for a significant number of rural and remote communities while also providing a major area of economic opportunity for Canada's Aboriginal peoples (National Climate Change Process 1999). How the resources allocated to timber production by the Canadian forest industry will be affected by incentives to sequester carbon merits attention as well.

The research undertaken in this project assesses the sensitivity of forest management decisions to an incentive mechanism and variety of key variables related to forest carbon management in Canada. The focus will be on different productivity and cost variables, their effect on carbon and timber management incentives and the resulting management decisions. An integrated modeling framework, designed for the incorporation of carbon management into an operational timber management modeling tool, is developed and described. Analysis is centred on changes to the forested landscape that occur as management decisions are made in response to alternative market incentives and regulatory regimes.

1.2 Research Objectives

This research project aims to provide insight into national policy discussions regarding carbon accounting incentives and is intended to inform industry and government about the potential implications of forest carbon management. There is still substantial debate over how to properly credit carbon sequestered in forests. Alternative market conditions and regulatory structures could produce very different responses in terms of rotation age, management intensity and harvest policy. These responses may also be conditioned by the forest landscape itself, including variables such as initial age-class structure and growing conditions (Kurz *et al.* 2002).

While the costs of producing carbon offsets through forestry activity have been widely investigated (Sohngen and Mendelsohn 2003; van Kooten *et al.* 2004), the impact of a market for carbon on the response from individual forestry firms has not had substantial attention in the literature.[4] Furthermore, most economic analyses to date have included only simple representations of forest carbon dynamics. The objectives of this study can thus be summarized in the following points:

[4] A notable exception is Maynes (2003), who studies the forest management implications of different carbon accounting "stances" under various market incentive and regulatory structures. A carbon accounting stance reflects the collection of forest carbon pools which are considered eligible to generate carbon credits.

1. Develop a framework for integrating a detailed depiction of forest carbon dynamics into an operational timber management modeling tool. The goal for this framework is to derive optimal harvest scheduling models based on the accounting of both timber and carbon offset values.
2. Apply this integrated forest management model to a representation of a forested landscape for the Boreal Plains ecozone in Canada.[5] Describe how the landscape will change as a result of management decisions taken under different carbon market incentives and regulatory regimes.
3. Analyze the sensitivity of forest carbon management decisions to the past disturbance regime (as reflected by the initial age-class structure) and the rate of time preference.
4. Assess how the cost structure of current forest management regimes may be altered by the introduction of incentives for forest carbon management.
5. Describe how the policy environment will affect forest management decisions under the various model scenarios.

Analysis in this study will address the following types of questions: (i) given certain carbon market incentives, which types of forest are most likely to be managed for carbon?, (ii) what silvicultural practices are most likely to be used?, (iii) where on the forest landscape is carbon management most likely to occur?, (iv) how will forest policy affect the decision to manage for carbon?, and (v) what return will be realized from carbon management relative to timber management alone?

[5] For a map of the terrestrial ecozones in the Canadian boreal forest, refer to Figure A-1 in the Appendix.

1.3 Synopsis of Integrated Modeling Approach

The effects of carbon market incentives on forest management decisions are examined by applying a linear programming model to a representation of a forest in the boreal plains ecozone of Canada. Given an initial age-class structure, the Woodstock forest modeling package (Remsoft Inc. 1998) is utilized to develop an optimal harvest schedule for the region of interest. Carbon dynamics are incorporated using carbon yield curves developed with the Carbon Budget Model of the Canadian Forest Sector (Canadian Forest Service 2005). These carbon yields capture stocks and fluxes between biomass and dead organic matter carbon pools and are integrated directly into the Woodstock forest management model.[6] This approach allows for a detailed accounting of net carbon stock changes for the forest ecosystem. Simulations run in the Carbon Budget Model allowed for the generation of carbon yields specific to individual forest cover types, productivity levels, management intensities, stand disturbance histories and harvest rotation lengths.

1.4 Thesis Structure

The remaining chapters of this thesis lay the basic groundwork of the study, present the modeling framework and key results, and discuss relevant policy considerations and future research extensions. Chapter 2 includes a discussion of the biological dynamics related to carbon supply and management in the boreal forest, covers the economic theory and literature concerning the economics of forest carbon management and establishes the key issues pertaining to carbon market structure.

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[6] Carbon "stocks" refer to the static volume of carbon stored in an ecosystem carbon pool, while carbon "flux" refers to transfers of carbon between two ecosystem carbon pools or between an ecosystem carbon pool and the atmosphere.

Chapter 3 presents the integrated modeling framework developed for this study, with particular attention paid to describing the methods and challenges associated with representing forest carbon dynamics. The overall experimental design, including forest landscape characteristics, management options and carbon incentive mechanisms for incorporation into the modeling framework, is laid out in Chapter 4. Chapter 5 presents the results from this study, covering the predicted landscape carbon dynamics, the expected benefits of carbon relative to timber management, the landscape impacts of forest carbon management decisions and the cost implications of different factors in the experimental design. Chapter 6 concludes with a discussion of key findings, important areas for future research and a final project summary.

Chapter 2: Background

This chapter lays out the background information necessary to investigate how a market for carbon will influence forest management decisions in Canada's boreal forest. The alternative approaches to forest carbon management are a key consideration in this regard. Accordingly, the first two sections are dedicated to building an understanding of the biological dynamics related to carbon supply and management in the boreal. Subsequently, section three covers the significant elements from previous research that has been conducted on the economics of forest carbon sequestration. The literature concerning economically optimal harvest rotations and the overall costs of carbon management is therefore surveyed and presented. The fourth section establishes the key issues pertaining to the structure of a market for carbon as well as several concerns related to the overall policy and regulatory framework. The key issues are restated in the summary at the end of the chapter.

2.1 Forest Carbon Dynamics

Through the process of photosynthesis, forest ecosystems are able to absorb carbon dioxide (CO_2) from the atmosphere and store it for extended periods of time, creating a sink. Conversely, the carbon stored in forests will ultimately be released back into the atmosphere through natural decomposition, the emissions associated with disturbances such as fire, or removal by harvest. Individual stands may therefore act as net carbon sinks or net carbon sources, depending on local conditions, stand age and disturbance history (Kurz *et al.* 2002).

Stand level carbon stocks can be separated into two major pools; the living forest biomass (both aboveground and belowground) and dead organic matter (including detritus and soil organic matter). Carbon pool content and flux is determined mainly by the dynamics of the living biomass. As a forest grows, carbon dioxide is absorbed, converted into fibre and stored as biomass in tree stems, branches, foliage and roots. Varying proportions of carbon are then transferred from biomass to dead organic matter (DOM) pools as litterfall accumulates on the forest floor and as the forest is subjected to different types of disturbance (Apps *et al.* 2000).

For the boreal forest, carbon stored in the DOM pool tends to dominate the overall stock of carbon in a forest stand. Higher DOM carbon stocks are associated with ecozone that have lower mean annual temperatures and with productive forests that produce larger quantities of biomass input (Kurz and Apps 1999). Biomass input is largely dependent on the type of forest cover present and the particular disturbances to which the stand is subjected. According to Apps *et al.* (2000), whether the stand is dominated by deciduous or coniferous species affects carbon flux through different rates of foliage, root, branch, bark and dead stem litterfall. Meanwhile, Kurz *et al.* (1998) describe how disturbances such as fire, insect mortality and harvesting differ in the resulting quantity of carbon transferred to DOM pools.[7]

[7] Harvest events remove the biomass in merchantable timber from the stand, transfer faster decomposing foliage and branches to the DOM carbon pool and release carbon to the atmosphere through disturbance of the stand. Insect infestation results in a much larger transfer from the biomass to the DOM pool through additions of dead trees to litter and coarse woody debris piles. Wildfire releases biomass and soil carbon to the atmosphere through oxidization but also leaves some biomass as larger branches, roots and stemwood for transfer to DOM pools (Kurz *et al.* 1998).

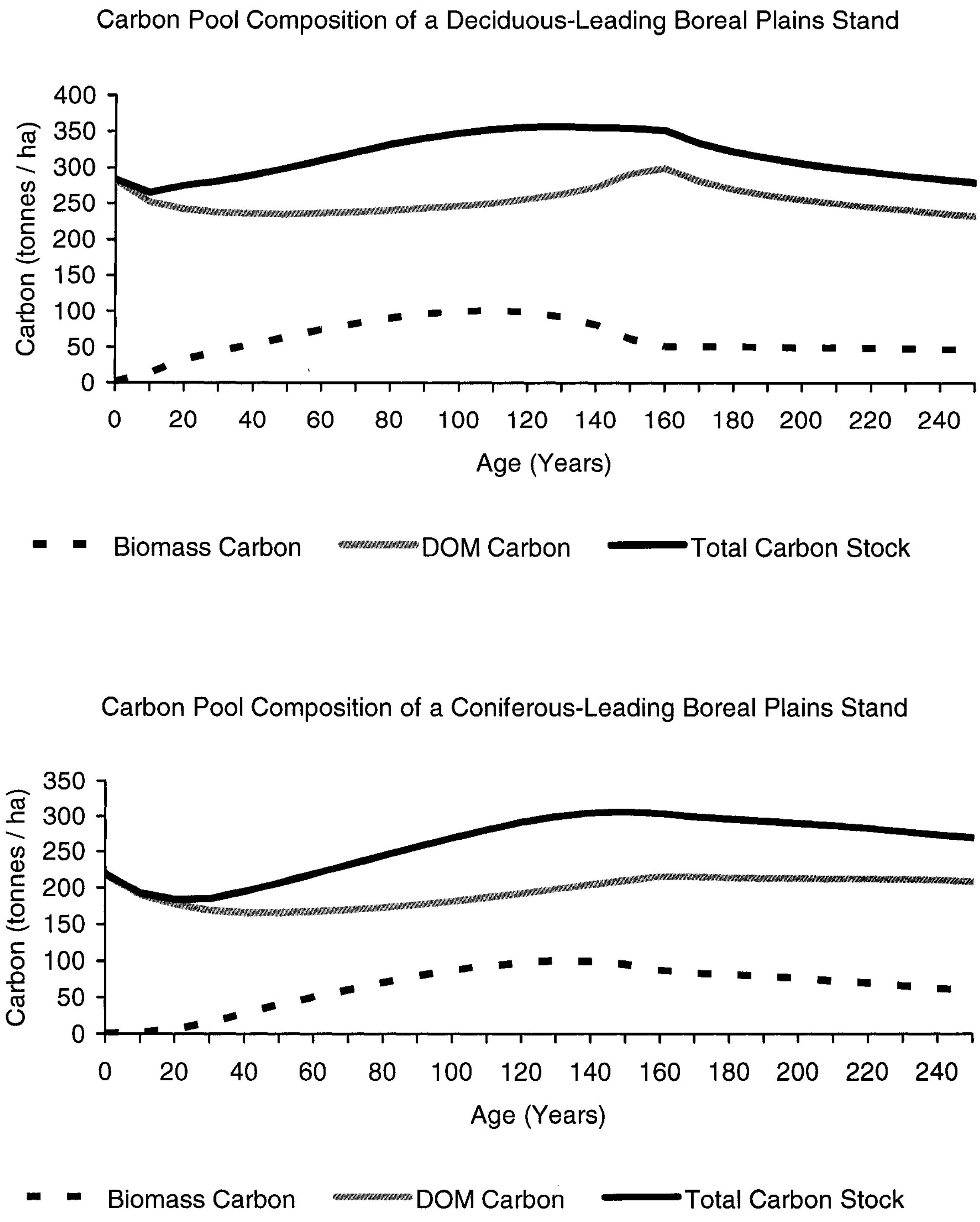


Figure 2-1 Example of the carbon pool dynamics for one hectare each of a deciduous-leading and a coniferous-leading boreal plains stand following a stand replacing disturbance event.

Figure 2-1 provides examples of the carbon dynamics following a stand replacing disturbance for deciduous-leading and coniferous-leading stands on the boreal plains. Following the disturbance event (which occurs in period zero), total carbon stocks undergo a period of decline. This decline is due both to the removal of the stand's biomass stock as well as the decay of carbon in the DOM pool. The decomposition rate of DOM carbon accelerates due to the increased exposure of the forest floor, resulting in a change in the site microclimate (Apps *et al.* 2000; Bhatti *et al.* 2001). The increased rate of DOM decomposition eventually subsides through the regeneration of forest cover, which both reduces exposure of the forest floor and increases litterfall input.

Quicker regeneration in the deciduous-leading stand results in a more rapid reversal of the initial decline in total carbon stock. Increased sequestration in the biomass pool balances out the carbon released from the DOM pool. The deciduous-leading stand also sees an interesting "peak" in its DOM carbon stock, culminating around 150 to 160 years of age. This "peak" is generated by large transfers of biomass carbon to the DOM pool as the hardwood species in the stand undergo natural breakup and senescence. The resulting flux of carbon is also apparent in the stand's biomass carbon curve, which declines as the stand moves from about 110 to 160 years of age. The remaining biomass post-160 years of age is found in the secondary softwood species of the stand.

Overall, carbon pool stock and flux at the stand level is determined by stand age, region, forest cover type and site productivity class (Adams *et al.* 1999). The carbon balance of a forest landscape can be estimated by summing across the carbon pools of the individual stands making up the forest.[8] Landscape level carbon dynamics are mainly determined by the past disturbance regime (as reflected by the current age-class structure) as well as by current growing conditions and disturbance patterns (Kurz *et al.* 2002).

2.2 Alternative Strategies for Forest Carbon Mitigation

> *The intent of any mitigation option is to reduce atmospheric CO_2 relative to that which would occur without implementation of that option (Metz* et al. *2001: p.315).*

Potential approaches to forest carbon management include: conservation, which attempts to maintain a forest ecosystem's existing stock of carbon, and sequestration, which looks to maintain and/or increase the rate at which a forest removes and stores carbon from the atmosphere.[9] In application, the most beneficial combination of management strategies will depend largely on a site's disturbance history, productivity level, and the timeframe under consideration (Sampson and Scholes 2000; Metz *et al.* 2001).

Management activities which alter the frequency of disturbance can be particularly important in determining the overall level of carbon stored and transferred throughout a forest ecosystem (Price *et al.* 1997; Kurz *et al.* 1998; Kurz and Apps 1999). DOM carbon dynamics play a significant role in this process. DOM pools have been

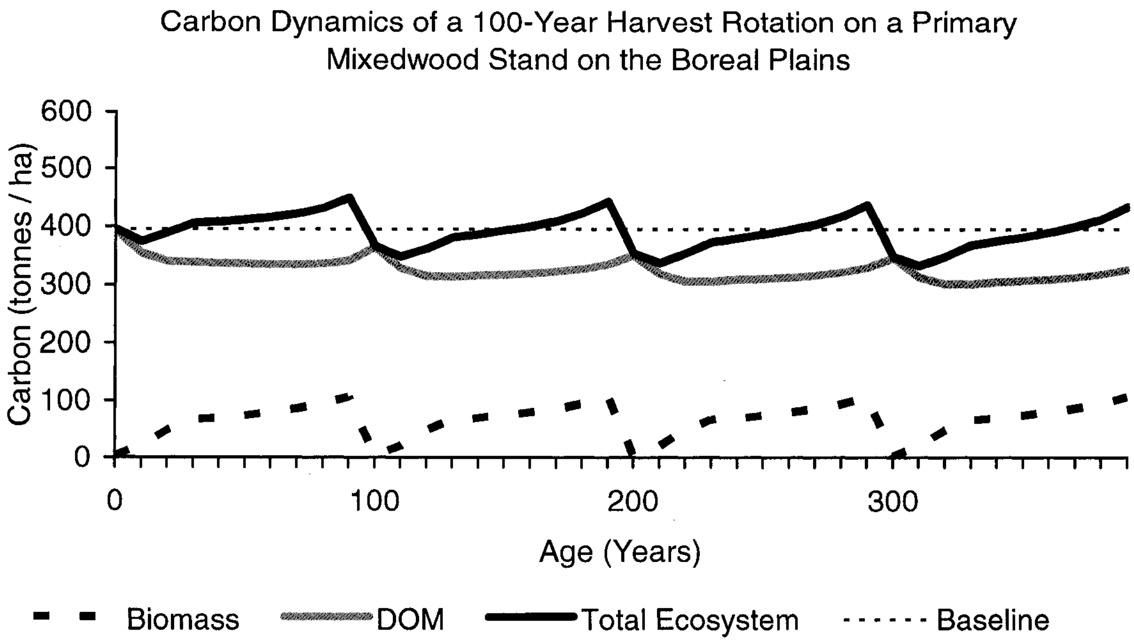
[8] At the landscape level, a forest is composed of many stands that vary in species composition, age-class structure and productivity.

[9] Other management alternatives for carbon mitigation include the substitution of wood products for more energy intensive industrial materials and the burning of wood in place of non-renewable fossil fuels. However, pending the Canadian Government's decision on the inclusion of forest management under Article 3.4 of the Kyoto Protocol, the accounting status of carbon stored in forest products remains uncertain. Under the carbon accounting rules of the Kyoto Protocol, any carbon removed from the forest as harvested material is considered directly emitted back into the atmosphere.

found to generate a net carbon source during transition to more frequent disturbance regimes and a net carbon sink when disturbances become less frequent. These DOM pool dynamics reflect adjustments in the balance between emissions through decomposition and new carbon input through litterfall (Apps *et al.* 2000; Bhatti *et al.* 2001).

Figure 2-2 demonstrates the effect of applying a relatively short (100-year) versus a relatively long (140-year) harvest rotation to a primary mixedwood stand on the boreal plains. An historical natural disturbance regime of stand-replacing fire is simulated prior to active forest management, and is assumed to occur at the mean fire return interval for the region. While biomass carbon dynamics reflect a direct relationship to the growth and removal of stand timber volume, the DOM carbon dynamics are influenced to a greater extent by previous disturbance events. In Figure 2-2, the relatively short harvest rotation causes the level of carbon stored in the DOM pool to decline from one disturbance to the next. The longer harvest rotation in Figure 2-2 allows soil carbon to build up in the ecosystem. These dynamics indicate a shift in the relationship between living biomass, litter and soil carbon pools and emphasize the importance of a site's disturbance history in determining present DOM carbon stocks (Bhatti *et al.* 2001).[10]

[10] Of note, the peaks in the DOM curve which can be observed immediately following disturbance are related to transfers from quickly decomposing branches and foliage that accumulate on the forest floor during harvest.



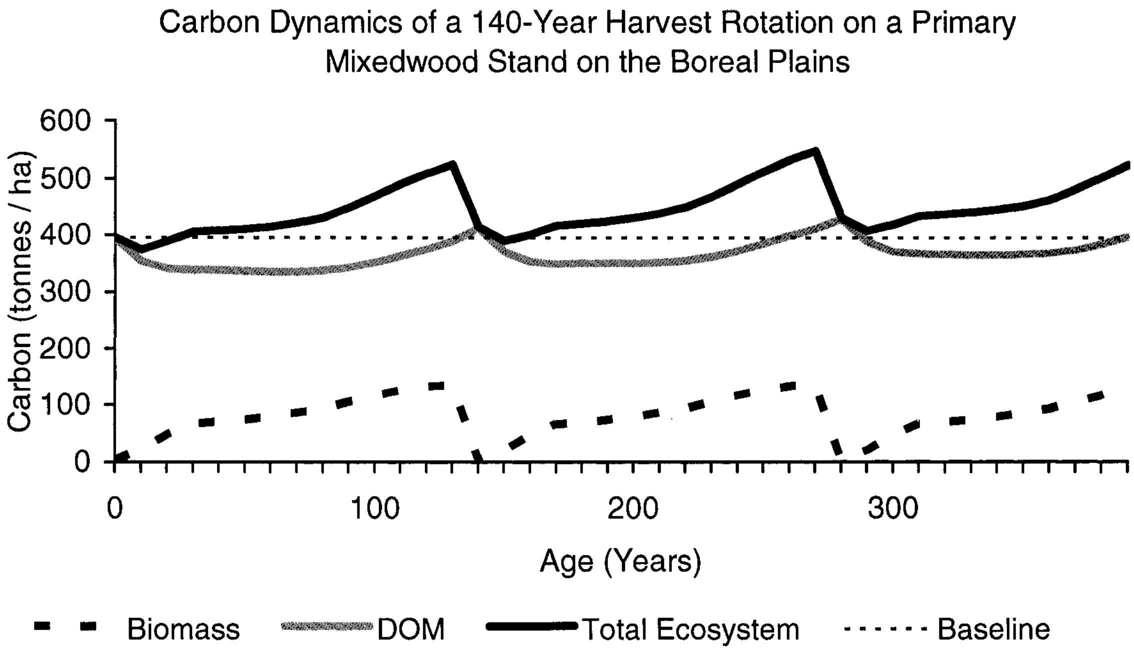


Figure 2-2 Example of the carbon dynamics that result from applying a 100-year and a 140-year harvest rotation to one hectare of a primary mixedwood stand on the boreal plains.

In the boreal forest, the effects of disturbance can reverberate through a stand's soil carbon pool over long periods of time (Kurz and Apps 1995).[11] Intensive forest management practices such as planting and species manipulation (to reduce regeneration delays), controlling stand density and enhancing soil nutrients have been proposed as measures to try and speed the restoration of a productive forest to the landscape. Plantations have been identified as a particularly reliable method to quickly regenerate and increase biomass growth on a site following harvest (Sedjo and Botkin 1997; Metz *et al.* 2001), but their shorter rotation lengths may also be linked to a lower overall carbon storage level (Neilson *et al.* 2006). Lee et al (2002) find that partial cutting is beneficial for the total carbon stock of a harvested stand, however this result largely depends on the use of cut timber and the accounting rules for forest products (Sedjo *et al.* 1995; *Binkley et al.* 1997).[12] Further questions surround the possible benefits of stand fertilization, as it can help to stimulate post-harvest biomass growth rates but may also influence soil processes and generate environmentally harmful emissions of N_2O and NO_X (Hoen and Solberg 1994; Sampson and Scholes 2000).

Nevertheless, the general indication is that the effectiveness of various carbon management strategies will depend on the initial age-class structure and disturbance regime of the forest ecosystem. While intensive management can accelerate the accumulation of carbon in relatively young or frequently disturbed stands, disturbance of old-growth and mature forests may considerably reduce carbon storage capacity for a

[11] The long adjustment period is due to the slow rate of carbon turnover in the soil as it tends towards a new steady-state condition. Slow DOM turnover is caused by the boreal's short growing seasons, low temperatures and high moisture content (Bhatti *et al.* 2001).
[12] Hoen and Solberg (1994) have also found release thinning to be inefficient for carbon management purposes, as increased stand density leads to greater biomass growth in the early periods of regeneration.

number of years, even following regeneration (Sampson and Scholes 2000; Bhatti *et al.* 2001; Metz *et al.* 2001). Also, investing in protection against natural disturbances such as fire, insect and disease outbreaks may be a necessary corollary for most carbon management activities.[13] Amiro *et al.* (2002) have demonstrated that forest fires in Canada make up a significant proportion of annual CO_2 emissions, and may increase as a result of future climate change.

2.3 Economics of Forest Carbon Management

The central focus of many economic studies into forest carbon management has been how optimal rotation lengths may change when returns to both timber and sequestered carbon are realized. 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. Plantinga and Birdsey (1994), van Kooten *et al.* (1995), Hoen and Solberg (1997) and Creedy and Wurzbacher (2001) have all found that the inclusion of carbon values will lengthen the optimal harvest rotation versus a rotation which maximizes the net present value of timber alone.

Murray (2000) contributes to the above findings by showing that the sensitivity of optimal rotation ages to relative changes in timber versus carbon prices will differ across forest species types. Moreover, the study by van Kooten *et al.* (1995) indicates that certain tax/subsidy regimes may lead to an economically efficient solution of never

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[13] Protection may be particularly important in instances where carbon management involves lengthened harvest rotations, as age increases the susceptibility of forests to natural disturbances like fire, insects and disease (Sedjo *et al.* 1995; Price *et al.* 1997).

harvesting the forest. Creedy and Wurzbacher (2001) reach a similar, no-logging, conclusion, dependent on the present age-class structure of the forest. Both studies find that the value of sequestered carbon can dominate timber values under the right set of conditions.

The cost of producing carbon offsets through forest management activities is another central issue receiving substantial attention in the literature (Sedjo 2001; Sohngen and Mendelsohn 2003; van Kooten *et al.* 2004; Krcmar and van Kooten 2005). Metz *et al.* (2001) provide a good review of the relevant literature and cites the costs of sequestering "modest" amounts of carbon in developed countries as ranging from US$20 to US$100/t C. Costs are found to vary depending on anticipated forest growth rates and the opportunity cost of land. Lewis *et al.* (1996) add that regional differences in forest inventory will affect the how the costs of sequestering and storing carbon are distributed over the landscape.

For the boreal forest in particular, the relatively low productivity rates of native species could impact the cost of sequestering carbon through intensive management practices.[14] Anderson and Luckert (*in press*), however, recently found that the use of a faster-growing species, hybrid poplar, could increase the financial viability of many projects. By reducing pressures to degrade areas of natural forest (Sedjo and Botkin

[14] Rodriguez *et al.* (1998) show how the large initial investment in relation to low productivity gains from native species make many investments in intensive silviculture financially unviable in the boreal.

1997), intensive plantations could help reduce the cost of protecting and conserving carbon stocks in more mature or primary forest stands. [15]

Furthermore, it has been recognized that forest carbon management activities could be made more efficient by balancing them with other economic, environmental and social goals of land use (Metz *et al.* 2001). Potentially important ancillary benefits and costs of carbon management include impacts for habitat provision, biodiversity conservation and ecosystem productivity levels. Englin and Callaway (1995) conduct one of the few studies in this regard, and show that the effects of carbon management on forest amenities could be considerable. Accordingly, to the extent that forest carbon management strategies are able to supplement the sustainable forest management objectives and regulatory constraints faced by firms, the lower their costs of adoption will be.[16]

2.4 Market, Policy and Regulatory Issues

2.4.1 Forest Carbon Credits and Carbon Market Structure

While the rules of a domestic market for carbon have yet to be laid out in detail, Article 3.4 of the Kyoto Protocol allows human-induced activities related to land use, land-use change and forestry (LULUCF), including forest management, to be used to generate carbon credits during the first commitment period (2008-2012). The Marrakesh

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[15] It is important to note that there are regulations in place that may constrain the use of non-native species (such as hybrid poplar) on public land in Canada's boreal plains. See, for instance, the Alberta Forests Act, Timber Management Regulations 60/73 and the Standards for Tree Improvements in Alberta (Ref. T/037).
[16] As a potentially low-cost measure with the ability to provide additional societal benefits, van Kooten *et al.* (1997) identify forest carbon management as a possible "no-regrets" strategy for mitigating the effects of climate change.

Accords, which adopted the definitions, rules and guidelines relating to LULUCF activities under Article 3 of the Kyoto Protocol, define a 'forest' as consisting of either closed forest formations or open forest. Young natural stands and all plantations which have yet to reach minimum stocking level and height constraints are still included under a 'forest', as are areas normally forming part of the forest which are temporarily unstocked as a result of disturbance (human or natural) but are expected to revert to forest cover. 'Forest management' is then defined as a system of practices for stewardship and use of forest land aimed at fulfilling relevant ecological, economic and social functions of the forest.

There is still substantial debate over how to properly credit carbon sequestered in forests. Alternative policy structures could produce very different responses in terms of rotation age, net present value and harvest policy. For example, some groups advocate that forest land must be set aside from harvesting entirely in order to earn carbon credits, as opposed to a more flexible policy that would recognize all forest management activities (including harvest). Moreover, whether currently inaccessible stands should be eligible for generating credits, if they are permanently set aside, is also contentious. Sun and Sohngen (2006) examine these issues under three different types of crediting schemes for carbon, and find that while more flexible crediting regimes sequester more carbon, resulting timber price and landscape effects vary considerably over the different policies.[17]

[17] For instance, if currently inaccessible forest areas are considered eligible when land must be set-aside entirely to generate carbon credits, large areas of remote forests in Canada and Russia are permanently set-aside for carbon management. This is due to high carbon intensity but low marginal timber values in the boreal (Sun and Sohngen 2006).

Several mechanisms for generating incentives to sequester carbon in forests have been discussed in the literature. Politylo (2004) and McCarney *et al.* (2006) investigate incentives for firms to enter into specified level contracts with carbon seeking agents, in which a specified level of carbon stock is guaranteed to be maintained over a defined time period. Alternately, a credit/debit system could be implemented, through which firms would be rewarded or penalized for accumulations and removals of carbon from the forest ecosystem. For example, van Kooten *et al.* (1995) and Hoen and Solberg (1997) analyze the use of policy frameworks involving carbon taxes and subsidies. However, there has been relatively little research to date on how a carbon market will affect the operations and objectives of forestry firms.

A key issue pertaining to carbon market structure concerns the permanence of a carbon offset credit. For a carbon credit system to be viable, there must be assurances that an additional quantity of carbon is sequestered in the forest, as a credit would become valueless should carbon not be sequestered or, alternatively, be released (Sedjo 2001). To avoid questions of whom, in the case of unplanned forest carbon losses, would be required to compensate the purchaser of a carbon offset or credit, Sedjo (2001) argues that credits should be defined as temporary, versus permanent, carbon offsets.[18] A temporary credit system would reduce the liability complications associated with carbon losses, whether inadvertent or not.[19] Since temporary credit purchasers would therefore assume the risk associated with renewing credits at future market prices, the value of

[18] In Canada, the question of whether liability would rest with the forestry firm, as opposed to the forest owner (i.e. the provincial government), is currently unsettled. Alternatively, liability could rest with the carbon credit purchaser, in which case no compensation would be required.

[19] This would particularly be the case if temporary carbon credit payments to firms were based on quantities of carbon sequestered in previous periods (Sedjo 2001).

temporary carbon credits must be discounted compared to that of permanent carbon offsets (Chomitz and Lecocq 2003).

2.4.2 Regulatory Framework

With most harvest activity occurring on public lands, forestry firms in Canada have historically faced sustained yield and regeneration regulations which constrain their operations. The regulatory framework faced by firms operating on the boreal plains may restrict their ability to sequester additional amounts of carbon through delayed harvest or intensive management. For instance, the Alberta Forests Act states that Forest Management Agreements are assigned "for the purpose of establishing, growing and harvesting timber in a manner designed to provide a perpetual sustained yield" (Alberta Forests Act, F-22, 2.16.1). Alberta also enforces regeneration standards pertaining to the level of re-growth and performance of desirable species on harvested forest land (Alberta Regeneration Survey Manual 2006).

Social concerns such as maintaining productivity, employment levels and meeting industry demands for timber may also constrain the management options available to forestry firms. Another important issue in this regard concerns who owns the rights to carbon sequestered in a forest ecosystem. Provincial governments, forestry companies and local aboriginal communities may all be able to claim ownership rights, and each will have their own social priorities for forest use. If forest carbon sequestration is to be a viable means of mitigating the effects of climate change, the challenges posed by existing social priorities and regulatory frameworks will need to be addressed.

2.4.3 Carbon Baselines

Determining an appropriate emissions baseline is critically important for assessing forest carbon management alternatives and opportunities. Carbon mitigation goals are measured against a predetermined baseline, with carbon sinks (sources) occurring when realized carbon stocks are in excess (deficit) of the baseline quantity. Watson *et al.* (2000) provide a good overview of the many carbon baseline options available for consideration; the two most relevant being a business as usual (BAU) scenario and a constant carbon baseline. A BAU baseline would measure carbon mitigation activities against the carbon stocks resulting from a normal progression of forest management activities (i.e. if no incentives for carbon management were present). Alternatively, a constant carbon baseline would compare realized carbon stocks against a horizontal line set at a specific level; such as current carbon stocks, or possibly, in the case of the Kyoto Protocol, 1990 carbon levels.

It is noteworthy that in negotiating an appropriate baseline, carbon suppliers are likely to push scenarios that will maximize their projected benefits from carbon management (Watson *et al.* 2000). Accordingly, the lowest acceptable baseline level of carbon would be given priority. In the case of Canada's boreal forest, this may mean the adoption of a declining baseline, as the relatively mature current age-class structure could indicate net declines in ecosystem carbon under BAU conditions (Kurz and Apps 1999). Rules regarding the acceptability of a declining baseline have yet to be determined.

Constant baselines, however, may generate disincentives for forestry firms to engage in carbon markets where BAU carbon stocks are expected to decline.[20]

2.4.4 Time and Discounting

In a study of the temporal implications for forest carbon management, Marland *et al.* (1997) show that different mitigation strategies can yield very different time paths of results. Depending on the method implemented, benefits to carbon management may accrue as permanent carbon offsets, temporary carbon storage or may even release stored carbon in the name of increasing future sequestration. Discounting assigns greater value to those strategies that generate current, as opposed to future, benefits.

How the costs and benefits of mitigation are valued now versus in the future is thus important in determining which carbon management strategies are selected, and how they will impact the forest landscape. Management strategies which rely on disturbing the landscape now in order to increase future rates of sequestration will be especially sensitive to the discount rate chosen. Meanwhile, for mature forests, or those with relatively low productivity rates, conserving existing carbon stocks by avoiding disturbance may be the only strategy which generates near-term benefits (Marland *et al.* 1997; Metz *et al.* 2001).

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[20] Interestingly, the opposite holds true where carbon stocks are expected to increase under a BAU scenario. The constant carbon baseline would then be preferable to suppliers, provided it was set at the initial carbon stock level.

2.5 Summary

This chapter has surveyed the main issues related to carbon management in Canada's boreal forest and the policies and incentives required to entice forestry firms to generate carbon offsets. The first section established the biology of forest carbon dynamics and demonstrated how carbon pool content and flux, following a disturbance, can vary depending on forest cover type. The alternative management strategies for forest carbon conservation/sequestration were then laid out, and the effectiveness of each option was shown to depend on the initial age-class and disturbance history of a particular stand. Issues in the economic literature related to carbon management; including the potential to lengthen optimal harvest rotations, perhaps infinitely, and the factors affecting the costs of carbon offsets, were also presented. Finally, market structure, policy and regulatory concerns were discussed, covering debates such as: (i) how to properly credit carbon stored/sequestered in forests and the effects of different policy stances, (ii) the proper incentive mechanisms to use in enticing forestry firms to adopt carbon management practices, (iii) the challenges for forest carbon management presented by regulatory frameworks and other social priorities, (iv) the use of BAU or constant carbon baselines and (v) discounting and how it could affect the time path of carbon reductions. The following chapters will apply these background issues to develop a framework for analyzing the impacts of carbon market incentives on forest management decisions in the boreal.

Chapter 3: Integrated Modeling Framework

For the purposes of this research, it was necessary to develop an integrated modeling approach, capable of incorporating both forest carbon and timber value considerations within an optimal management framework. Furthermore, the approach taken had to allow for considerable flexibility in the specification of alternative market condition and regulatory scenarios, while presenting a range of possible management intensity and harvest scheduling options across the landscape. A linear programming model is adopted for these purposes. The approach is applied in practice by integrating a detailed representation of forest carbon dynamics into an operational timber management modeling tool.

Within this framework, research is focused on how different productivity and cost variables affect timber and carbon management incentives over the forest landscape. Analysis centres on changes in the management regimes applied across forest stands under alternative market and regulatory conditions. Forest stands are associated with a specific cover type, site productivity level, and distance to mill (represented as a haul zone). Management regimes include both the harvest schedule and silvicultural intensity applied to an individual stand. When taken together, a forest stand and applied management regime form a specific development type, which refers to an area of forest that follows a particular set of yield and cost curves. Market and/or regulatory incentives that alter the development types found over a forest landscape are expected to alter the appearance of that landscape.

These modeling considerations are applied to a representation of a forest landscape in the boreal plains ecozone of Canada. Given an initial age-class structure, the Woodstock forest modeling package (Remsoft Inc. 1998) is utilized to develop an optimal harvest scheduling model for the region. A detailed account of the forest carbon balance is incorporated into this analysis. Using the Carbon Budget Model of the Canadian Forest Sector (Canadian Forest Service 2005), separate biomass and DOM carbon yield curves are developed for each unique development type and integrated directly into the Woodstock forest management model. Carbon is assumed to be of temporary value, with the excess (deficit) carbon stored in each period, as compared to that period's baseline carbon stock, generating a credit (debit) according to the market value of carbon.[21]

3.1 Linear Programming Model Formulation

The basic modeling framework is set up as a Model II timber harvest scheduling problem similar to that described by Johnson and Scheurman (1977). This formulation is applied to an aggregated representation of a forest that includes a number of forest stand types and age-classes (i.e. a forest landscape). Management activity is studied in discrete ten-year periods over a planning horizon of 200 years.[22] It is assumed that the objective of the forest manager is to maximize the net present value (NPV) of the forest landscape, where value accrues from both timber harvest and temporary carbon credits.

[21] This carbon accounting procedure is consistent with the rules laid out under Article 3.4 of the Kyoto Protocol.
[22] A 200 year planning horizon is the current standard for forest management planning in Alberta.

Objective Function:

$$\max_{X_{ijk},W_{ij}} \sum_{i=1}^{I}\sum_{j=-A_i+1}^{k-p_i}\sum_{k=1}^{N}\left[Y_{ijk}X_{ijk}-\sum_{m=1}^{M}\left(C_{ijk}^{H}+C_{ijk}^{T}+C_{i}^{R_m}\right)X_{ijk}^{m}\right]e^{-\delta 10k}+\sum_{k=1}^{N}Ze^{-\delta 10k}\left[S_k-S_k^B\right] \tag{3.1}$$

Subject to:

Area Constraints:

$$\sum_{k=1}^{N}X_{iak}+W_{ia} = G_{ia} \qquad \forall\ i,a \tag{3.2}$$

$$\sum_{l=k+1}^{N}X_{ikl}+W_{ik} - \sum_{j=-A_i+1}^{k-p_i}X_{ijk} = 0 \qquad \forall\ i,k \tag{3.3}$$

Regulatory Constraints:

Harvest Volume Constraints:

$$F_k = \sum_{i=1}^{I}\sum_{j=-A_i+1}^{k-p_i}V_{ijk}X_{ijk} \qquad \forall\ k \tag{3.4}$$

$$(1-\alpha)F_k - F_{t+1} \le 0 \qquad \begin{array}{l} k=\lambda \\ t=\{1,2,\ldots,N-1\} \end{array} \tag{3.5}$$

$$(1+\beta)F_k - F_{t+1} \ge 0 \qquad \begin{array}{l} k=\lambda \\ t=\{1,2,\ldots,N-1\} \end{array} \tag{3.6}$$

$$D_k = \sum_{i=1}^{I}\sum_{j=-A_i+1}^{k-p_i}U_{ijk}X_{ijk} \qquad \forall\ k \tag{3.7}$$

$$(1-\alpha)D_k - D_{t+1} \le 0 \qquad \begin{array}{l} k=\lambda \\ t=\{1,2,\ldots,N-1\} \end{array} \tag{3.8}$$

$$(1+\beta)D_k - D_{t+1} \geq 0 \qquad \begin{array}{l} k = \lambda \\ t = \{1,2,...,N-1\} \end{array} \qquad (3.9)$$

Regeneration Constraints:

$$\sum_{j=-A_q+1}^{k-p_q} \left[\sum_{m=\mu}^{M} X_{qjk}^{m} - X_{qjk} \right] = 0 \qquad \forall\ q,k \qquad (3.10)$$

Inventory Accounting Rows:

$$R_{ia1} = G_{ia} \qquad \forall\ i,a \qquad (3.11)$$

$$R_{ial} = R_{iak} - X_{iak} \qquad \begin{array}{l} \forall\ i,a,k; \\ l = k+1 \end{array} \qquad (3.12)$$

$$R_{ijk} = \sum_{l=k}^{N} X_{ijl} + W_{ij} \qquad \begin{array}{l} \forall\ i; \\ j = \{1,2,...,N-1\}; \\ k = \{j+1, j+2,...,N\} \end{array} \qquad (3.13)$$

$$\sum_{m=1}^{M} R_{ikl}^{m'} = \sum_{a=1}^{A_i} X_{iak} \qquad \begin{array}{l} \forall\ i,k; \\ l = k+1 \end{array} \qquad (3.14)$$

$$R_{ikl}^{m} = \sum_{j=1}^{k-p_i} X_{ijk}^{m} \qquad \begin{array}{l} \forall\ i,k; \\ l = k+1 \end{array} \qquad (3.15)$$

Carbon Accounting Rows:

$$S_{iahk} = \theta_{iahk} R_{iahk} + \phi_{iahk} R_{iahk} \qquad \forall\ i,a,h,k \qquad (3.16)$$

$$S_k = \sum_{i=1}^{I} \sum_{a=1}^{A_i} \sum_{h=1}^{H} S_{iahk} \qquad \forall\ k \qquad (3.17)$$

Non-Negativity Constraints:

$$R_{ijk} \geq 0; R_{ijk}^{m} \geq 0; X_{ijk} \geq 0; X_{ijk}^{m} \geq 0; W_{ij} \geq 0; F_k \geq 0; D_k \geq 0; R_{iahk} \geq 0$$

$$\forall\ i,k,m,a,h; \quad j = \{-A+1, -A+2, \ldots, N\} \tag{3.18}$$

Definition of Indexes:

i	Development types: a development type refers to an area of forest that follows a particular set of yield and cost curves. Yield and cost curves are assigned on the basis of; cover type, site productivity class, distance to mill (based on haul zones), and management/silvicultural intensity.
q	A subset of index *i*: refers to all development types that are classified with a coniferous-leading or mixedwood cover type.
m	Management/Silvicultural intensity: used to classify development types more specifically according to their management intensity level.
m'	Specifies the prescription of a new management/silvicultural intensity to a development type.
M	The most intensive level of management activity which can be applied following harvest.
μ	The least intensive level of management activity which, when applied following harvest, will still comply with the relevant regeneration regulations.
λ	Reference period for the harvest volume constraints.

p_i The number of periods required for development type i to meet the minimum harvest standard for Alberta of 47.5 m^3/ha.

h Disturbance history: captures the different disturbance regimes that are applied to the landscape throughout the planning horizon, up to the current period. A disturbance regime is classified as the timeline of disturbance events (harvest activity) and regeneration practices applied to a particular site in the forest.

a The range of initial inventory age-classes (in periods) at the start of period one.

A_i Age (in periods) of the oldest age-class present for development type i in period one.

N The number of periods in the planning horizon.

Definition of Parameters:

G_{ia} Initial area (ha) for development type i and initial age-class a in period one.

Y_{ijk} Revenue ($/ha) associated with timber from development type i which is born in period j and harvested in period k.

C_{ijk}^{H} Harvesting cost ($/ha) associated with development type i which is born in period j and harvested in period k. Includes both the direct costs of harvesting and the crown timber dues rate.

C^T_{ijk} Transportation/Hauling cost ($/ha) associated with removing timber from development type i which is born in period j and harvested in period k.

$C^{R_m}_i$ Regeneration costs ($/ha) associated with development type i when management intensity m is prescribed.

S^B_k Baseline carbon stock (tonnes) associated with the total forest ecosystem in period k.

Z Market price of carbon ($/tonne).

θ_{iahk} Biomass carbon stock (tonnes/ha) associated with development type i of initial age-class a and disturbance history h at time period k.

ϕ_{iahk} DOM carbon stock (tonnes/ha) associated with development type i of initial age-class a and disturbance history h at time period k.

V_{ijk} Softwood merchantable volume (m^3/ha) associated with development type i which is born in period j and harvested in period k.

U_{ijk} Hardwood merchantable volume (m^3/ha) associated with development type i which is born in period j and harvested in period k.

α Maximum proportional decrease in harvest volume permitted in each period under the harvest volume of the reference period λ.

β Maximum proportional increase in harvest volume permitted in each period over the harvest volume of the reference period λ.

δ Discount rate (%).

Definition of Variables:

R_{ijk} Area (ha) of development type i which is born in period j and standing at the beginning of period k.

R_{ijk}^{m} Area (ha) of development type i which is born in period j, standing at the beginning of period k and prescribed to management intensity m.

R_{iahk} Area (ha) of development type i from initial age-class a and disturbance history h standing at the beginning of period k.

X_{ijk} Area (ha) of development type i which is born in period j and harvested in period k.

X_{ijk}^{m} Area (ha) of development type i which is born in period j, harvested in period k and prescribed to management intensity m.

W_{ij} Area (ha) of development type i which is born in period j and never harvested within the planning horizon.

S_{iahk} Carbon stock (tonnes) associated with development type i of initial age-class a and disturbance history h in period k.

S_k Carbon stock (tonnes) of the total forest ecosystem in period k.

F_k Softwood volume (m^3) harvested in period k.

D_k Hardwood volume (m^3) harvested in period k.

The objective function (Equation 3.1) restates the management objective of the model: to maximize the NPV of the forest landscape, where value accrues from both timber harvest and temporary carbon credits. More specifically, the objective function maximizes the discounted value from the sum of:

1. Net timber harvest revenues, summed across all development types i and age-classes j harvested in each period k. Net timber harvest revenue per period is defined as the gross revenues from harvested timber minus the costs of harvesting and transporting the timber and the costs of regenerating each harvested site to a prescribed management intensity.
2. Temporary carbon credits generated in each period k. Temporary carbon credits accumulate as the difference between the realized and baseline carbon stock for each period. The methods used to derive the baseline carbon stock are described in section 3.2.

The area constraints described by Equations 3.2 and 3.3 ensure that all of the forest area is either assigned to a harvest action or left as standing inventory at the end of the planning horizon. Equation 3.2 pertains to the initial forest area, while Equation 3.3 accounts for the areas born during the planning horizon.

The model also includes a series of regulatory constraints. The harvest volume constraints described by Equations 3.4 through 3.9 are formulated as a timber yield policy which is simultaneously applied to both softwood and hardwood harvest volumes. These equations are specified in order to allow for flexibility in the application of harvest volume constraints, depending on the values assigned to the parameters λ, α and β. If λ is set equal to one, then the constraints describe an even flow timber yield policy; with strict even flow regulation in the case of $\alpha=\beta=0$, and flexible even flow regulation in the case of $\alpha>0$, $\beta>0$. Alternatively, if $\lambda=t$ then the constraints describe a sequential yield policy.[23]

Equation 3.10 describes the different regeneration constraints imposed on the model. The constraint is specified as the set of management intensity levels $m=\{\mu,\ldots,M\}$ which, when applied following harvest, will meet the enforced regeneration regulations. Accordingly, if the enforced regulations require forestry firms to return a harvested area to its original species composition, then extensive (or leave-for-natural) management practices may not be sufficient following harvest of coniferous-leading or mixedwood stands. Extensive management would therefore be left out of the available set of management intensities. Alternatively, if no regeneration regulations are enforced, then $\mu=1$ and the set of all management intensity levels is available for use when harvesting on the landscape. It is assumed that no regeneration regulations ever apply to deciduous-leading stands.[24]

Inventory accounting rows, Equations 3.11 through 3.15, are used to track the transitions of forest areas from one period to the next. Equation 3.11 therefore specifies the initial inventory at the beginning of the first period, while Equation 3.12 tracks the area of initial inventory which is still standing at the beginning of each subsequent period through the planning horizon. Equation 3.13 accounts for the areas of forest born during the planning horizon. Equations 3.14 and 3.15, meanwhile, specify how areas of forest

[23] A non-declining yield (NDY) policy would be a special case of sequential yield in which $\alpha=0$, $\beta=\infty$.
[24] On the boreal plains, deciduous-leading stands are usually dominated by aspen species which regenerate quickly following harvest, even under extensive management conditions (Barker, pers. comm.).

are regenerated from one period to another following a harvest activity. Equation 3.14 states that forest areas are prescribed to a new management intensity level *m'* following their first harvest event in the planning horizon. Equation 3.5 then requires forest areas to remain prescribed to the same management intensity level *m* following all subsequent harvests.[25] This restriction forces some level of consistency on forest management decisions, while also, more importantly, easing the computational complexity involved with modeling carbon dynamics following harvest.

Similarly, the carbon accounting rows track the carbon stock transitions from one period to the next through the planning horizon. Equation 3.16 contains parameters for both biomass and DOM carbon stocks specific to each development type *i* of initial age-class *a* and disturbance history *h* in period *k*. Multiplying these parameters by their associated forest areas allows for a detailed depiction of carbon stocks and flux over the landscape, specific to individual forest cover types, productivity levels, management intensities, stand disturbance frequency and harvest rotation lengths. Equation 3.17 aggregates over all development types *i*, initial age-classes *a* and disturbance histories *h* to provide the total ecosystem carbon stock in each period *k*.

The final set of equalities (Equation 3.18) describes the non-negativity constraints that apply to all management activities undertaken on the landscape. In addition, it is important to specify that fire/pest management is assumed to occur over the forest

[25] Initial forest areas are assumed to be unmanaged at the beginning of period one, and accordingly are not assigned a management intensity until following their first harvest event.

landscape, and to be 100% effective. The effects of fire and insect disturbances are therefore not explicitly included in the modeling framework.

3.2 Deriving Appropriate Baseline Carbon Stocks

As discussed in Section 2.4.3, determining the appropriate carbon baseline is critically important for assessing forest carbon management alternatives and opportunities. Model runs are conducted with two separate baseline levels of carbon, a BAU carbon baseline and a constant carbon baseline, in order to evaluate the forest management and landscape implications of alternative policies in this regard. Baseline carbon stock levels are derived specifically for each alternative model scenario, representing alternative combinations of initial forest conditions, market incentives and regulatory constraints. While no allowance is made for roads, landings and other factors that can reduce the carbon baseline, these effects are expected to be minimal.

To derive the business-as-usual (BAU) carbon baselines, each model scenario is initially run with the price for carbon credits (Z) set equal to \$0/tonne, effectively removing the market incentives for carbon management. This approach is meant to simulate a normal progression of forest management activities, where the objective of forest managers is to maximize the NPV from timber harvest alone. The resulting levels of carbon stored in each period are recorded and classified as the BAU baseline values for the particular scenario being modeled. These records can then be formed into a time-dependent yield curve and re-inserted into the Woodstock model. The levels of carbon that result from model scenarios where market incentives for carbon management are present (i.e. $Z>0$) can subsequently be compared against the corresponding BAU level from this yield curve. Alternatively, constant carbon baselines are implemented as a horizontal line (or constant time-dependent yield curve) at the level of carbon present in period one of the BAU carbon baseline. This is meant to represent a constant baseline set at the initial carbon stock of the forest landscape.

3.3 Carbon Modeling Procedure

One of the primary contributions of this research is a detailed inclusion of forest carbon dynamics within an optimal forest management modeling framework. To date, most economic analyses have included only simple representations of forest carbon stock and flux. By using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3), this study attempts to capture a more rigorous and realistic depiction of forest carbon dynamics throughout the planning horizon. The CBM-CFS3 is used to develop separate biomass and DOM carbon yield curves for all development types occurring over the landscape.

The CBM-CFS3 is a simulation model which provides a general framework for the dynamic accounting of carbon pools and fluxes in Canada's forest ecosystems (Kurz and Apps 1999). It is designed to be consistent with current scientific understanding of forest carbon dynamics and compliant with evolving international carbon accounting rules (Kurz *et al.* 2002). Biomass accumulation curves derived from the national forest biomass inventory (Bonnor 1985) and the 1986 Canadian Forest Inventory (Forestry Canada 1988) are used to simulate aboveground biomass dynamics. Regression equations based on the literature are then used to derive belowground (root) biomass dynamics from aboveground biomass estimates (Li *et al.* 2003). A simulation approach, based on stand dynamics, disturbance and management history and mean annual temperature, is used to estimate the size and composition of DOM carbon pools (Kurz and Apps 1999).

The objective of the carbon modeling approach developed here is to capture the carbon content of both biomass and DOM pools, carbon growth and decomposition rates and carbon transfers from biomass to DOM as a forest area transitions from one model period to the next.[26] To achieve this, separate biomass and DOM carbon yield curves are developed by running simulation models through the CBM-CFS3. Each simulation run includes one hectare of forest area which is grown over a period equal to the planning horizon. The resulting quantity of carbon (tonnes/ha) for each period is used to calibrate the parameters θ_{iahk} and ϕ_{iahk} in Equation 3.16. Specific CBM-CFS3 simulation scenarios are designed to capture the carbon dynamics for each combination of forest cover type, site productivity level and initial age-class present at the beginning of the planning horizon. These factors represent the biological determinants of forest carbon dynamics discussed in Section 2.1. Furthermore, each simulation scenario is re-run according to a set series of management regimes; incorporating the carbon implications of transitions to alternative silvicultural intensities over a particular set of harvest frequencies and rotation lengths. In this way, the alternative strategies for forest carbon management described in Section 2.2 are accounted for.

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[26] Kurz and Apps (1999) identify these factors as the main indicators of carbon dynamics at the stand level.

A complexity involved with incorporating carbon dynamics is that there are multiple possible transitions between silvicultural practices that may occur over any harvest schedule through the planning horizon. For example, forestry firms may decide to use different silvicultural intensities for a particular stand following each subsequent harvest event, with the order of prescription differing for different stands. The specific progression of these regeneration techniques, combined with the choice of harvest rotation length, will influence the resulting carbon dynamics. Including all possible transitions would require a prohibitive number of separate carbon yield curves to be developed. Accordingly, a stylized approach to forest carbon modeling is designed. This approach involves a set of assumptions that are intended to reduce the number of carbon curves that need to be simulated while still capturing the specific carbon dynamics related to each potential management regime (including silvicultural intensity and harvest schedule) available to forest managers. This carbon modeling technique is described in greater detail in Sub-Sections 3.3.1 and 3.3.2 below.

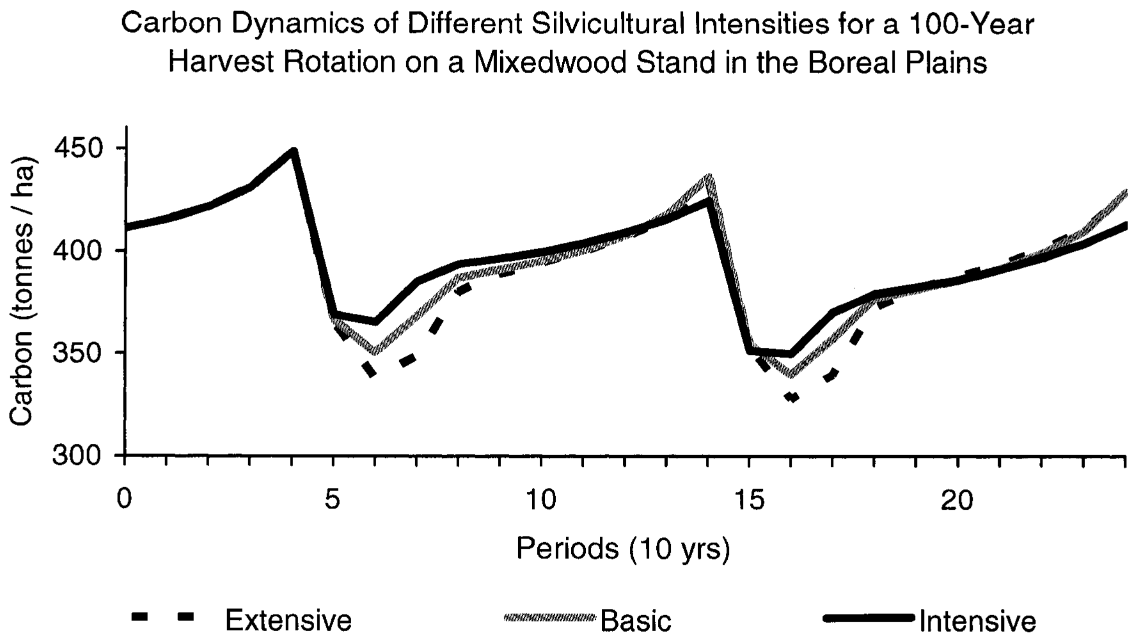
3.3.1 Carbon Dynamics of Alternative Silvicultural Intensities

Every time a new silvicultural or management practice is applied following a harvest event, new biomass and DOM yield curves are required in order to properly capture the continuing carbon dynamics of that forest area. Moreover, the shape and magnitude of the new DOM carbon curve will largely depend on the previous management intensities applied to that particular forest area. Consequently, in order to capture the entire range of carbon dynamics that are possible following each harvest event, separate carbon yield curves have to be developed and incorporated for all silvicultural activities that may be applied, while also accounting for any potential sequence of management practices through the planning horizon up to that point.

The assumptions made in order to reduce the complexity of modeling these carbon dynamics were presented in Section 3.1 (referring to Equations 3.14 and 3.15). Management activities are constrained so that a forest area may only be prescribed to a new silvicultural intensity following the first harvest event that is applied to it. The forest area is then assumed to be managed under the same silvicultural practice for the remainder of the planning horizon, limiting the number of carbon pathways that need to be simulated for each subsequent harvest.[27] Figure 3-1 depicts the simulation results that follow from this modeling assumption. The figure presents three alternative silvicultural intensities which are applied to high-productivity stands of different cover types. The forest areas shown are initially 5 periods (50 years) of age and are managed on a 10 period (100 year) harvest rotation. Yield curves represent one hectare of forest area tracked over the planning horizon. Forest areas are assumed to follow an initial, or 'natural', management carbon curve, specific to each cover type and site productivity level, until the first harvest event.[28] Differences in the effect of management practices between forest cover types result due to differences in the proportion of deciduous to coniferous timber re-growth for the stand, combined with changing regeneration delays.

[27] Accordingly, for the first harvest event, carbon pathways need to be developed for the entire set of possible forest cover types, site productivity levels and initial age-classes to transition to all of the available silvicultural practices that may be applied. However, each subsequent harvest event will only require one carbon pathway, following the same silvicultural intensity that was previously applied.

[28] The cover types shown in Figures 3-1 are for a mixedwood and a coniferous-leading stand. A deciduous-leading cover type is not shown. Deciduous-leading stands regenerate quickly on the boreal plains, which precludes the use of similar silvicultural techniques.



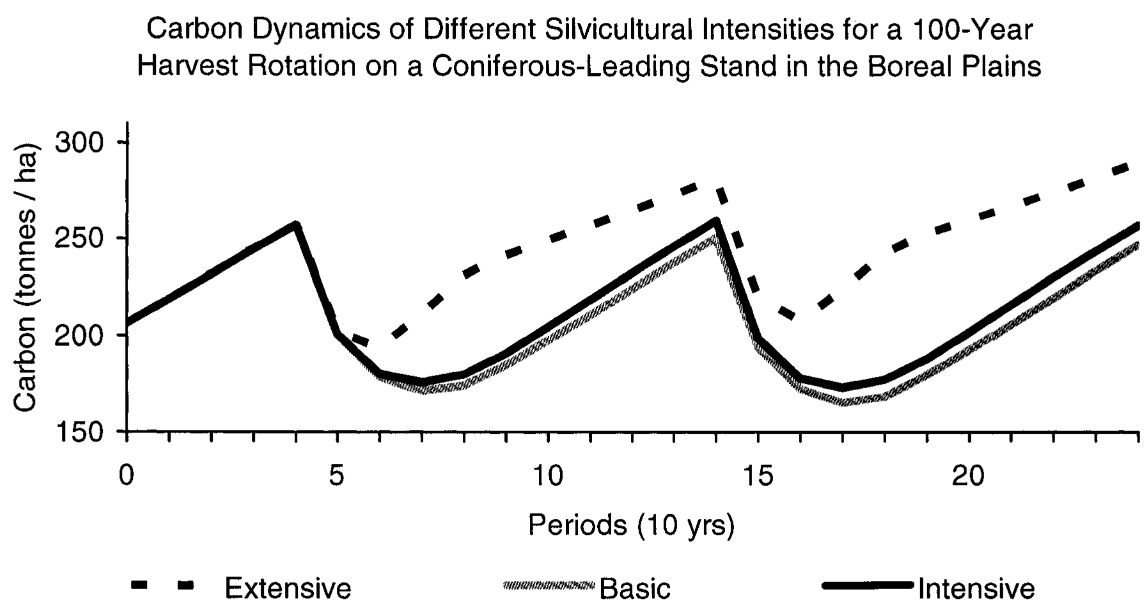


Figure 3-1 Total ecosystem carbon dynamics that result from applying different silvicultural intensities over a 100-year harvest rotation for a mixedwood and a coniferous-leading stand on the boreal plains. The intensity of management increases from extensive to basic to intensive silvicultural practices.

3.3.2 Carbon Dynamics of Alternative Harvest Schedules

For a forest area that remains assigned to the same cover type, site productivity level and silvicultural intensity, biomass carbon will generally accumulate at the same rate and in the same manner following every harvest in a management schedule. DOM carbon dynamics, on the other hand, are also influenced by the disturbance history for that specific site (i.e. the number and frequency of past disturbances).[29] Properly capturing the carbon dynamics for a forest area therefore requires a set of different DOM carbon curves for each harvest rotation. The number of curves in each set will equal the product of multiplying all the possible periods in which a harvest decision could be made in that rotation by the number of different sequences of harvest that could have been scheduled up to that point in the planning horizon. This procedure obviously grows increasingly complex as the model moves further along the planning horizon and more harvests are scheduled to take place for each forest area.

In order to reduce the complexity of modeling these DOM carbon dynamics, an approach is adopted which reduces the set of DOM curves that need to be developed for each harvest rotation. This approach is basically a 'rounding' procedure which is based upon the shape of the DOM carbon yield curves themselves. The difference in magnitude of DOM carbon stocks for a forest area, following disturbance in one period versus the next, can be determined by looking at the slope of the current DOM curve. Where the slope of the DOM curve is steepest, the difference in DOM carbon stocks that will be generated by delaying harvest for one period is greater than where the slope of the curve is more gradual. Accordingly, where a DOM carbon curve is gradually sloped,

[29] These carbon dynamics were described in greater detail in Section 2.2 and are illustrated in Figure 2-2.

and the difference in delaying harvest by a period is minimal, the DOM carbon dynamics following a harvest activity can be 'rounded' to a representative yield curve, which covers several possible periods of harvest, without a significant loss in modeling accuracy.

Modeling complexity is further reduced by adopting an assumption about the progression of management decisions through time. The number of DOM carbon yield curves developed is reduced for the third and fourth harvest rotations on a forest area, and the curves included are clustered around a narrower range of harvest ages within those rotations. The particular DOM yield curves included are based on the rotation lengths observed for the first two harvest activities in that specific forest area, therefore reflecting an assumption that management decisions will tend towards a constant rotation age. The greater the extent that the third and fourth round harvest decisions deviate from this narrowed band of rotation ages, the greater the degree of rounding that will be required to get to the closest representative DOM yield curve.

Figure 3-2 depicts this framework as applied over the first harvest rotation of a high-productivity mixedwood stand that is left for natural regeneration following harvest. The yield curves represent the DOM carbon stock on one hectare of the forest area. This procedure for modeling DOM carbon dynamics through the planning horizon, and over several scheduled harvest events, can also be represented in a basic decision tree framework. An example of this framework is presented in Figure 3-3. Second rotation options are presented following initial harvest at an age of twelve periods. Each branch of the decision tree represents a separate DOM carbon yield curve that must be developed and included in the Woodstock model for each combination of initial forest cover type, site productivity level and silvicultural intensity. For longer initial rotation lengths, fewer (and younger) DOM yield curves are developed for the third rotation due to the constraints imposed by the end of the planning horizon. Similarly, DOM curves for the fourth rotation only need to be developed following a second harvest age of seven periods.

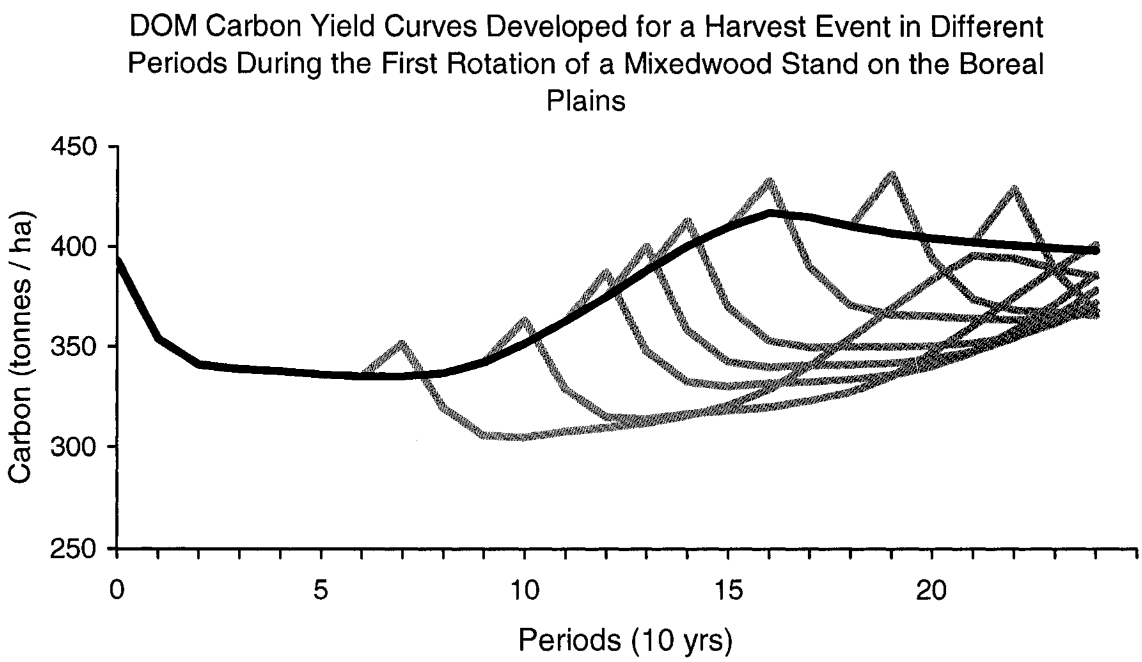


Figure 3-2 DOM carbon yield curves developed to capture the DOM carbon dynamics following a harvest event occurring at different periods during the first harvest rotation. The forest area shown is representative of a high-productivity mixedwood stand that is regenerated naturally following harvest. The solid black curve represents the DOM carbon stock if no harvest event occurs. Grey lines depict harvest events at periods 7, 10, 12, 13, 14, 16, 19 and 22 respectively. Periods without a specific DOM yield curve are 'rounded' to the most appropriate representative curve, based on the rounding rules depicted in Figure 3-3.

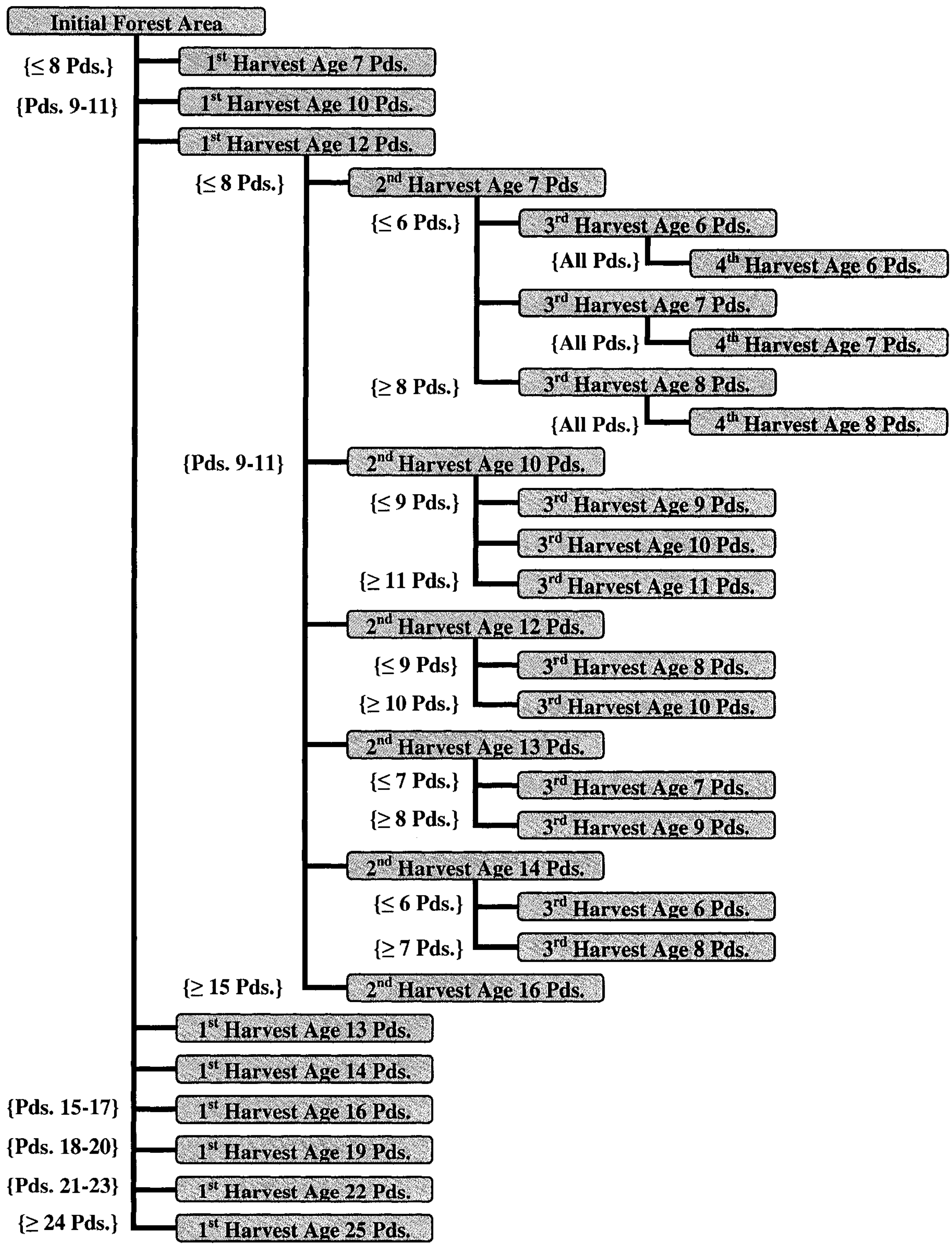


Figure 3-3 Decision tree framework for modeling DOM carbon dynamics through the planning horizon and over several scheduled harvest events. Branches of the tree represent separate DOM carbon yield curves that will have to be developed for each separate combination of forest cover type, site productivity level and silvicultural intensity. Figures in parentheses indicate harvest ages in periods that are 'rounded' to the corresponding representative DOM yield curve.

Chapter 4: Experimental Design

Starting with a representation of a forested landscape on the boreal plains, the objective of this study is to analyze how forest management decisions on that landscape will change following the introduction of incentives for carbon management. Contrasting hypothetical forest landscapes are designed, and incremental changes in forest management decisions are examined under different carbon market incentives and regulatory regimes. The hypothetical landscapes are chosen so that behaviour can be studied over a range of initial starting conditions and structural attributes of the forest. Management options include changing harvest schedules and applying different silvicultural intensities over varying proportions of the landscape. Carbon management incentives are incorporated as a range of market prices, and include a policy switch affecting the baseline level for comparison. Alternative regulatory regimes can affect regeneration practices, the flow of harvested timber and the costs of management. The following sections describe this overall experimental design, and provide the data which are input into the integrated modeling framework from Chapter Three.

4.1 Forest Landscape Structure

The hypothetical forest landscapes developed for this study combine stands that are defined by their initial age-class range, mix of coniferous and deciduous species components and site-productivity level. Timber growth and yield curves, specific to site-productivity and species mix characteristics, are assigned to stands over fixed proportions of the landscape. Each stand on the forest landscape is also assigned to a particular haul zone, which incorporates a spatial aspect to the landscape by representing a general distance from the mill.

4.1.1 Species Mix & Growth and Yield

Species mix and growth and yield characteristics for the boreal plains ecozone are based on data provided by Daishowa-Marubeni International Ltd. (DMI) for part of their Forest Management Agreement Area in North-Central Alberta, Canada.[30] The data provided by DMI are advantageous for carbon modeling for two reasons. First, DMI specifically conducted volume plot sampling in stands greater that 119 years of age in order to increase predictability for growth and yield modeling in chronologically older areas (DMI 2002). Since incentives for carbon management are theoretically predicted to increase optimal rotation lengths (as discussed in Section 2.3), accurate modeling of growth and yield in older aged stands is essential. Secondly, DMI utilize a landscape-level succession modeling system to develop several of their yield projections.[31] Succession modeling leads to 'ecologically reasonable' growth and yield trajectories by not assuming that stand structures remain the same through time (DMI 2002). Succession modeling may also increase carbon budget modeling accuracy by capturing changes in the mix of coniferous and deciduous species as stands age. The species mix of a forest stand can affect both biomass carbon growth and transfers between biomass and DOM carbon pools.

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[30] Preliminary species mix and growth and yield data estimates were also obtained through the efforts of Stewart Elgie (Elgie, pers. comm..).
[31] DMI's succession-based yield strata are derived using the SeraLogix succession modeling system, developed by Geographic Dynamics Corp.

Table 4-1 describes the species mix and growth and yield characteristics implemented on the hypothetical forest landscape. Five separate forest cover types are modeled; aspen-leading cover, aspen and white spruce mixedwood cover, white spruce-leading cover, pine-leading cover and mixed coniferous cover.[32] Each of these forest cover types is assigned to a particular growth and yield trajectory, or ‘yield stratum’, developed by DMI and summarized in their Growth and Yield Information Package (DMI 2002). In keeping with the convention employed by DMI, the “>>” symbol represents the succession based growth and yield projections. Each cover type succeeds to the next as the forest stand ages, assuming a process of natural senescence and mortality without the occurrence of ‘catastrophic’ disturbances such as fire. Growth and yield projections described without the “>>” symbol are modeled on static, or non-succession, trajectories. The species mix for static cover types is assumed to remain the same as the stand ages through time.[33] The use of a hyphen in describing static growth and yield trajectories represents a co-dominant species mix.

Table 4-1 also describes the overall proportion of the hypothetical landscape area allocated to each forest cover type. This allocation is based on the proportion of area assigned to each particular growth and yield trajectory by DMI for a specific segment of their Forest Management Agreement Area.

[32] While black spruce-leading cover types are also common on the boreal plains landscape, they typically do not produce economically usable timber and it is recommended that they not be considered part of the net merchantable land base (DMI 2002).
[33] While some of the cover types represented by static growth and yield trajectories are candidates for succession modeling, limited sample plot data currently prevents the use of succession modeling techniques (DMI 2002).

Table 4-1 Species Mix and Growth and Yield Characteristics Assigned to the Hypothetical Boreal Plains Forest Landscape. Growth and Yield Trajectories are Developed by DMI and Summarized in their Growth and Yield Information Package (DMI 2002).

Hypothetical Forest Cover Types	Associated DMI Growth and Yield Trajectories/Strata	Proportion of Hypothetical Forest Landscape
Aspen (PO)	*DMI Stratum 1: Aspen>>Shrub* Stands initially dominated by trembling aspen, succeeding to open, shrub dominated stands due to the short lifespan of aspen.	54%
Mixedwood (MW)	*DMI Stratum 4: Aspen>>Early Mixed>>White Spruce* Stands begin aspen dominant and succeed early to aspen-white spruce mixedwoods, followed by white spruce-fir dominant stands. Eventually, stands succeed to a state of self-perpetuating multi-aged fir cover.	11%
White Spruce (SW)	*DMI Stratum 6: White Spruce>>White Spruce* Stands begin white spruce dominant or white spruce leading mixedwoods that succeed very early to a state of white spruce dominant cover. Eventually, stands succeed to a state of self-perpetuating multi-aged fir cover.	12%
Pine (PI)	*DMI Stratum 7: Pine* Stands composed of at least 80% pine species.	7%
Mixed Coniferous (MC)	*DMI Stratum 9: Pine-Black Spruce-White Spruce* Stands composed of at least 20% pine species and/or black spruce, with a higher proportion of white spruce/fir than deciduous cover.	16%

4.1.2 Productivity

Site specific productivity levels are integrated into the structure of the hypothetical boreal plains forest landscape. Productivity is an important factor when determining the silvicultural practices to employ on a particular stand, and may be instrumental in determining the incentives to harvest when value can also be derived from forest carbon management. The margin for timber harvesting on low productivity sites may be small, while the re-growth of biomass following disturbance, and consequently the resumption of carbon sequestration, can be slow. In developing their growth and yield trajectories, DMI employs an eco-site modeling system to identify a range of separate productivity classes (DMI 2002).[34] Productivity classes are defined by the

[34] DMI's productivity groupings are derived using the SiteLogix landscape level eco-site modeling system, developed by Geographic Dynamics Corp.

availability of soil moisture and soil nutrients to trees, and are specific to the edaphic conditions characteristic of each individual forest cover type.

The yield strata associated with the aspen (PO) and white spruce (SW) forest cover types are identified to occur over three separate eco-site productivity classes, and these are incorporated in the hypothetical forest landscape as high, medium and low site productivity levels. The yield strata associated with the mixedwood (MW), pine (PI) and mixed coniferous (MC) forest cover types are only identified over two eco-site productivity classes, which are incorporated onto the hypothetical landscape as high and low site productivity levels. Productivity levels are captured by variations in the growth and yield trajectories for each forest cover type. Figures A-2 through A-6, in the appendix, depict the natural growth and yield trajectories assigned to each forest cover type, by productivity level.

4.1.3 Forest Area, Initial Age-Class Structure and Distance to Mill

One of the primary determinants of the carbon balance for a forested landscape is the past disturbance regime, as reflected in the current age-class structure (Kurz *et al.* 2002). Age-class structure is also an important factor in determining the potential effectiveness of various carbon management strategies (Bhatti *et al.* 2001), as well as the level of timber yield that can be sustained over the planning horizon.[35] Accordingly, three hypothetical initial age-class structures are created for this study, representing; a fully regulated normal forest, a forest with a surplus of mature timber and a forest with a

[35] The relationship between initial-age class structure, forest carbon dynamics and forest carbon management is discussed in greater detail in Sections 2.1 and 2.2.

deficit of mature timber. This approach is based on the methods utilized by Armstrong (2004), and is meant to allow the behaviour of the model to be examined over a range of initial starting conditions.

Table 4-2 represents the three hypothetical initial age-class structures, each of which are modeled over a forest landscape area of 900,000 ha. Forest cover types are allocated over this landscape according to the proportions described in Table 4-1. The aspen (PO) age-class range for the mature hypothetical forest is truncated at age-class 11 due to the relatively short lifecycles of aspen species.[36] Productivity classes are assumed to be homogeneously distributed over the landscape areas described in Table 4-2. High, medium and low productivity classes are each assigned to one-third of the area for both the aspen and white spruce cover types, while high and low productivity classes are respectively assigned to half of the area for each of the mixedwood, pine and mixed coniferous cover types.

Each forest cover type and productivity class combination is assumed to be equally distributed over the three distinct haul zones. Haul zones are incorporated in the hypothetical forest landscape in order to test the hypothesis that timber and carbon management incentives will be affected by the costs of transporting harvested timber to the mill. Each haul zone represents a different average distance of stands from the mill. According to Kuhnke *et al.* (2002), the distance to the mill from general logging areas in

[36] DMI (2002) identify deciduous tree species as having lifecycles of only 100-120 years, followed by early senescence and early and extensive mortality.

Table 4-2 Initial Age-Class Structures (ha per age-class) for the Deficit, Normal and Mature Hypothetical Boreal Plains Forest Landscapes.

Initial Age-class (decades)	Deficit Forest					Normal Forest					Mature Forest				
	PO	MW	SW	PI	MC	PO	MW	SW	PI	MC	PO	MW	SW	PI	MC
1	97200	19800	21600	12600	28800	48600	9900	10800	6300	14400	0	0	0	0	0
2	97200	19800	21600	12600	28800	48600	9900	10800	6300	14400	0	0	0	0	0
3	97200	19800	21600	12600	28800	48600	9900	10800	6300	14400	0	0	0	0	0
4	97200	19800	21600	12600	28800	48600	9900	10800	6300	14400	0	0	0	0	0
5	97200	19800	21600	12600	28800	48600	9900	10800	6300	14400	0	0	0	0	0
6	0	0	0	0	0	48600	9900	10800	6300	14400	81000	9900	10800	6300	14400
7	0	0	0	0	0	48600	9900	10800	6300	14400	81000	9900	10800	6300	14400
8	0	0	0	0	0	48600	9900	10800	6300	14400	81000	9900	10800	6300	14400
9	0	0	0	0	0	48600	9900	10800	6300	14400	81000	9900	10800	6300	14400
10	0	0	0	0	0	48600	9900	10800	6300	14400	81000	9900	10800	6300	14400
11	0	0	0	0	0	0	0	0	0	0	81000	9900	10800	6300	14400
12	0	0	0	0	0	0	0	0	0	0	0	9900	10800	6300	14400
13	0	0	0	0	0	0	0	0	0	0	0	9900	10800	6300	14400
14	0	0	0	0	0	0	0	0	0	0	0	9900	10800	6300	14400
15	0	0	0	0	0	0	0	0	0	0	0	9900	10800	6300	14400

Alberta ranges from 15 to 400 km, with the average distance being 111.4 km.[37] Hauling distances of 100 km, 200 km and 350 km are therefore assigned to the three haul zones, depicting close, medium and far distances to the mill, respectively.

4.2 Forest Management Options

Subject to certain regulatory constraints, forestry firms are able to respond to the introduction of carbon management incentives by adjusting the management regime that they prescribe for a forested landscape. In this study, the firm's management regime is assumed to consist of two options; adjusting the harvest schedule and applying different silvicultural intensities following harvest. The optimal timing and combination of these management practices for each hypothetical forest landscape is determined by the linear programming model, and is dependent on the cost of implementing each alternative as well as the regulatory regime imposed.

4.2.1 Economic Rents Accruing through Timber Harvest

To determine the economic rents accruing to forestry firms through timber harvest activity a couple of factors require consideration. First of all, there is no active market for logs in most of the boreal plains region from which to derive a value for harvested timber. Log markets do not exist since most harvest in the boreal plains occurs on public land where forest management regulations require firms to also construct a mill for timber processing. In addition, for the use of publicly owned timber, provincial governments charge forestry firms with 'stumpage' fees. As a result, the portion of economic rent accruing to the firm through timber harvest is commonly calculated as the

[37] The data presented in Kuhnke *et al.* (2002) was compiled during the 1996 through 1998 logging seasons.

value of timber at the mill gate less the rent owing to the provincial government as stumpage and the marginal costs of harvest and regeneration practices (Haener 1998).

Table 4-3 provides the mill gate timber values and stumpage rates applied to forestry operations in this study. The value of timber at the mill gate is derived from discussions held with Alberta forest industry experts as well as a review of literature.[38] Stumpage, incorporated as separate softwood and hardwood crown timber dues, is obtained from Alberta Sustainable Resource Development (the provincial ministry charged with setting timber dues rates). Stumpage rates are calculated as the six month average of the dues rates for coniferous and deciduous timber observed between January and June, 2006.[39]

Table 4-3 Mill Gate Timber Values and Stumpage Rates ($/m³) Employed to Calculate the Economic Rents Associated with Timber Harvest on the Hypothetical Boreal Plains Landscape.

	Softwood ($\$/m^3$)	Hardwood ($\$/m^3$)
Value of Harvested Timber at the Mill Gate	45.00	35.00
Stumpage Rates	3.00	0.20

The marginal costs associated with harvesting timber on the hypothetical boreal plains landscape are summarized in Table 4-4. The costs of logging to roadside, loading and accessing timber in Alberta are derived from PricewaterhouseCoopers (2005). These figures are based on a compilation of proprietary benchmarking data accumulated

[38] The value of timber at the mill gate can also be considered as the willingness-to-pay of the mill for fibre.
[39] Alberta crown timber dues rates can be located on the Sustainable Resource Development website, at: http://www.srd.gov.ab.ca/forests/fmd/directives/currdues.html (cited June 17, 2006). Softwood stumpage is calculated from Table 1: "Coniferous Lumber, Pulpwood and Roundwood Timber Dues Rates". Hardwood stumpage is calculated from Table 3: "Deciduous Pulpwood Timber Dues Rates".

through PricewaterhouseCoopers' annual surveys of Canadian woodlands operations. Hauling costs are based on a figure of $0.07 per m^3-km, obtained from the Alberta Logging Cost Survey (Kuhnke *et al.* 2002), and inflated to 2005 dollars using the Raw Materials Price Index for Mineral Fuels.[40]

Table 4-4 Marginal Costs ($/$m^3$) of Harvesting Timber on the Hypothetical Boreal Plains Landscape.

Timber Harvest Costs		($/$m^3$)
Cost of Logging to Roadside		13.00
Loading Cost		1.50
Access / Road Cost		2.50
Hauling Costs (Distance to Mill)	Close Haul Zone (100 km)	7.00
	Mid-Distance Haul Zone (200km)	14.00
	Far Haul Zone (350 km)	24.50

Three different silvicultural intensities (extensive, basic and intensive) are incorporated into the modeling framework for mixedwood and coniferous-leading forest cover types. Extensive silviculture assumes that forest areas are left to regenerate naturally following harvest. Natural regeneration for the boreal plains is modeled to increase the proportion of deciduous components in stands, so that coniferous-leading forest areas regenerate to a coniferous-deciduous state, while coniferous-deciduous mixedwoods regenerate to a deciduous-coniferous state (Barker, pers. comm.).[41] Basic

[40] The hauling cost figures, originally cited as $/t-km, are converted into $/$m^3$-km using the conversion factors provided in Appendix 2 of Kuhnke *et al.* (2002). The use of the Raw Materials Price Index for Mineral Fuels is based on the assumption that fuel costs make up the majority of the hauling costs faced by forestry firms. The Raw Materials Price Index can be found on the Statistics Canada website, at: http://www.statcan.ca/l01/cst01/prim43e.htm (cited June 17, 2006).

[41] Growth and yield trajectories for extensively managed stands are largely based on the transitions modeled by DMI for naturally regenerated areas in their Forest Management Agreement Area. Figures A-3 through A-6, in the appendix, depict the extensive management growth and yield trajectories assigned to mixedwood and coniferous-leading forest cover types, by productivity level.

silviculture assumes that site-preparation and planting practices are undertaken by the firm following harvest, in order to return stands to their original forest cover characteristics.[42] Planting is assumed to be 100% successful over the forest landscape. Basic silviculture can therefore be viewed as the minimum management intensity required to maintain the original species composition of the landscape. Intensive silviculture adds a stand tending prescription, which follows the basic silvicultural practices and is assumed to help forest areas reach a free-to-grow state more quickly following harvest.[43] Intensive silviculture is modeled as a ten year reduction in the regeneration period for the coniferous component of a forest area.

Basic and intensive silvicultural options, as described above, are not modeled for deciduous-leading forest areas. Deciduous cover types on the boreal plains usually regenerate quickly following harvest, even under extensive management conditions, and are not typically prescribed for planting activities (Barker, pers. comm.). Extensive silviculture is therefore assumed to maintain the original species characteristics of deciduous cover types. Intensive management is incorporated for deciduous-leading forest areas as an option to establish plantations of hybrid poplar. Hybrid poplar growth and yield information is adopted from the work of Anderson and Luckert (*in press*).[44]

[42] Kuhnke (1989) observes that most planting in Canada receives site-preparation ahead of time.
[43] Stand tending has been found to be important in Canadian forestry to ensure that managed stands reach a free-to-grow state (Kuhnke 1989).
[44] Anderson and Luckert (*in press*) estimate a yield curve for hybrid poplar specific to the Western Canadian Boreal Regions. The hybrid poplar growth and yield trajectory is provided in Figure A-2 of the appendix.

Hybrid poplar plantations are constrained to provide no more than 17% of the hardwood volume shipped to the mill in each period, and are only permitted in the close and medium distance haul zones (representing 100 km and 200 km to the mill, respectively). These constraints are based on Alberta-Pacific Forest Industries Inc.'s objectives for hybrid poplar management, one of the few boreal forestry firms currently establishing hybrid poplar plantations on an operational basis.[45] The restriction on the percentage of volume shipped from hybrid poplar plantations is also intended to implicitly recognize that there may be regulatory and social issues surrounding the use of hybrid species in Canadian forests (Reedy 2003; Anderson and Luckert, *in press*). A further constraint on hybrid plantations prevents them from being established on low productivity sites, and is based on speculation that nutrient limitations in boreal regions may present challenges in achieving higher growth rates (Weih 2004).

Table 4-5 provides marginal costs associated with applying the different silvicultural practices described above. The extensive, basic and intensive management costs are cited from Insley *et al.* (2002).[46] The extensive management figure simply reflects the costs of data management and monitoring for a forest area. Basic management costs include a higher data management and monitoring figure, in addition to site preparation, nursery stock and planting costs. Intensive management adds the cost of two additional stand tending operations to the figure for basic management. The costs

[45] Alberta-Pacific has a stated target to eventually supply 17% of their mill's fibre requirement from leased areas of hybrid poplar, and only seeks to lease land for hybrid poplar plantations within 200 km of the mill (Alberta-Pacific 2004).

[46] Although the silvicultural costs cited from Insley *et al.* (2002) are developed for boreal forest units in Northern Ontario, they are found to be similar to boreal plains silvicultural costs previously used by industry experts in Alberta.

of establishing hybrid poplar plantations are found in Anderson and Luckert (*in press*), and include the costs of initial site preparation and planting activities plus additional cultivation and herbicide treatments.

Table 4-5 Marginal Costs ($/ha) Associated with Applying Different Silvicultural Intensities to Eligible Forest Cover Types on the Hypothetical Boreal Plains Landscape.

Silvicultural Intensity	Applicable Forest Cover Types	Management Cost ($/ha)
Extensive Silviculture	All	5
Basic Silviculture	MW, SW, PI, MC Only	930
Intensive Silviculture	MW, SW, PI, MC Only	1180
Hybrid Poplar Plantations	PO Only	1231

4.2.2 Forest Carbon Management Incentives

Incentives to manage carbon stocks on the hypothetical forest landscape are incorporated as a market price for forest carbon that is sequestered or conserved above a baseline level. Under the modeling framework employed (Equation 3.1), this carbon price reflects the value of a temporary credit for carbon stored over one period (10 years). To interpret this value, it is necessary to consider the costs of securing temporary, as opposed to permanent, carbon offsets.

Although there is general agreement that a temporary carbon credit should sell at a discount, the size of this discount remains uncertain. Chomitz and Lecocq (2003) argue that the discount rate will depend on the expected future costs of permanent carbon offsets. Temporary credits would sell at a steep discount, relative to permanent credits, when restrictions on carbon emissions are expected to tighten, but would gain value when the price of permanent credits is expected to remain constant. Temporary credits would also gain value if expected to bridge a gap to new technology and relatively inexpensive permanent emissions abatement. More generally, the relationship between the costs of permanent and temporary carbon credits is expected to depend on rates of time preference, the expected life of a temporary credit and the perceived risk of each instrument (Sedjo 2001).

Estimates of the costs of permanent offsets from the literature are quite broad. Baseline estimates by van Kooten *et al.* (2004), derived through a meta-analysis of 55 different studies, provided a range of US \$46.62 to US \$260.29/t C. Metz *et al.* (2001) cite the costs for sequestering "modest" amounts of carbon as ranging from US \$20 to US \$100/t C. Meanwhile, market prices from active carbon credit trading in Europe, observed between February and June, 2006, range from US \$11.55 to US \$31.99/t CO_2 (equating to US \$42.35 to US \$117.30/t C).[47]

Given the broad assessment of carbon credit costs from the literature, and considering the uncertainty of how steeply to discount temporary versus permanent carbon offsets, the incentives associated with a range of carbon market prices are tested on the hypothetical forest landscape. The range of carbon market prices selected cover relatively steep discount rates to near equal values for temporary versus permanent carbon credits, when considering the minimum values estimated in the literature and observed in active markets. These values then increase up to \$US 98.80/t C, capturing a

[47] See the EU Price Assessment available at http://www.pointcarbon.com (cited June 6, 2006). For conversion: 1 unit of C = 3.6667 or 44/12 units of CO_2 (44/12 is the ratio of the molecular weight of carbon to carbon dioxide).

value slightly larger than that cited by Metz *et al.* (2001) but discounted by approximately 20% from the maximum European price assessment.

Table 4-6 provides the range of assumed carbon market prices in both CAD $/t C and CAD $/t CO_2. Equivalent US $/t C are provided for easy comparison with the range of carbon values cited from the literature. The forest carbon management incentives derived from this range of market prices are assessed under two alternate carbon market policies: one requiring the use of a BAU carbon baseline, the other a constant carbon baseline. The merits of BAU versus constant carbon baselines are discussed in sub-section 2.4.3, and the methods for deriving each baseline in Section 3.2.

Table 4-6 Assumed Market Prices of a Temporary Credit for Carbon Stored over One Period (10 years) on the Hypothetical Boreal Plains Landscape.

CAD $/t C	CAD $/t CO_2 [a]	US $/t C [b]
10.00	2.73	8.98
25.00	6.82	22.45
55.00	15.00	49.40
110.00	30.00	98.80

a For conversion: 1 unit of C = 3.6667 or 44/12 units of CO_2.
b Exchange rate of 0.898150 USD/CAD assumed (June 6, 2006).

4.2.3 Regulatory Environment

The forest management regulations imposed on Canadian forestry firms will affect their ability to respond to incentives for carbon management as well as the costs of doing so. The economic rents derived from timber harvesting are also subject to the costs of adhering to forest management regulations. Sustained yield policies and regeneration regulations are implemented on the hypothetical boreal plains landscape. Both types of regulations have historically been faced by the forestry sector in Alberta.

For instance, existing forest management legislation in Alberta requires timber to be harvested in a manner which provides a perpetual sustained yield from Forest Management Agreement Areas (Alberta Forests Act, F-22, 2.16.1). Harvest volume constraints (described by Equations 3.4 through 3.9) are thus imposed on the model. In the absence of carbon management incentives, these constraints are formulated as a strict even flow policy from period to period on both softwood and hardwood harvest volumes.[48]

It is currently unclear, however, whether or not timber yield policies will be reconsidered if incentives for forest carbon management become a reality. Accordingly, three different regulatory scenarios are studied. The first enforces an even flow policy for timber harvested from period to period, but allows the model to determine the optimum level of harvest over the planning horizon, given both timber and carbon management incentives. This scenario allows the forestry firm the flexibility to reduce harvest volumes, potentially to zero, when presented with the opportunity to increase revenue by generating temporary carbon credits. The second and third regulatory scenarios restrict this flexibility by forcing the firm to maintain harvest levels either equivalent to, or

[48] For the initial forest age-class structure depicting a deficit of mature timber, the sustained yield regulations require a slight adjustment. Instead of a strict even flow timber yield policy over the entire planning horizon, a sequential yield policy is enforced over the first harvest rotation (the first 100 years). The young initial age-class structure in this scenario prevents the model from being able to establish a realistic even flow timber harvest volume over the first harvest rotation period. Strict even flow is then enforced for the remainder of the planning horizon.

within +/- 25%, respectively, of the even flow harvest volume realized prior to the introduction of carbon management incentives.[49]

The flexibility of forestry firms to respond to incentives for carbon management may be largely affected by the flexibility of sustained yield policies. Furthermore, the significance associated with these regulatory scenarios may depend to a large extent on who owns the rights to carbon sequestered in Canadian forest ecosystems. Forestry firms which own and operate their own mills may have an incentive to maintain the flow of timber to the mill, even when faced with the possibility of additional revenues from carbon management. Governments, meanwhile, may want to preserve timber yields in order to maintain regional economic stability, given the importance of the forest industry in Canada.

Strict regeneration standards, pertaining to the level of re-growth and performance of desirable species on harvested forest land, are also currently enforced in Alberta (Alberta Regeneration Survey Manual 2006). Regeneration standards may influence forest carbon management practices by preventing forestry firms from adjusting their silvicultural practices and, potentially, from altering the species mix found on managed forest stands. Regeneration constraints may also raise the costs associated with harvesting timber from certain forest cover types.

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[49] In their study estimating the carbon flows associated with a long-range forest management planning model, Hoen and Solberg (1994) implement similar harvest volume constraints in order to ensure reasonable activity among forest owners and to meet expected demand for timber from mills. These constraints are set at the mean of their case study area's annual harvest from the previous 8 years.

Two regulatory scenarios are examined concerning the enforcement of regeneration standards on the hypothetical forest landscape. The first requires forestry firms to return a harvested area to its original forest cover type, and is roughly equivalent to the current standards enforced in Alberta.[50] Accordingly, the extensive management option would be excluded from consideration for mixedwood and coniferous-leading forest cover types, since natural regeneration results in a higher proportion of deciduous cover than previously existed. The second regulatory regime removes this regeneration constraint. The alternative regeneration standards are enforced by adjusting the index μ in Equation 3.10.

4.3 Linear Programming Model Scenarios

A total of 300 linear programming models scenarios are performed for this study. These scenarios capture all of the forest landscape, carbon management incentive and regulatory regime variations discussed above, in addition to the implementation of two different discount rates. The discount rates, incorporated at 3% and 7% levels, are intended to reflect a social and a market rate of time preference, respectively.

Table 4-7 summarizes 288 of these 300 model scenarios. Each column of the table represents a parameter or index in the linear programming model that is tested across the range of values shown. In addition to these 288 model runs, 12 additional runs are conducted in the absence of carbon management incentives (i.e. carbon cost equals

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[50] Regeneration standards in the Province of Alberta require forest areas to be regenerated to one of four "strata standards", defined as: Coniferous, Coniferous-Deciduous, Deciduous-Coniferous, and Deciduous. Standards also ensure adequate stocking, survival and growth rates following harvest (Alberta Regeneration Survey Manual 2006).

CAD \$0/t C), in order to establish the baseline carbon stock level for each initial age-class structure, at each discount rate, under both regeneration standards.[51]

Table 4-7 Summary of Linear Programming Model Scenarios when Incentives for Carbon Management are Introduced for the Hypothetical Boreal Plains Forest Landscape.

Initial Age-Class Structure	Market Cost of Temporary Carbon Credits	Baseline Carbon Stock	Discount Rate	Regulatory Environment
Deficit of Mature Timber	CAD \$10/t C	Business-as-Usual Carbon Baseline	3%	x 3 Sustained Yield Harvest Volume Policies
Fully Regulated Normal Forest	CAD \$25/t C			
Surplus of Mature Timber	CAD \$55/t C	Constant Carbon Baseline	7%	x 2 Regeneration Standards
	CAD \$110/t C			

[51] The scenarios without carbon management incentives need only be run under one harvest volume constraint, a strict even flow timber yield policy from one period to the next.

Chapter 5: Results

The objective of this study is to assess the sensitivity of forest management decisions to an incentive mechanism and variety of key variables related to forest carbon management in Canada. Results are generated by incorporating the experimental design characteristics from Chapter 4 into the integrated modeling framework developed in Chapter 3. Analysis, in this chapter, focuses on questions such as: (i) what return will be realized from carbon management relative to timber management alone?, (ii) how will forest policy affect the decision to manage for carbon?, (iii) which types of forest are most likely to be managed for carbon versus timber, and what intensity of silviculture is most likely to be used? (iv) where on the forest landscape is carbon management most likely to occur? To answer these questions, results are presented and described to show changes to the landscape that result from management decisions taken according to different carbon market incentives and regulatory regimes.

The first section of this chapter describes the carbon dynamics associated with the landscape that occur when management decisions consider returns to timber harvest only. These baseline carbon results are critical to understanding the changes in net present value (NPV) from forest management that occur when the landscape is managed for both timber and carbon considerations. The changes in NPV stemming from carbon market values, and the relative contributions of returns to carbon versus timber, are discussed in section 5.2. Incorporating carbon management incentives can also alter the timber management practices of forestry firms on the landscape. These landscape impacts are investigated in section 5.3. The cost implications of different aspects of the experimental design are then discussed in the fourth section, before the chapter is concluded with a summary of findings.

5.1 Carbon Baseline Results

Figure 5-1 describes the BAU carbon baselines derived by solving the integrated modeling framework with a carbon cost of $0/t C. Constant carbon baselines are inferred from these results as a horizontal line at the initial carbon stock for each hypothetical forest scenario. The progression of these baselines through time is critically important for assessing carbon management opportunities. Temporary carbon credits (debits) are generated according to the level of carbon stored in excess (deficit) of the baseline quantity at the end of each ten year period through the planning horizon.

The importance of initial forest age-class structure in determining the shape of the carbon baseline is evident. While forest carbon stocks are expected to increase in the BAU scenario on a landscape with an initial deficit of mature timber, they are expected to decrease sharply on a landscape with an initial surplus of mature timber. The preferred carbon baseline policy of a forestry firm undertaking carbon management could thus be expected to differ depending on the initial age-class structure of their forest management agreement area.[52] Meanwhile, the expected BAU carbon stocks also differ more generally in terms of the discount rate and the enforcement of regeneration standards over the different initial age-class structures. Such differences stem from the sequence of

[52] As discussed in Section 2.4.3, carbon suppliers are likely to push for baseline policies that will maximize their projected benefits from carbon management (Watson *et al.* 2000). BAU (constant) carbon baseline policies would therefore be preferred when forest carbon stocks are projected to decline (increase). Note also that no allowance is made for roads, landings and other operations that can reduce the carbon baseline.

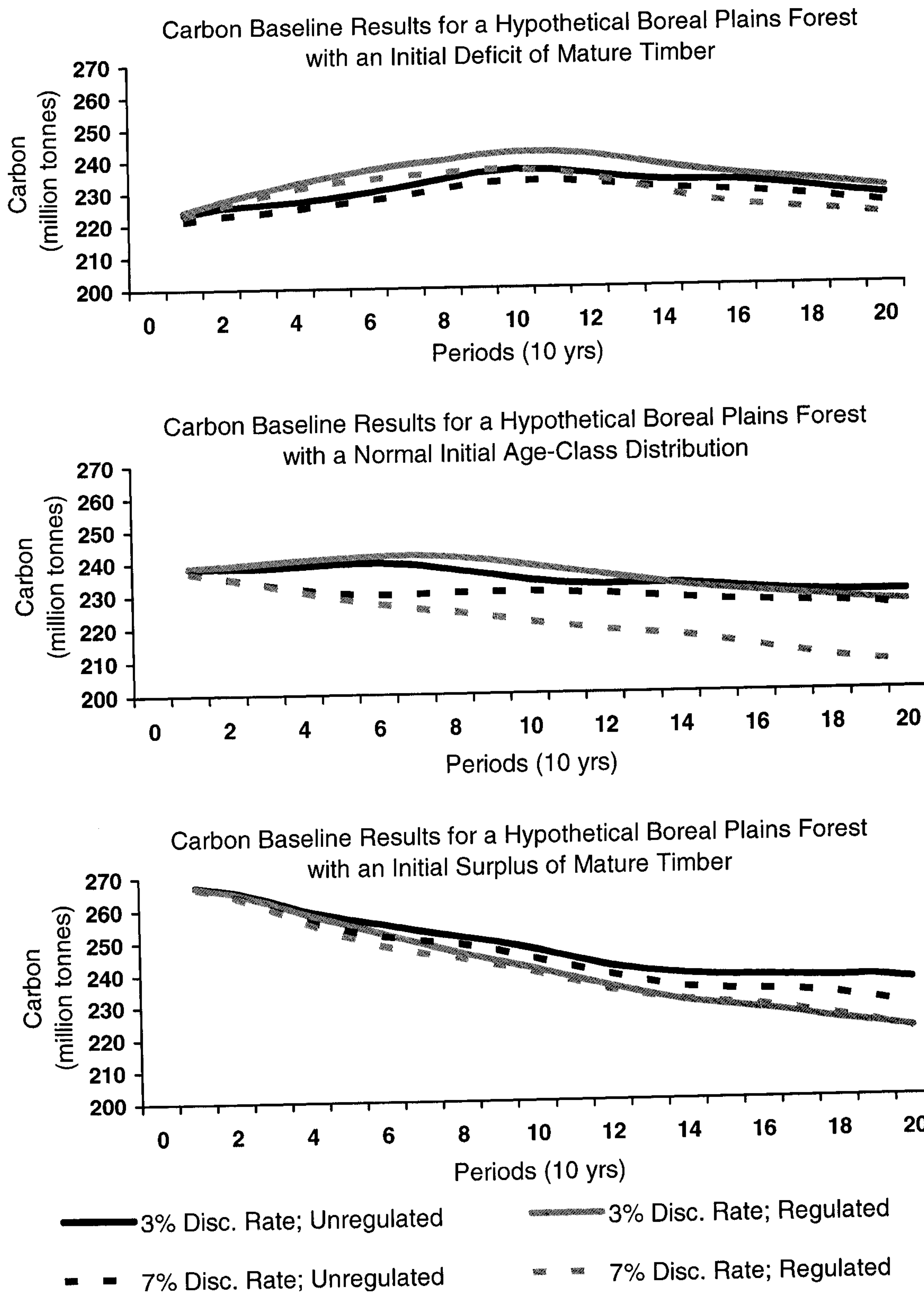

Figure 5-1 BAU carbon baseline results for a hypothetical boreal plains forest landscape. Scenarios depicted are for landscapes assigned an initial deficit of mature timber, a normal initial age-class distribution and an initial surplus of mature timber, respectively. Regulated forests indicate the presence of regeneration standards as defined in sub-section 4.4.2.

harvest over different forest cover types, as well as the silvicultural practices employed in the absence of regeneration regulations.

5.2 Net Present Value Results for the Hypothetical Forest Landscape

The objective of the linear programming model is to maximize the net present value (NPV), or the projected benefits, of managing the hypothetical forest landscape under different regulatory and policy scenarios. Returns to management when value accrues from both timber harvest and temporary carbon credits are then compared to returns when the landscape is managed for timber harvest alone. This section considers how changes in NPV, following the introduction of carbon management incentives, vary depending on the regulatory and landscape characteristics of a managed forest.

Tables 5-1 and 5-2 describe the percentage change in NPV derived from managing a forest landscape for returns to both timber and carbon management, relative to returns from timber management alone. Table 5-1 includes temporary carbon credits calculated versus a BAU baseline, while carbon credits in Table 5-2 are calculated against a constant carbon baseline. Model scenarios which produce a positive change in NPV indicate that the incorporation of carbon management will be beneficial to the forestry firm. A negative change in NPV indicates that the forestry firm is better off in the absence of value for forest carbon stocks.[53]

[53] The results provided here provide a general indication of the forest landscape characteristics, regulatory regimes and carbon cost structures that would cause the introduction of carbon management incentives to be beneficial for a forestry firm. Politylo (2004) provides a more in depth analysis of the conditions under which a forest management firm could be expected to undertake a carbon supply contract.

Table 5-1 Percentage Change in NPV (% Δ $) Associated with Timber and Carbon Management Incentives vs. Timber Management Incentives Alone. Calculated with a BAU Carbon Baseline.

Regulatory Environment		Carbon Cost ($/t C)	3% Discount Rate			7% Discount Rate		
			Deficit Forest (% Δ $)	Normal Forest (% Δ $)	Mature Forest (% Δ $)	Deficit Forest (% Δ $)	Normal Forest (% Δ $)	Mature Forest (% Δ $)
No Regeneration Standards	*Harvest Volume can be Adjusted*	*10*	188.17	91.81	54.65	77.57	20.28	9.91
		25	615.31	366.69	249.66	329.29	148.83	85.29
		55	1473.67	926.71	669.03	844.43	447.42	306.53
		110	3047.35	1953.43	1438.07	1788.86	994.83	713.07
	Harvest Volume Equal to Baseline Level	*10*	175.62	31.28	18.43	77.53	5.03	3.67
		25	529.31	113.98	67.87	308.79	28.22	20.25
		55	1244.58	302.41	181.50	778.40	95.57	60.88
		110	2559.65	654.94	406.09	1641.97	239.63	144.81
	Harvest Volume +/- 25% Baseline Level	*10*	181.90	62.79	40.52	77.57	16.50	16.23
		25	554.90	199.45	131.43	314.92	73.61	46.35
		55	1307.83	490.33	329.92	797.18	205.52	135.22
		110	2691.96	1033.85	706.87	1682.69	458.80	305.41
Regeneration Standards Applied	*Harvest Volume can be Adjusted*	*10*	234.68	136.76	78.40	104.19	46.71	9.20
		25	736.71	489.99	336.43	407.43	238.72	114.96
		55	1740.76	1197.98	860.15	1016.35	645.19	372.90
		110	3581.51	2495.96	1820.30	2132.70	1390.37	845.80
	Harvest Volume Equal to Baseline Level	*10*	191.11	34.21	20.96	91.68	6.55	3.98
		25	566.23	133.33	81.59	344.06	39.59	23.66
		55	1329.67	353.92	221.81	857.39	127.77	73.72
		110	2735.82	767.79	491.82	1803.52	311.25	173.34
	Harvest Volume +/- 25% Baseline Level	*10*	208.63	81.61	51.79	97.22	30.93	10.69
		25	617.90	250.93	170.26	363.30	111.58	58.87
		55	1445.64	607.82	416.56	903.14	288.40	164.67
		110	2969.21	1274.25	881.44	1896.33	627.30	364.88

Table 5-2 Percentage Change in NPV (% Δ $) Associated with Timber and Carbon Management Incentives vs. Timber Management Incentives Alone. Calculated with a Constant Carbon Baseline.

Regulatory Environment		Carbon Cost ($/t C)	3% Discount Rate			7% Discount Rate		
			Deficit Forest (% Δ $)	Normal Forest (% Δ $)	Mature Forest (% Δ $)	Deficit Forest (% Δ $)	Normal Forest (% Δ $)	Mature Forest (% Δ $)
No Regeneration Standard	*Harvest Volume can be Adjusted*	*10*	249.26	89.46	12.61	100.63	8.06	-5.63
		25	768.04	360.80	144.58	386.91	118.27	46.44
		55	1809.68	913.77	437.85	971.21	380.20	221.06
		110	3719.36	1927.54	975.70	2042.43	860.39	542.11
	Harvest Volume Equal to Baseline Level	*10*	236.71	28.93	-23.61	100.58	-7.20	-11.87
		25	682.04	108.09	-37.21	366.42	-2.34	-18.60
		55	1580.58	289.47	-49.68	905.18	28.35	-24.60
		110	3231.67	629.05	-56.28	1895.54	105.18	-26.14
	Harvest Volume +/- 25% Baseline Level	*10*	243.00	60.43	-1.52	100.62	4.27	0.69
		25	707.63	193.56	26.35	372.55	43.05	7.49
		55	1643.84	477.38	98.74	923.96	138.30	49.75
		110	3363.97	1007.96	244.50	1936.26	324.36	134.45
Regeneration Standards Applied	*Harvest Volume can be Adjusted*	*10*	401.03	146.96	18.46	196.95	29.50	-10.13
		25	1152.58	515.49	186.59	639.35	195.70	66.62
		55	2655.67	1254.07	530.49	1526.56	550.54	266.56
		110	5411.34	2608.13	1160.98	3153.12	1201.08	633.13
	Harvest Volume Equal to Baseline Level	*10*	357.46	44.41	-38.98	184.45	-10.66	-15.35
		25	982.10	158.83	-68.26	575.98	-3.43	-24.68
		55	2244.58	410.01	-107.85	1367.60	33.12	-32.62
		110	4565.65	879.96	-167.50	2823.94	121.95	-39.33
	Harvest Volume +/- 25% Baseline Level	*10*	374.98	91.81	-8.15	189.98	13.72	-8.64
		25	1033.77	276.42	20.42	595.21	68.56	10.53
		55	2360.56	663.91	86.90	1413.35	193.75	58.33
		110	4799.05	1386.43	222.12	2916.75	438.01	152.20

In general, introducing carbon management incentives for hypothetical forest landscapes with younger initial age-classes is found to generate a larger increase in NPV than for landscapes with more mature initial age-class structures. This result is consistent with predictions of carbon sequestration potential currently found in the literature (Sampson and Scholes 2000, Bhatti *et al.* 2001). Furthermore, as carbon values increase, the incorporation of carbon management is found to dramatically increase the NPV associated with the forest landscape (in many cases by over 1000% of the NPV with timber management alone). The magnitude of such increases suggests that, for certain model scenarios, carbon management could significantly alter the practices of forestry firms over the landscape.

The use of a BAU carbon baseline to calculate the returns to carbon management (Table 5-1) is found to increase the NPV of the forest landscape in all model scenarios which include carbon management, versus those with timber management only. A policy mandating the use of a constant carbon baseline (Table 5-2), however, is found to cause carbon management to decrease NPV from the forest landscape in certain cases. In particular, carbon management is found to decrease returns in all model scenarios which use a constant baseline to calculate carbon values for a forest landscape with an initial surplus of mature timber, while forcing harvested volume to equal the baseline level of timber produced.

The discount rate appears to significantly affect returns to carbon management as well. This result highlights that most of the benefits and/or costs of carbon management occur in future, more heavily discounted, periods. Accordingly, a lower discount rate can increase returns to carbon management by assigning greater value to future carbon gains, but can also lead to higher costs in scenarios with future carbon losses. An interesting trend can also be observed in the results for scenarios with and without enforced regeneration standards. In almost all cases where the returns to carbon management are positive, scenarios with regeneration standards see NPV of the forest landscape increase by a larger percentage than scenarios without similar regulations. If returns to carbon management are found to be negative, regeneration standards cause a larger percentage decrease in NPV.

Reducing the flexibility of forest managers to adjust the volume of timber harvested from the landscape in pursuing carbon management objectives limits the benefits that can be derived from carbon management, as would be expected. The only scenarios that produce interesting results in this regard concern forest landscapes with an initial surplus of mature timber, a 7% discount rate and a carbon value of $10/t C. In these instances, NPV is actually larger when forest managers are constrained to be within 25% of baseline harvest levels than when they are free to adjust the even flow level of timber harvested. Accordingly, this observation suggests that for more mature forests and low carbon prices, when assuming a higher discount rate, the benefits of being able to fluctuate harvested volumes within a +/- 25% range from period to period outweigh the advantages of more flexibility to adjust the volume of timber harvested, but being forced to maintain an even flow of timber from one period to the next.

In order to further investigate the general relationships between forest landscape characteristics, regulatory and policy environments and the relative importance of carbon versus timber management incentives, simple OLS regressions are estimated by treating each model scenario as an independent observation.[54] The dependent variable for analysis is the percentage of total NPV derived from temporary carbon credits. Independent variables considered include dummy variables for the initial age-class structure of the forest, the discount rate applied, the carbon baseline policy used, whether regeneration regulations were in place and which harvest volume policy was enforced. Carbon values are incorporated as a continuous variable, and are also included as a squared term in order to capture potential differences in effect as carbon prices increase. Regression results are presented in Table 5-3.[55]

Coefficients on variables estimating the effect of carbon price, the discount rate used and the harvest volume policy are all strongly significant in explaining changes in the percentage of NPV attributed to revenues from temporary carbon credits. Dummy variable results indicate that the percentage of returns from carbon management is also affected by the initial age-class structure of the forest landscape, although the difference between the normal and mature age-class structures is less significant that that between the normal and deficit scenarios. Contrary to the observations from Tables 5-1 and 5-2, the effect of regeneration regulations is found to be insignificant for explaining variations

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[54] This approach yielded a set of 288 observations for regression analysis.

[55] This regression analysis technique provides a simple and useful picture of the preferences that best fit the large set of observations generated through the modeling framework and experimental design. This approach to analyzing data is similar to the CART (Classification and Regression Trees) technique developed by Breiman *et al.* (1984) and applied in Horowitz and Carson (1991) and Arentze and Timmermans (2005).

in the percentage of carbon revenues in total NPV. Accordingly, while these regulations appear to affect the general level of NPV associated with a forest landscape, the shifts in NPV do not appear to alter the proportions attributed to timber and carbon revenues. Carbon baseline policy is also insignificant in the regression analysis, likely reflecting contrasting effects on the proportion of revenues derived from carbon over different initial age-class structures.

Table 5-3 OLS Regression Results Estimating the Effects of Experimental Design Characteristics on the Relative Importance of Carbon vs. Timber Management Incentives.

Independent Variables	Dependent Variable: Carbon NPV/Total NPV
Carbon Cost	0.0172* (0.00367)
Carbon Cost Squared	-0.00012* (0.000029)
Deficit Forest[d] (vs. Normal Forest)	0.2064* (0.0727)
Mature Forest[d] (vs. Normal Forest)	-0.1302** (0.0727)
7% Discount Rate[d] (vs. 3% Discount Rate)	-0.1693* (0.0593)
Constant Carbon Baseline[d] (vs. BAU Carbon Baseline)	-0.0447 (0.0593)
Regeneration Regulations Applied[d] (vs. No Regeneration Regulations)	0.0913 (0.0593)
Harvest Volume Equal to Baseline Level[d] (vs. Adjustable Harvest Volume Policy)	-0.2498* (0.0727)
Harvest Volume +/- 25% Baseline Level[d] (vs. Adjustable Harvest Volume Policy)	-0.1777* (0.0727)
Constant	0.5341* (0.1125)

1 "d" denotes dummy variable; base case provided in parentheses.
2 Standard errors provided in parentheses.
3 * indicates significance at the 5% level or better.
4 ** indicates significance at the 10% level or better.

Coefficients estimating the effect of increased carbon value on the percentage of NPV attributable to carbon revenue provide interesting results. While the proportion of returns to carbon management initially increases with the price of temporary carbon credits, the negative coefficient on the squared carbon value term indicates that the marginal effect of increasing carbon prices decreases as these prices reach higher levels. This result could simply imply that carbon revenues approach a large percentage of total NPV even at relatively low carbon values. However, it could also be interpreted to suggest that, as the revenue from each temporary carbon credit increases, relatively costly timber management practices become more feasible to implement on the landscape. Accordingly, returns to both timber and carbon management could be increased at higher carbon prices.

5.3 Effects of Carbon Management on the Hypothetical Forest Landscape

The tables and figures, presented in the following sub-sections, describe how carbon market incentives affect; the volume of timber harvested from the hypothetical landscape, the type and age of timber harvested, the distribution of timber management activities over the landscape, and the intensity of management/silvicultural practices. Furthermore, in order to clarify the general relationships between forest landscape characteristics, regulatory and policy environments and the relative importance of carbon versus timber management incentives, simple OLS regressions are estimated using the linear programming model results.[56] Regression analysis aids significantly in presenting

[56] Regressions are estimated by treating each model scenario as an independent observation. Again, this approach to analyzing data is similar to the CART technique developed by Breiman *et al.* (1984).

the substantial quantity of data obtained from each scenario modeled in the linear programming framework.

Interestingly, a preliminary investigation of the model results shows that, while timber management practices vary depending on the forest landscape characteristics, regulatory environment and relative significance of carbon to timber price incentives, forest management decisions are exactly the same under both BAU and constant carbon baseline policies. This result suggests that, for a given landscape and a specified value for temporary carbon credits, forestry firms will adjust their operations to an optimal balance of timber and carbon management practices independent of the number of carbon credits actually earned. Accordingly, most of the regression analyses conducted below include observations from 156 model scenarios; composed of 144 experimental design variations for initial age-class structure, carbon market price, discount rate and regulatory environment conducted over one of the baseline carbon stock policies, plus the twelve baseline (timber management incentive only) models.

All regression models were developed by following a similar process. An initial specification is tested, in which the dependent variable is regressed against a set of independent variables including all the factors of the experimental design.[57] Accordingly, the base model considered includes dummy variables for the initial age-class structure of the forest, the discount rate applied, whether regeneration regulations were in place and which harvest volume policy was enforced. Carbon values are again incorporated as a

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[57] This approach leads to an initial model specification similar to that depicted in Table 5-3, minus the dummy variable capturing the effect of carbon baseline policy.

continuous variable, with a squared term included to capture any non-linear effects as these values increase. This base model is then expanded, in most cases, to include dummy variables which capture estimated effects specific to each forest cover type. The regression specified to predict harvest activity across haul zones and productivity levels is the only exception to this rule, as the dataset in this instance is delineated by haul zone/productivity class as opposed to species type.[58] In all model specifications, variables which interact the effects of carbon value (and carbon value squared) with each dummy variable are also included in the initial formulation. These interaction terms are meant to capture how the estimated effect of each experimental design characteristic changes with carbon price.[59] Finally, control variables are added to the regression equations in order to address specific questions by holding key effects constant.

Interestingly, independent variables capturing the effects of the discount rate, initial age-class structure and regulatory regime are found to lose all explanatory power in several model specifications once total harvest activity is controlled for. In such instances, these variables are dropped from the estimated equation, as they have no bearing on the regression results. Any interaction terms found to be insignificant in base model scenarios are also omitted from the final specifications presented in the sub-sections below.

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[58] Accordingly, dummy variables capturing effects specific to different distances from the mill and productivity levels are specified instead.

[59] Regressions estimating relationships between independent variables and management intensity also interact the dummy variables for each forest cover type with the variable specifying whether regeneration regulations are enforced, as this effect is hypothesized to be significant.

5.3.1 Harvest Activity Levels and Optimal Rotation Lengths

Figure 5-2, which separates the number of hectares harvested over the planning horizon into four different age-class groups, provides an indication of how increasing incentives for carbon management are expected to affect total harvest activity levels and optimal rotation lengths on the forest landscape.[60] Changes in the aggregate number of hectares harvested within each of the four age-class groupings are considered for the deficit, normal and mature initial forest age-class distributions separately. The results shown include all forest cover types (except hybrid poplar) and are averaged over the model scenarios including different discount rates and regulatory constraints. In addition, a column for the number of forest hectares never subjected to a harvest event is included, to depict how the area of un-accessed forest changes along with optimal rotation ages.

Figure 5-2 shows that, on average, fewer hectares of forest containing timber between five and nine periods of age will be harvested through the planning horizon when incentives for carbon management are present. This reduction in the area of younger forest harvested increases as the market value for temporary carbon credits rises. Moreover, as harvest activity in forest areas containing young timber declines with higher carbon values, harvesting of areas which contain older age-classes of timber remains relatively constant. Such a pattern indicates a general decline in harvesting activity as carbon management incentives become stronger, and also points to an increase in average harvest rotation age. This pattern appears to be consistent across all three

[60] The age-class groupings shown are for the number of hectares of forest harvested at 5-9, 10-14, 15-19 and 20+ periods of age, respectively. Each period represents 10 years of the planning horizon. The only forest cover type harvested at an age less than 5 periods is hybrid poplar, which, due to its unique growth and yield characteristics, is excluded from analysis in this section.

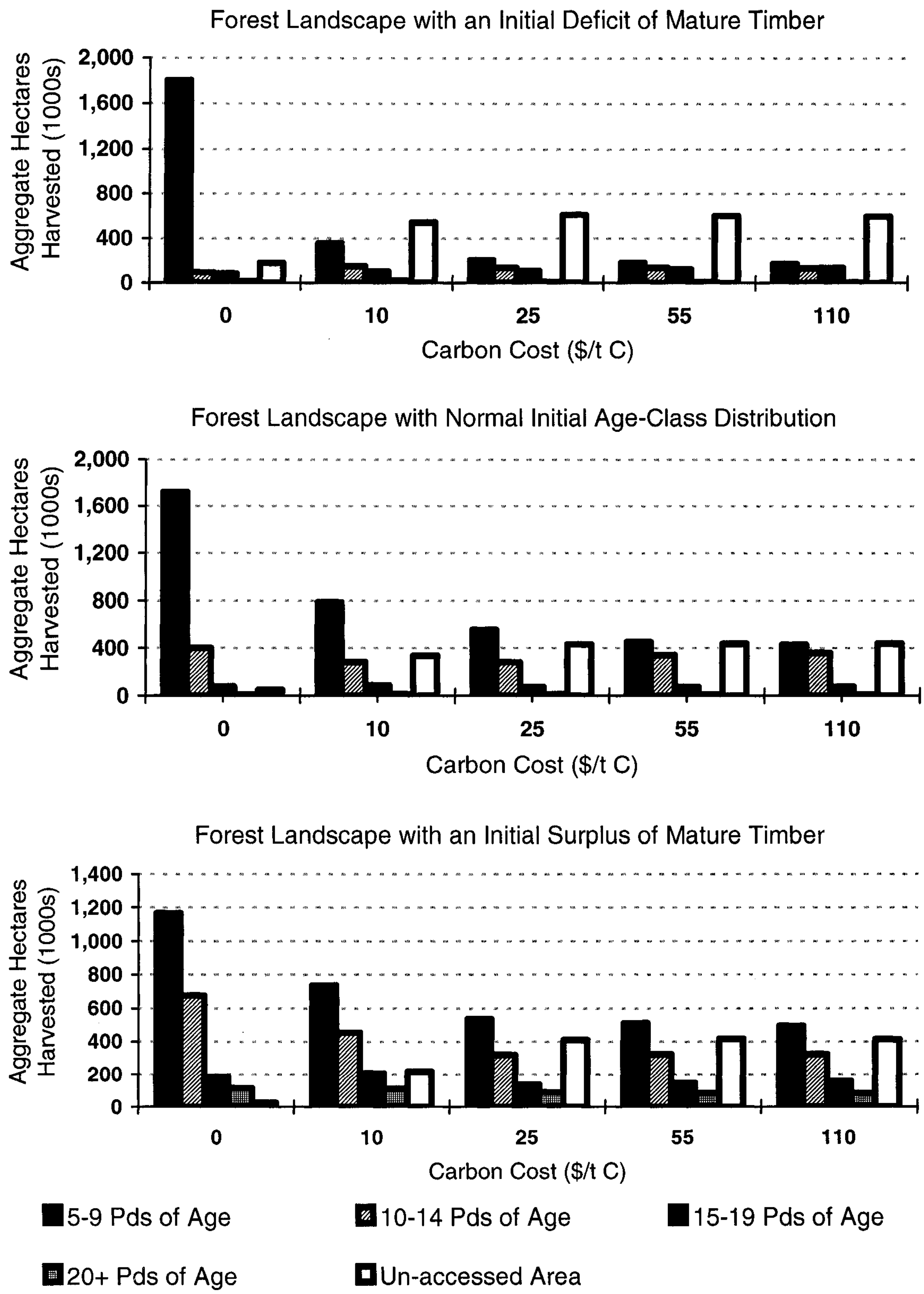

Figure 5-2 Harvested areas (ha) at different incentive levels for carbon management, by age-class at time of harvest. One period of age equals 10 years. Results included are averaged across model scenarios with different discount rates and regulatory environments

initial age-class distributions modeled, with only the aggregate number of hectares harvested changing between them.

A special consideration when investigating optimal rotation length is the potential for an infinitely long rotation period, indicating no harvest activity for a particular forest area.[61] For each of the initial age-class distributions in Figure 5-2, the area of forest that is never accessed for timber harvest increases with incentives for carbon management, up to a carbon price of about $25/t C, and remains relatively constant thereafter. Accordingly, as the aggregate number of hectares harvested over the planning horizon decreases, the harvest activity that does occur in conjunction with incentives for carbon management appears to take place over a smaller area of the forest landscape.[62]

An interesting question concerning the increasing number of hectares assigned to an infinite harvest rotation concerns which cover types, typical to a boreal plains landscape, are preferable to never harvest. Is carbon management more likely to lead to the conservation of one forest cover type than another? Taking the total area of forest never harvested over the planning horizon as the dependent variable, a regression is estimated to analyze the change in conserved (never harvested) area of each species type on the hypothetical forest landscape as incentives for carbon management increase.

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[61] Both van Kooten *et al.* (1995) and Creedy and Wurzbacher (2001) have found that optimal harvest rotations can lengthen to infinity with value for sequestered carbon and the right set of conditions.
[62] A simple reduction in the aggregate number of hectares harvested does not suggest, a priori, that the area of forest accessed for harvest will decrease. Aggregated harvest area is calculated by summing the number of hectares harvested in each period across the entire planning horizon. Accordingly, an actual hectare of forest may be included several times in this calculation, depending on the number of harvest rotations which occur on that hectare over the 20 period planning horizon. To be accessed, that same hectare need only be harvested one time.

Independent variables for the regression include the market value for temporary carbon credits and dummy variables for the specific forest cover types. Interaction terms between carbon value and species type capture the specific effects of increasing carbon incentives on conserving specific cover types. A control variable for the total area of the forest landscape accessed for harvesting purposes is added as well, so as to isolate changes in un-accessed area for each species type from changes in total un-accessed area for the forest landscape as a whole. Figure 5-3 displays the estimated relationship between incentives for carbon management and the area of each cover type conserved (never harvested), holding total area accessed for timber harvest constant. Detailed regression results are included in the appendix (Table A-2).

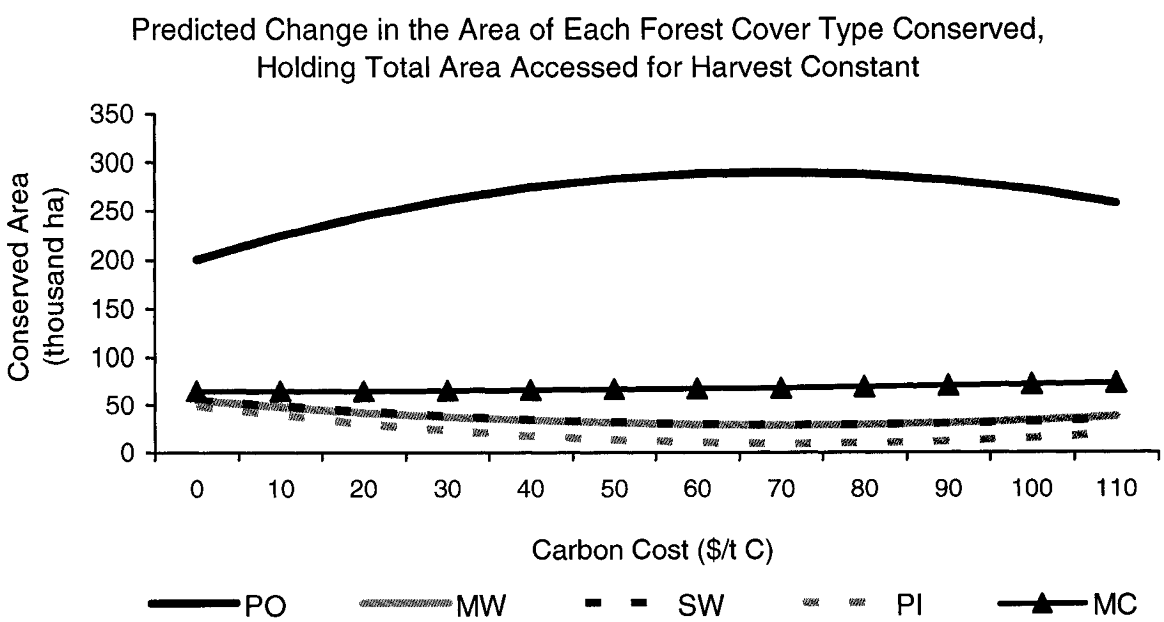


Figure 5-3 Regression results predicting the area (ha) of each forest cover type conserved (never harvested over the planning horizon) at different incentive levels for carbon management. Trends show changes in un-accessed areas for each forest cover type while holding the total forest area accessed for harvesting constant.

The results in Figure 5-3 predict that a forest manager on the boreal plains will prefer to conserve more aspen (PO) forest when provided with carbon management incentives. Larger areas of mixedwood (MW), white spruce (SW) and pine (PI) would then be accessed, in order to make up for the decline in timber management on aspen stands. Managed areas of mixed coniferous (MC) forest are predicted to remain relatively unaffected by carbon management incentives.

These results suggest that conserved areas of aspen would increase on the boreal plains under carbon management, ceteris paribus. Interestingly, however, the area of conserved aspen is predicted to peak at a carbon price of approximately $70/t C, before beginning to decline as the value of stored carbon grows progressively higher.[63] Conversely, the area of conserved mixedwood, white spruce and pine forest is estimated to recover slightly as carbon price increases above $70/t C. This result may simply reflect that the conserved area of aspen cover approaches it maximum observed value at carbon values less than $110/t C. Alternatively, at very high estimates of temporary carbon credit value, the cost of decreasing the area of aspen accessed could increase, causing a reduction in the area of aspen cover that is predicted to be conserved.

Re-focusing attention on the incentives for forest managers to conserve forest area within each species type, rather than across species, a different picture emerges. Figure 5-4 displays the results of re-estimating the regression, holding the aggregate number of hectares harvested from each species over the planning horizon constant but allowing

[63] Despite this decline, the area of aspen conserved on the hypothetical landscape remains above the level predicted for a carbon price of $0/t C throughout the observed range of carbon values.

total accessed area to vary. The dependent variable under consideration is also changed from total conserved (never harvested) area to the percentage of initial area for each cover type conserved. Detailed regression results are again provided in the appendix (Table A-3).

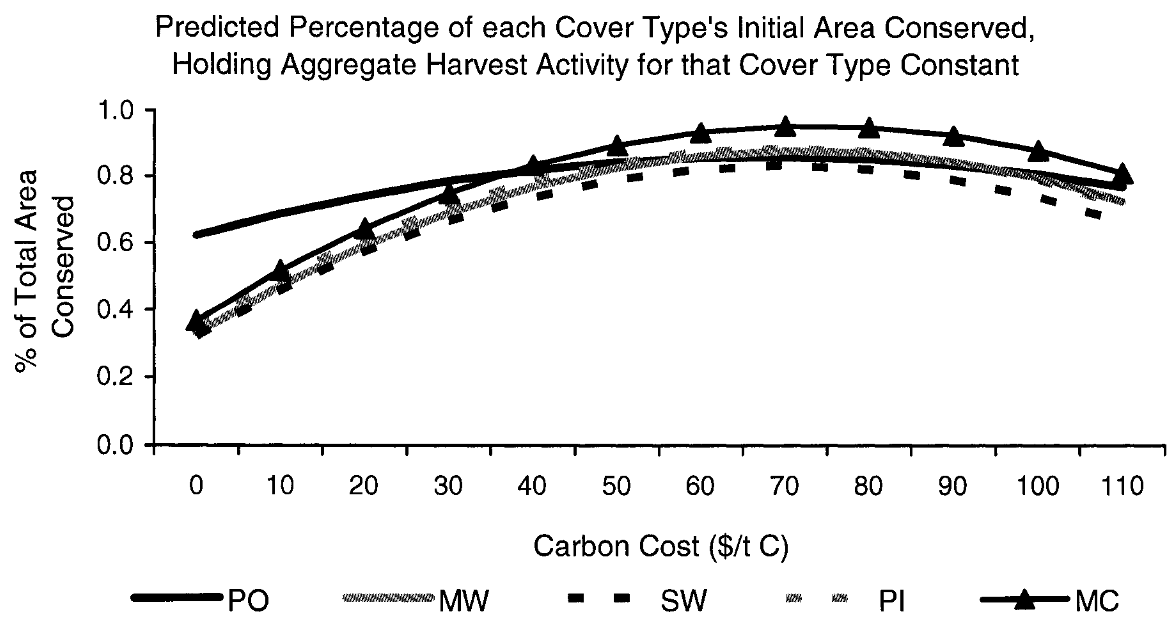


Figure 5-4 Regression results predicting the percentage of initial area for each forest cover type conserved (never harvested over the planning horizon) at different incentive levels for carbon management. Trends show changes in the percentage of un-accessed area for each forest cover type while holding the aggregate number of hectares harvested of that species constant. Scenario depicted is for a normal initial age-class distribution, a discount rate of 3% and no regulatory constraints. Aggregate harvested hectares are included at their mean value for each cover type.

Figure 5-4 shows that, as carbon management incentives increase, the percentage of each cover type's initial area that is never accessed for harvest over the planning horizon also increases, even with the aggregate number of harvested hectares from each species remaining constant. This result indicates that, as the market value for temporary carbon credits grows, forest managers on the boreal plains will prefer to maintain previous levels of harvest activity for each cover type by increasing the frequency of harvest over a smaller portion of the land base. The percentage of each species' initial area conserved would therefore increase. Similar to the results in Figure 5-3, however, this trend is predicted to peak at approximately $70/t C, and to begin reversing thereafter.[64]

Furthermore, dummy variables indicating the initial age-class distribution, discount rate and regulatory regime are all found to be significant in explaining the percentage of each forest cover type left un-accessed at the end of the planning horizon. Ceteris paribus, more mature initial age-class distributions and higher discount rates are expected to reduce the percentage of each cover type conserved, although the reduction from increasing the discount rate is predicted to decrease at higher market values for carbon. Meanwhile, regulations on regeneration practices are estimated to increase the area of each cover type left un-accessed, while also flattening out the slope of the trend-lines in Figure 5-4. The percentage of conserved area for each species type is less responsive to increasing carbon incentives when regeneration regulations are enforced, likely because management intensity of accessed forest areas is relatively high before the introduction of value for stored carbon. Finally, variables included to control the effects of restricting firms from adjusting harvest volumes to carbon incentives are found to decrease the percentage of each species' initial area conserved.

[64] Again, despite this decline, the percentage of each forest cover types' initial area remains above the level predicted for a carbon cost of $0/t C throughout the observed range of carbon values.

5.3.2 Timber Harvest Volumes

By influencing the optimal rotation age and increasing the conserved area for different forest cover types, carbon management incentives could have a significant impact on the total volume of timber harvested from the hypothetical forest landscape. In this sub-section, the effects of a carbon market on timber harvest volumes are first considered for basic model scenarios, in which no regeneration regulations or constraints on adjusting the even flow level of harvested timber are enforced. The effects of implementing each type of regulatory constraint are then considered and compared to the basic, unregulated model case. Finally, regression analyses are used to estimate how the combination of carbon management incentives with elements of the experimental design affect the extent of timber management on the forest landscape, as well as the distribution of timber management over different forest cover types.

<u>Basic Model Scenarios: No Regulations Concerning Regeneration Practices or the Level of Harvest Activity</u>

Table 5-4 describes the percentage change in harvested volume (% Δ m^3) from the baseline case, which has incentives only for timber management, to model scenarios where incentives for both carbon and timber management are incorporated. Results are provided for each individual forest cover type on the hypothetical landscape. The scenarios shown cover the range of initial age-class structures and carbon values incorporated into the experimental design, at both a 3% and a 7% rate of discount.

The changes in harvested volume that follow the introduction of a market value for carbon reflect different species selection for timber management and changes in harvest rotation lengths. A percentage change in harvest volume of -100% in Table 5-4 indicates that all harvest of that particular forest cover type ceases on the hypothetical landscape following the introduction of carbon management incentives. Accordingly, it is apparent that an efficient solution of never harvesting applies to almost all basic model scenarios with a carbon price greater than or equal to \$25/t C.[65] The only exception to this observation is for a forest landscape with an initial surplus of mature timber, which continues to produce minimal harvest activity at \$25/t C, but has harvesting cease when carbon price is equal to or above \$55/t C.

Furthermore, harvested volume always decreases for all forest cover types when the discount rate is at 3%. Interestingly, though, a steeper discount rate generates scenarios where the harvesting of certain species may increase with incentives for carbon management. In Table 5-4, the volume of timber harvested from mixedwood, pine and mixed coniferous stands all increase when the discount rate is 7%, the cost of carbon is \$10/t C and the forest landscape is initially in deficit of mature timber. The volume of timber harvested from mixed coniferous stands again increases at \$10/t C for a forest landscape with an initial surplus of mature timber and a 7% discount rate. Moreover, harvest volumes from all forest cover types generally decrease by a lesser percentage, versus their baseline levels, at the higher rate of discount. These observations reflect that most of benefits from carbon management occur in future periods.

[65] Choosing to never harvest a stand can be considered an infinitely long harvest rotation (van Kooten *et al.* 1995).

Table 5-4 Percentage Change in Total Harvested Volume (% Δ m^3) from the Baseline Case to Basic Model Scenarios with Timber and Carbon Management Incentives.

Discount Rate	Initial Age-Class Structure	Carbon Cost ($/t C)	PO Harvested (% Δ m^3)	MW Harvested (% Δ m^3)	SW Harvested (% Δ m^3)	PI Harvested (% Δ m^3)	MC Harvested (% Δ m^3)
3%	*Deficit Forest*	*10*	**-94.64%**	**-88.18%**	**-66.80%**	**-56.96%**	**-64.81%**
		25	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		55	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		110	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
	Normal Forest	*10*	**-90.06%**	**-83.26%**	**-77.31%**	**-68.75%**	**-65.76%**
		25	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		55	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		110	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
	Mature Forest	*10*	**-84.53%**	**-39.91%**	**-39.83%**	**-22.37%**	**-19.55%**
		25	**-100.00%**	**-100.00%**	**-99.02%**	**-100.00%**	**-90.42%**
		55	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		110	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
7%	*Deficit Forest*	*10*	**-33.44%**	**5.71%**	**-10.08%**	**0.60%**	**36.04%**
		25	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		55	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		110	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
	Normal Forest	*10*	**-64.50%**	**-17.19%**	**-24.25%**	**-24.60%**	**-19.90%**
		25	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		55	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		110	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
	Mature Forest	*10*	**-34.53%**	**-15.68%**	**-5.19%**	**-4.86%**	**0.68%**
		25	**-99.88%**	**-94.58%**	**-91.13%**	**-93.40%**	**-84.09%**
		55	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		110	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%

Note: Rows in bold indicate scenarios in which timber harvest activity continued to be undertaken. In all other scenarios, the presence of carbon management incentives caused timber harvest activity to cease entirely (i.e. a 100% decline).

The forest cover type that experiences the greatest decline in harvested timber volume under all scenarios with incentives for carbon management is aspen (PO). The remaining cover types experience more or less reduction in harvest volumes versus each other depending on the particular model scenario in question, although the harvested volume from white spruce (SW) is always reduced more than that in pine (PI) and mixed coniferous (MC) stands. These differences in the rate of harvest of different forest cover types, following the introduction of carbon management incentives, affect the flow of hardwood versus softwood timber that is generated over the planning horizon. These differences are depicted for the case of $10/t C temporary carbon credit costs in Table 5-5.[66]

Table 5-5 Flow of Harvested Timber (m^3 per period) over the Planning Horizon in Basic Model Scenarios with $0/t C and $10/t C.

Initial Age-Class Structure	Carbon Cost[a] ($/t C)	3% Discount Rate			7% Discount Rate		
		HWD Harvested (m3)	SWD Harvested (m3)	Total Harvest (m3)	HWD Harvested (m3)	SWD Harvested (m3)	Total Harvest (m3)
Deficit Forest[b]	*0*	5,533,063	2,743,373	8,276,436	5,314,748	2,521,118	7,835,866
	10	295,864	1,104,504	1,400,369	3,543,908	3,347,209	6,891,117
Normal Forest[c]	*0*	7,473,147	4,715,062	12,188,210	9,249,347	5,325,887	14,575,234
	10	737,578	1,428,352	2,165,929	4,080,381	3,885,922	7,966,303
Mature Forest[c]	*0*	8,834,604	6,132,038	14,966,642	9,768,615	6,587,949	16,356,565
	10	1,717,633	4,056,181	5,773,813	6,297,488	6,380,361	12,677,849

a A carbon price of $0/t C represents results for the baseline model runs.
b Figures presented for the Deficit Forest are the average per period harvest volume.
c Even flow policies constrain harvested volume to be the same in all periods for both the Normal and Mature Forests.

66 The case of $10/t C is the only one depicted in Table 5-5 since the efficient solution for almost all other carbon prices is not to harvest at all. While some harvest does occur for certain forest cover types on initially mature forest landscapes at $25/t C, this harvest is minimal.

For each initial forest age-class structure, the baseline scenario (with incentives for timber management only) generates a higher per period flow of hardwood than softwood timber.[67] The addition of carbon management incentives (at $10/t C), and the different percentage change in harvested volume that results across the various forest cover types (Table 5-4), causes the flow of hardwood to decline by a greater amount than softwood timber flow. As a result, at a 3% discount rate, softwood displaces hardwood as the primary timber product generated through management of the forest landscape. A discount rate of 7% causes the flow of hardwood and softwood timber to roughly balance out at half of the forest timber production each. Interestingly, in the case of a 7% discount rate and a younger initial age-class distribution, the volume of softwood harvested from the landscape actually increases with carbon management incentives.

Model Scenarios with Regeneration Regulations Enforced

Incorporating a policy which requires forest managers to return harvested areas to their original forest cover type changes the relationships between harvested volumes and incentives for carbon management described for basic model scenarios. Table 5-6 describes the percentage change in harvested volume (% Δ m^3) from the baseline case to model scenarios where incentives for both carbon and timber management are incorporated. Regeneration regulations are enforced by preventing the use of extensive silviculture (leave-for-natural regeneration practices) on mixedwood and coniferous-leading forest cover types.

[67] Recall that aspen-leading stands make up 54% of the hypothetical boreal plains forest landscape. This large area of deciduous-leading forest cover may explain the larger per period harvest of hardwood in the baseline model runs.

Table 5-6 Percentage Change in Total Harvested Volume (% Δ m^3) from the Baseline Case to Model Scenarios with Timber and Carbon Management Incentives and Regeneration Regulations Enforced.

Discount Rate	Initial Age-Class Structure	Carbon Cost ($/t C)	PO Harvested (% Δ m^3)	MW Harvested (% Δ m^3)	SW Harvested (% Δ m^3)	PI Harvested (% Δ m^3)	MC Harvested (% Δ m^3)
3%	*Deficit Forest*	*10*	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		25	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		55	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		110	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
	Normal Forest	*10*	**-91.41%**	**-100.00%**	**-93.03%**	**-98.61%**	**-100.00%**
		25	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		55	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		110	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
	Mature Forest	*10*	**-86.12%**	**-77.92%**	**-62.93%**	**-74.98%**	**-94.97%**
		25	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		55	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		110	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
7%	*Deficit Forest*	*10*	**-44.21%**	**-90.69%**	**-91.15%**	**-100.00%**	**-100.00%**
		25	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		55	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		110	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
	Normal Forest	*10*	**-65.71%**	**-66.00%**	**-70.07%**	**-84.86%**	**-79.91%**
		25	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		55	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		110	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
	Mature Forest	*10*	**-35.03%**	**-16.79%**	**-0.37%**	**-8.50%**	**-11.37%**
		25	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		55	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%
		110	-100.00%	-100.00%	-100.00%	-100.00%	-100.00%

Note: Rows in bold indicate scenarios in which timber harvest activity continues to be undertaken. In all other scenarios, the presence of carbon management incentives causes timber harvest activity to cease entirely (i.e. a 100% decline).

Enforcing regeneration regulations on the hypothetical boreal plains landscape causes harvested volumes to decrease further in almost all scenarios, for all cover types, than they do in the absence of regeneration regulations. In particular, for the case of a forest with an initial deficit of mature timber and a 3% discount rate, regeneration constraints cause all harvest activity to cease for all cover types. Furthermore, while the addition of regeneration regulations changes aspen harvest volumes relatively little, the effect is much more pronounced on the other forest cover types on the landscape.[68] Consequently, the proportional decline in aspen harvest volume is no longer always greater than or equal to that for all the other cover types in all scenarios.

Regeneration regulations may alter the proportional harvest volume declines among the different cover types on the landscape for a couple of reasons. First, by preventing the use of extensive silviculture on mixedwood and coniferous-leading forest areas, the regeneration policy makes timber management for these cover types more costly relative to carbon management. In addition, periods of decline in total carbon stock following harvest for stands of mixedwood or coniferous cover types may be extended due a regulation preventing any changes in forest cover composition. By requiring forest managers to return harvested areas to their original cover type, the regeneration policy does not allow the deciduous components of stands to be increased. Accordingly, the opportunity to regenerate forest areas more rapidly, by increasing the proportion of deciduous re-growth, is lost. Temporary carbon debits may thus be

[68] The different effect of regeneration constraints on aspen versus other forest cover types intuitively makes sense, since the policy preventing the use of extensive silvicultural practices is not applied to deciduous-leading stands.

incurred for a longer period of time following harvest of mixedwood or coniferous forest cover types.[69]

The enforcement of regeneration regulations also alters the proportion of hardwood and softwood timber produced from the hypothetical boreal plains landscape. Table 5-7 describes the quantities of hardwood and softwood timber produced, in the baseline and $10/t C scenarios, when regeneration constraints are applied in the modeling framework.[70]

Table 5-7 Flow of Harvested Timber (m^3 per period) over the Planning Horizon in Model Scenarios with Regeneration Regulations Enforced and Carbon Incentives of $0/t C and $10/t C.

Initial Age-Class Structure	Carbon Cost[a] ($/t C)	3% Discount Rate			7% Discount Rate		
		HWD Harvested (m3)	SWD Harvested (m3)	Total Harvest (m3)	HWD Harvested (m3)	SWD Harvested (m3)	Total Harvest (m3)
Deficit Forest[b]	*0*	4,940,076	3,504,318	8,444,394	4,915,309	3,842,450	8,757,759
	10	0	0	0	2,120,809	478,347	2,599,156
Normal Forest[c]	*0*	7,330,091	4,188,061	11,518,153	9,871,301	5,288,678	15,159,979
	10	436,432	241,391	677,823	3,063,592	1,619,066	4,682,658
Mature Forest[c]	*0*	9,024,064	6,534,559	15,558,623	9,712,273	6,915,149	16,627,422
	10	1,083,160	1,626,707	2,709,867	6,731,571	5,936,539	12,668,110

a A carbon price of $0/t C represents results for the baseline model runs.
b Figures presented for the Deficit Forest are the average per period harvest volume.
c Even flow policies constrain harvested volume to be the same in all periods for both the Normal and Mature Forests.

[69] As discussed in Section 2.1, stand replacing disturbance events on the boreal plains landscape lead to periods of decline in total carbon stocks, due to the removal of forest biomass and decay of DOM carbon. Deciduous cover types can lead to a more rapid reversal of this decline, due to their quicker regeneration characteristics. Extensive, or leave-for-natural, regeneration practices are modeled to increase the deciduous component of stands on the hypothetical boreal plains landscape.

[70] As in Table 5-5, the case of $10/t C is the only one depicted in Table 5-7 since the efficient solution for all other carbon prices is not to harvest at all.

At a 3% discount rate, the introduction of forest carbon management incentives to a landscape upon which regeneration regulations are enforced causes substantial reductions in the flow of harvested timber. The proportion of hardwood versus softwood timber in such cases is found to depend on the initial age-class structure. At a 7% discount rate, a higher percentage of the original timber flow is maintained, and the regeneration constraint means that timber flow remains composed of more hardwood than softwood timber at a carbon price of $10/t C.

Model Scenarios which Constrain the Firm's Flexibility to Adjust Harvest Activity Levels for Carbon Management Purposes

Incentives to maintain the flow of harvested timber to the mill may restrict the flexibility of forestry firms to adjust their timber management practices for carbon conservation or sequestration purposes. Model scenarios are evaluated which force hardwood and softwood timber flows to be maintained equal to, or within 25% of, baseline timber harvest levels. However, while flexibility in hardwood and softwood timber flow is constrained, the modeling framework does allow the species (or cover type) composition of the timber yield to be adjusted according to carbon management incentives. Tables 5-8 and 5-9, reflecting a 3% and a 7% discount rate, respectively, describe the percentage change in harvested volume (% Δ m^3) for each forest cover type observed due to the introduction of carbon management incentives, while restricting the forest manager's flexibility to adjust timber harvest volumes.

Table 5-8 Percentage Change in Total Harvested Volume (% Δ m^3) from the Baseline Case to Model Scenarios with Timber and Carbon Management Incentives when Restrictions are Placed on the Flexibility to Adjust the Flow of Harvested Timber. Discount Rate = 3%.

Flexibility to Adjust Timber Flow	Initial Age-Class Structure	Carbon Cost ($/t C)	PO Harvested (% Δ m^3)	MW Harvested (% Δ m^3)	SW Harvested (% Δ m^3)	PI Harvested (% Δ m^3)	MC Harvested (% Δ m^3)
Hardwood & Softwood Timber Flow Forced Equal to Baseline Level	*Deficit Forest*	*10*	-0.66%	-45.48%	-52.25%	-56.50%	-35.11%
		25	8.10%	-61.57%	-64.38%	-50.88%	-40.25%
		55	13.06%	-76.61%	-59.89%	-65.28%	-40.00%
		110	13.65%	-74.33%	-48.52%	-81.27%	-47.78%
	Normal Forest	*10*	0.41%	5.99%	-9.55%	3.29%	0.67%
		25	7.94%	1.34%	-5.62%	-4.69%	-20.13%
		55	11.82%	0.14%	-3.93%	-14.06%	-29.29%
		110	13.20%	0.64%	-1.57%	-24.19%	-31.81%
	Mature Forest	*10*	-3.61%	12.52%	0.76%	0.91%	3.83%
		25	-4.06%	17.14%	1.81%	-8.65%	5.19%
		55	-2.01%	14.36%	-0.49%	-31.86%	10.80%
		110	-2.23%	23.21%	6.61%	-48.19%	5.56%
Hardwood & Softwood Timber Flow Forced Within 25% of Baseline Level	*Deficit Forest*	*10*	-24.05%	-47.55%	-49.24%	-50.25%	-27.91%
		25	-12.85%	-77.54%	-79.31%	-63.72%	-50.87%
		55	-7.22%	-93.80%	-71.13%	-83.33%	-52.87%
		110	-6.32%	-92.39%	-66.99%	-93.56%	-56.70%
	Normal Forest	*10*	-23.48%	-17.26%	-38.89%	-30.49%	-20.66%
		25	-15.44%	-32.77%	-36.14%	-35.13%	-37.11%
		55	-10.66%	-43.99%	-37.09%	-47.06%	-38.72%
		110	-8.60%	-51.16%	-28.23%	-70.47%	-37.61%
	Mature Forest	*10*	-32.04%	-1.28%	-22.48%	-13.60%	-7.58%
		25	-24.62%	-21.22%	-24.46%	-43.72%	-22.09%
		55	-20.82%	-33.71%	-15.89%	-59.38%	-28.49%
		110	-19.44%	-42.62%	-13.64%	-71.68%	-23.89%

Table 5-9 Percentage Change in Total Harvested Volume (% Δ m^3) from the Baseline Case to Model Scenarios with Timber and Carbon Management Incentives when Restrictions are Placed on the Flexibility to Adjust the Flow of Harvested Timber. Discount Rate = 7%.

Flexibility to Adjust Timber Flow	Initial Age-Class Structure	Carbon Cost ($/t C)	PO Harvested (% Δ m^3)	MW Harvested (% Δ m^3)	SW Harvested (% Δ m^3)	PI Harvested (% Δ m^3)	MC Harvested (% Δ m^3)
Hardwood & Softwood Timber Flow Forced Equal to Baseline Level	*Deficit Forest*	***10***	-12.57%	-29.13%	-41.36%	-29.44%	-9.70%
		25	-0.32%	-41.70%	-54.72%	-54.58%	-40.96%
		55	8.68%	-56.06%	-58.97%	-62.43%	-49.64%
		110	10.41%	-58.54%	-53.02%	-68.07%	-56.52%
	Normal Forest	***10***	0.76%	-0.01%	-1.10%	-3.68%	-0.45%
		25	0.69%	-0.69%	-1.26%	-4.49%	0.87%
		55	-0.50%	19.76%	-4.25%	-6.22%	-8.20%
		110	0.34%	25.66%	4.95%	-18.42%	-19.15%
	Mature Forest	***10***	-1.19%	3.01%	1.82%	-1.40%	1.43%
		25	-2.58%	7.60%	1.47%	-1.94%	3.89%
		55	-2.97%	12.50%	-1.40%	-1.43%	3.52%
		110	-3.12%	19.20%	-4.01%	-6.99%	2.87%
Hardwood & Softwood Timber Flow Forced Within 25% of Baseline Level	*Deficit Forest*	***10***	-36.77%	-12.81%	-20.77%	-6.67%	-4.31%
		25	5.05%	-30.13%	-54.94%	-64.04%	-48.85%
		55	15.28%	-46.68%	-59.05%	-71.42%	-57.64%
		110	22.03%	-63.57%	-55.02%	-69.27%	-68.84%
	Normal Forest	***10***	-33.04%	-10.29%	-21.29%	-13.88%	-7.53%
		25	-2.24%	12.64%	-12.45%	-31.28%	-16.44%
		55	1.87%	17.43%	-4.43%	-35.56%	-9.09%
		110	4.71%	23.49%	-0.08%	-36.37%	-7.00%
	Mature Forest	***10***	-31.57%	-8.08%	3.63%	-8.20%	3.17%
		25	-25.23%	-11.58%	-15.31%	-25.48%	-12.76%
		55	-19.04%	-4.09%	-25.91%	-40.55%	-16.82%
		110	-17.66%	0.92%	-16.68%	-44.86%	-19.05%

Restricting the flow of harvested timber produced with carbon incentives to equal that which was produced without consideration for carbon stock introduces considerable variability into how harvested volume is allocated across the different forest cover types. In both the 3% and 7% discount rate cases, carbon management incentives generate proportional changes in harvested volume which alternate between positive and negative values across specific forest cover types, as well as within cover types, depending on the carbon price and initial age-class structure. For example, in a forest with an initial deficit of mature timber, aspen is the only species which experiences a proportional increase in harvest volume at any carbon value, while its harvested volume always decreases when the initial age-class structure has a surplus of mature timber. Alternatively, both mixedwood and mixed coniferous cover types always experience a proportional decrease in harvest volume when the initial age-class is younger, but conversely always increase in harvest volume when the initial age-class is more mature.

When restrictions on the flexibility to adjust harvested volume are slightly relaxed, allowing a +/- 25% change in timber flow following the incorporation of carbon management incentives, the results continue to display considerable variability both within and across forest cover types. Moreover, a difference in the effect of the discount rate is again apparent. With more flexibility to adjust the flow of timber produced, proportional changes in harvested volume decrease in all scenarios with carbon management at a 3% discount rate, but vary between proportional increases and decreases at a 7% discount rate. This effect is similar to that displayed when timber flow was allowed to freely adjust to carbon management incentives (Table 5-4). At a steeper discount rate, the present value of harvested timber can outweigh the subsequent carbon costs, incurred as forgone future carbon credits or, potentially, as future carbon debits.

Regression Analysis

Regression analysis is employed to estimate the relationship between carbon and timber management incentives for each forest cover type. The dependent variable for analysis is the volume of timber harvested from each forest cover type over the planning horizon, taken from each model scenario. Independent variables include the value of temporary carbon credits, carbon value squared, dummy variables indicating specific forest cover types and interactions between these factors. A control variable, included to hold total timber volume harvested constant, allows analysis to focus on how harvest volumes trade-off between cover types independent of changes in aggregate harvested volume. Accordingly, regression results, provided in Figure 5-5, are presented to address the following question: given a fixed volume of timber produced, do carbon management incentives alter how harvest activity is distributed among the forest cover types on the hypothetical landscape?

Faced with increasing incentives for carbon management, the results in Figure 5-5 predict that forest managers will prefer to trade-off an increased volume of timber harvested from mixedwood (MW), white spruce (SW) and particularly pine (PI) stands in favour of reduced timber management activity for aspen (PO).[71] Mixed coniferous stands (MC) also experience a slight decline in harvested volume as carbon prices increase.

[71] At very high estimates of temporary carbon credit value, however, the cost of reducing the volume of timber harvested from aspen stands appears to increase, generating a diminishing trend in the rate of decline of aspen harvest.

Detailed regression results are provided in the appendix (Table A-4). These findings complement those presented in sub-section 5.3.1, which suggest that carbon management incentives will reduce the area of aspen cover that firms manage for timber production, while increasing the areas of mixedwood, white spruce and pine forest that are accessed.

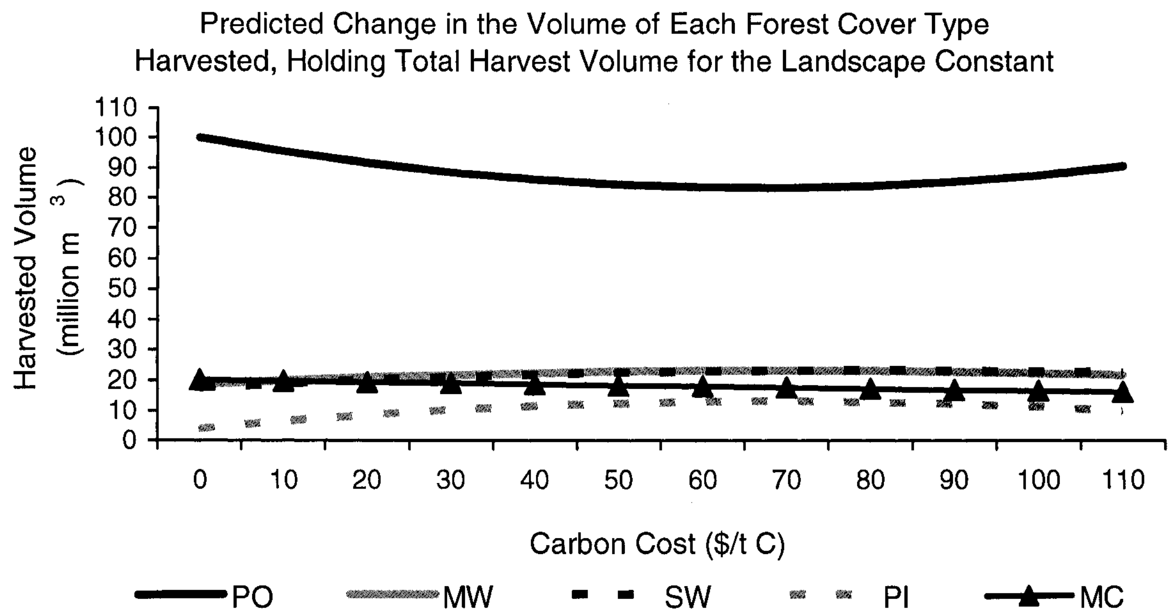


Figure 5-5 Regression results predicting the volume of each forest cover type harvested (m^3) over the planning horizon at different incentive levels for carbon management. Trends show changes in harvested volumes for each forest cover type while holding the total volume of timber harvested from the landscape constant.

5.3.3 Management Incentives across Haul Zones and Productivity Levels

Results in the previous sub-section demonstrate that incentives for carbon management on the hypothetical forest landscape are expected to either reduce timber harvest volumes, or re-allocate the proportion of timber harvested from different cover types, depending on the flexibility of forest managers to adjust their even flow harvest level. To further investigate where on the forest landscape these adjustments in harvested volume are expected to occur, regressions are used to estimate the relationship between carbon management incentives and harvest activity across the haul zones and productivity levels included in the experimental design. A control variable, holding the total volume of timber harvested from the landscape constant, is included in the estimated equation. Coefficients on variables interacting carbon prices with high and low productivity sites, as well as close, mid-distance and far haul zones, estimate the relative incentives for timber versus carbon management in each location independent of incentives to change the aggregate volume of timber harvested.[72]

Regression results, depicted in Figure 5-6, are interpreted to predict where a forest manager would be most likely to implement timber versus carbon management on the hypothetical landscape. The figure provided is for timber harvested from high productivity sites, and contains estimated changes in harvested volume from each of the three haul zones. Interestingly, the only significant difference in harvest activity observed between high and low productivity sites pertains to a generally lower volume of timber harvested from low productivity areas, which is independent of incentives for carbon management. For detailed output from the regression, see Table A-5 in the appendix.

[72] In order to derive a single classification of productivity levels across forest cover types, high and medium productivity levels for aspen and white spruce are aggregated into one "high" productivity classification for analysis in this sub-section.

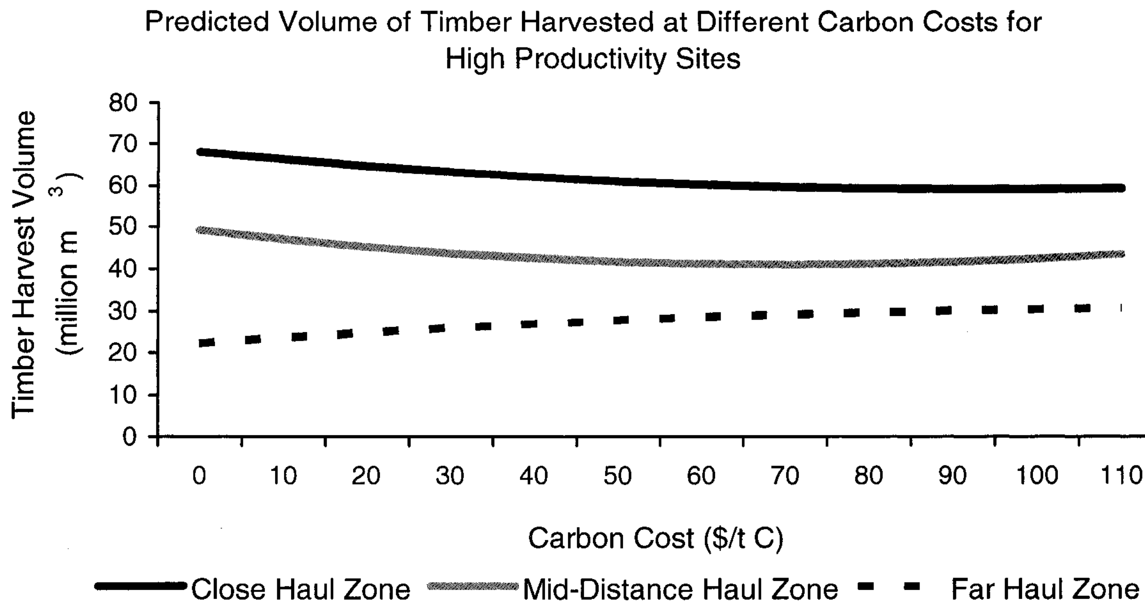


Figure 5-6 Regression results predicting the volume of timber harvested (m^3) from close, mid-distance and far haul zones for high productivity sites at different incentive levels for carbon management. Trends show changes in the distribution of timber management activities over the landscape while holding the total volume of timber harvested through the planning horizon constant.

The estimated relationship between harvested timber volume and carbon management practices, presented in Figure 5-6, predicts significant changes in the incentive to harvest in remote (or far) haul zones at higher carbon values. The furthest haul zone is predicted to experience a relatively low level of harvest activity prior to the introduction of carbon management incentives. However, timber management activity in these more remote areas is found to significantly increase at higher market prices for temporary carbon credits. Meanwhile, carbon incentives are estimated to generate reductions in timber management activity in both the close and mid-distance forest areas, when compared to scenarios with timber management incentives only. This overall trend is estimated to be similar for both high and low productivity sites. The only significant difference observed between productivity levels pertains to a weakly significant difference in the slope of the trend lines.

The results depicted in Figure 5-6 suggest that, while the majority of timber management activity takes place closer to the mill prior to the introduction of value for stored carbon, increasing carbon prices will create incentives for forest managers to spread their harvest activity out over the landscape. These changing incentives may reflect that, for a constant volume of harvested timber, the benefits of carbon management in aspen cover types and younger stands outweigh the costs of shifting harvest to older stands of other cover types that are further from the mill.[73] However, it is important to note that carbon management incentives are generally found to reduce harvest activity in all haul zones and from all site productivity levels. In particular, carbon management causes harvest activity on marginal sites located far from the mill to drop to negligible levels relatively quickly, even at low carbon values. The incentive for forest managers to spread harvest activity out over the landscape is only observed if firms are managing for carbon while also attempting to maintain harvested volume at pre-carbon management levels. In such cases, harvested volume tends toward an equal level across all haul zones, reflecting the carbon management decisions that are applied.

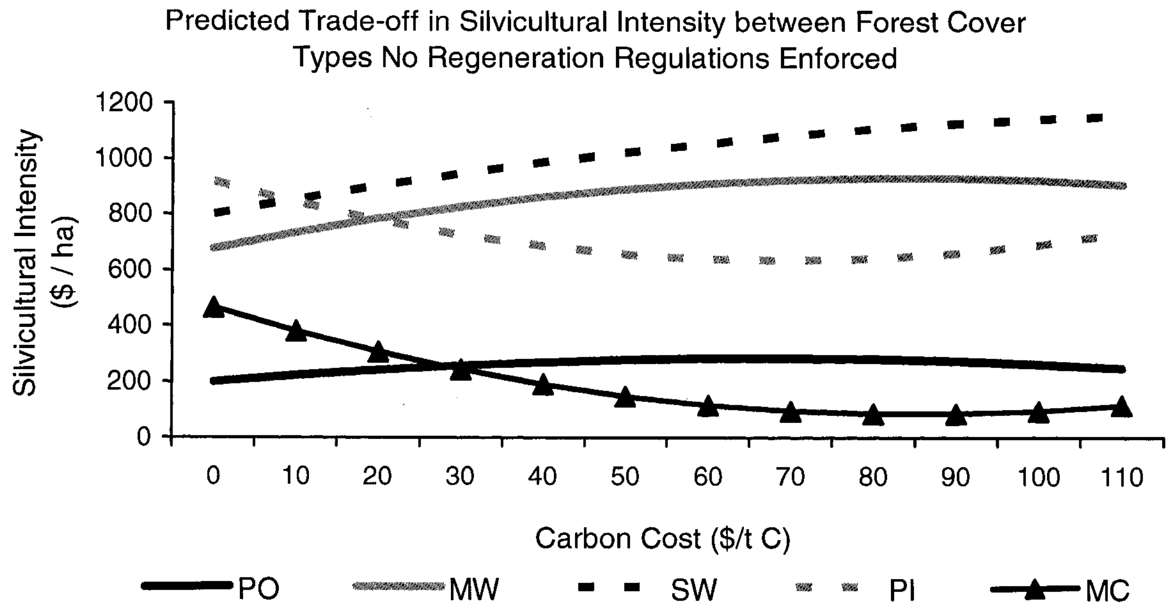
5.3.4 Management Intensity

Figure 5-7 addresses the following question: given a fixed budget for silviculture, how would incentives for carbon management be expected to affect silvicultural intensity

[73] Results in sub-sections 5.3.1 and 5.3.2 suggest that incentives for carbon management will create preferences to increase harvest rotation ages and reduce the volume of timber harvested from aspen in favour of increased mixedwood, white spruce and pine harvest.

across the different forest cover types on the landscape? The results shown are obtained through regressions on a dependent variable indicating the aggregate amount spent by the forestry firm on silviculture for each forest cover type over the planning horizon. Independent variables considered include the market value of temporary carbon credits (both a linear and a squared term) and dummy variables indicating whether regeneration regulations were enforced in the model scenario as well as the particular forest cover type observed. The indicators for forest cover type are interacted with both the linear and squared carbon price terms, as well as with the variable indicating regulations for regeneration practices. Control variables are included to hold total expenditure on silviculture and total hectares harvested from each cover type constant.

The results in Figure 5-7 predict if carbon management incentives will cause forest managers to trade-off intensive management of one species type versus another, independent of changes in total silviculture expenditure or changes in the area of each cover type managed. Model scenarios which allowed forest managers complete flexibility to adjust their timber harvest levels to carbon management incentives are not considered in the regression analysis, as these scenarios frequently cause timber management on the landscape to cease entirely. Since silvicultural practices are dependent on harvest activity in the experimental design, omitting such scenarios allows analysis of silvicultural intensity to focus on instances in which timber management actually occurs on the landscape. Detailed regression results for Figure 5-7 are included in the appendix (Table A-6).



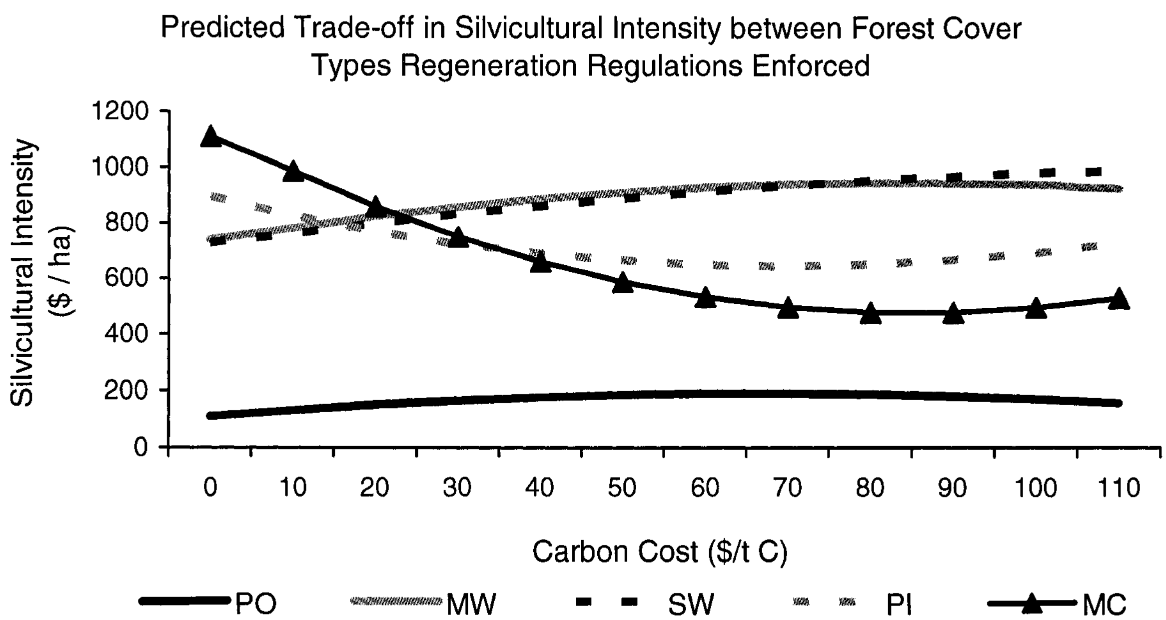


Figure 5-7 Regression results predicting trade-offs in the average silvicultural intensity (silvicultural expenditure per hectare) applied between forest cover types at different incentive levels for carbon management. Trends show changes in the allocation of a fixed budget for silviculture expenditure between forest cover types, while also holding the area of each cover type managed constant. Model scenarios are depicted with and without the enforcement of regeneration regulations while assuming a normal initial age-class distribution and 3% discount rate. Total expenditure on silviculture and total managed area for each cover type are included at their mean values.

Figure 5-7 shows that, given a fixed budget for silviculture expenditure, a forest manager faced with carbon management incentives for the hypothetical landscape is predicted to increase the intensity with which mixedwood (MW) and white spruce (SW) stands are managed, while reducing management intensity for pine (PI) and mixed coniferous (MC) stands. Silvicultural intensity for aspen (PO) stands is estimated to remain relatively constant across different incentive levels for carbon management.[74] Enforcing regeneration standards on the landscape, meanwhile, is predicted to increase the intensity with which pine and mixed coniferous stands are managed, but does not alter how silvicultural expenditure is estimated to trade-off between cover types as a result of carbon management activity.[75]

To gain a more general understanding of how carbon management incentives affect silviculture and timber management practices on the hypothetical boreal plains landscape, regressions predicting the management intensity applied to each forest cover type are re-estimated while allowing total expenditure on silviculture and total area managed to vary. Figure 5-8 presents this re-estimated relationship between carbon management and silvicultural intensity, while detailed regression results are included in Table A-7 of the appendix.

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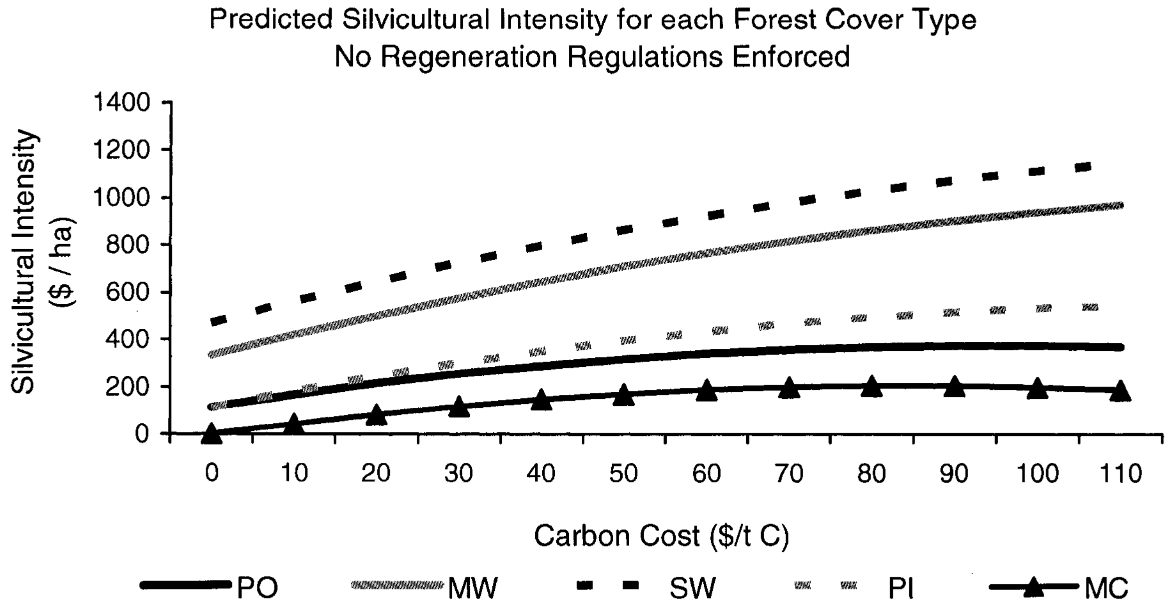
[74] The ability to adjust the management intensity on aspen stands may by restricted by the experimental design. The use of more intensive management practices for aspen, defined as the conversion of stands to plantations of hybrid poplar, is constrained to generate no more than 17% of all hardwood volume shipped to the mill in each period of the planning horizon.

[75] Silvicultural intensity is defined in Figure 5-7 as the average expenditure on silviculture ($/ha) for each forest cover type. Values in $/ha are obtained by dividing the total predicted expenditure on silviculture for each cover type by the mean area harvested for that cover type over the planning horizon.



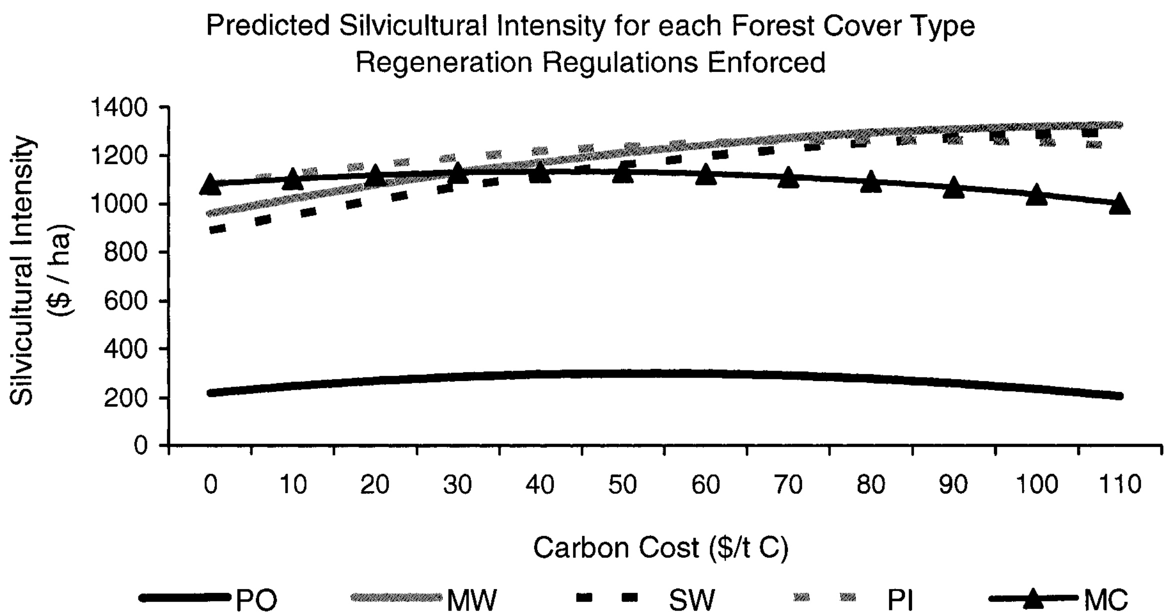


Figure 5-8 Regression results predicting the average silvicultural intensity (silvicultural expenditure per hectare) applied to each forest cover type at different incentive levels for carbon management. Model scenarios are depicted with and without the enforcement of regeneration regulations while assuming a normal initial age-class distribution and 3% discount rate.

The results in Figure 5-8 indicate that, when no regeneration regulations are enforced, the management intensity for all forest cover types is expected to increase with stronger incentives for carbon management. Furthermore, consistent with expectations from Figure 5-7, the intensity of silviculture applied to mixedwood and white spruce is predicted to increase more sharply with carbon price than it is for other forest cover types. However, while the proportion of management expenditure allocated to regenerating species other than mixedwood and white spruce is therefore predicted to decrease, the average management intensity for all cover types is able to grow with higher market values for carbon since total management expenditures are increased and applied over a smaller area of managed forest.[76]

Enforcing regeneration regulations changes the estimated relationship between the intensity of management for each cover type and carbon value. Mixedwood, white spruce and pine species still experience an increase in average silviculture expenditure per hectare, indicating a shift away from basic regeneration practices to more intensive management. Mixed coniferous and aspen cover types, however, are not predicted to be managed more intensively with increased carbon value. For areas of mixed coniferous timber, this may indicate that intensive silviculture was already extensively applied. Mixed coniferous forest areas have the highest predicted average management expenditure before carbon management is introduced.

[76] For analysis of how the area of each forest cover type managed on the landscape varies with incentives for carbon management, refer to Figure 5-4

Independent variables capturing the effect of different initial age-class structures indicate that management intensity increases with the age of initial timber stocks. Accordingly, a boreal plains landscape with an initial deficit of mature timber is estimated to be less intensively managed than a forest with a normal initial age-class distribution, while more mature forests would be the most intensively regenerated. This result is intuitively appealing, given the lack of younger age-classes from which to obtain future harvest volumes on a landscape with an initial surplus of mature timber. Assuming a lower discount rate is also predicted to increase the intensity of management over the forest landscape. The different effect between discount rates indicates that higher current expenditure on regeneration practices is justified when future carbon stocks and harvest rotations are assigned greater value.[77]

5.4 Shadow Price Analysis

Examining shadow prices produced by the linear programming model framework provides an indication of how certain assumptions of the experimental design affect carbon and timber management costs on the hypothetical boreal plains landscape. In particular, the shadow prices associated with three constraints of the model design are presented: the initial area constraints, the imposition of constraints on regeneration practices, and specific constraints limiting the extent of hybrid poplar management. Analysis is focused on how the costs of these constraints change with incentives for carbon management on the landscape.

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[77] In a study of the impact of sustained yield policies on soil productivity levels, Armstrong *et al.* (1997) also found that lower discount rates generate incentives for more intensive forest management.

5.4.1 Initial Area Constraints

Implicit values for different characteristics of the hypothetical boreal plains forest can be derived from the shadow prices associated with the initial age-class and forest cover type distributions. Comparing these values under changing incentives for timber versus carbon management provides an idea of how a market for temporary carbon credits would affect the worth of certain landscape characteristics to a forestry firm. The Woodstock forest modeling package (Remsoft Inc. 1998) produced shadow prices for initial area constraints specific to each forest cover type at each period of age in the initial age-class distribution. These shadow prices are also specific to the particular site productivity level and haul zone characteristics of the initial landscape areas.

Table 5-10 describes the baseline shadow prices derived for each forest cover type across the different initial age-class structures and regeneration regulations assumed for the hypothetical landscape, at a discount rate of 3%. Table 5-11 provides the same information, but at a 7% discount rate. The values presented in these tables can be interpreted as the average additional net present value (cost) from timber management that would be expected if the initial area of that cover type were expanded (reduced) by one hectare. Averages are taken across the site productivity levels and haul zones for each forest cover type, as well as over each period of age captured in the initial age-class distribution. Baseline models do not include incentives for carbon management (i.e. carbon price equals \$0/t C).

Table 5-10 Average Baseline Shadow Prices ($/ha) of the Initial Area Assumptions made for each Forest Cover Type on the Hypothetical Boreal Plains Landscape, at a Discount Rate of 3%.

Regulatory Environment	Initial Age-Class Structure	PO ($/ha)	MW ($/ha)	SW ($/ha)	PI ($/ha)	MC ($/ha)
No Regeneration Regulations	*Deficit Forest*	<u>173.85</u>	231.42	**237.67**	231.65	189.18
	Normal Forest	<u>327.00</u>	**494.90**	457.72	445.94	414.99
	Mature Forest	<u>401.75</u>	**687.81**	610.09	560.93	564.88
Regeneration Regulations Enforced	*Deficit Forest*	**176.25**	98.20	92.58	72.56	<u>55.61</u>
	Normal Forest	**327.78**	294.96	261.92	217.40	<u>175.81</u>
	Mature Forest	417.87	**549.61**	485.97	376.84	<u>348.02</u>

Note: Figures in bold indicate the cover type with the highest shadow price value in that model scenario. <u>Underlined</u> figures indicate the cover type with the lowest shadow price value in that model scenario. Each row represents a distinct model scenario.

Table 5-11 Average Baseline Shadow Prices ($/ha) of the Initial Area Assumptions made for each Forest Cover Type on the Hypothetical Boreal Plains Landscape, at a Discount Rate of 7%.

Regulatory Environment	Initial Age-Class Structure	PO ($/ha)	MW ($/ha)	SW ($/ha)	PI ($/ha)	MC ($/ha)
No Regeneration Regulations	*Deficit Forest*	56.87	81.68	**85.19**	74.85	<u>43.20</u>
	Normal Forest	<u>154.34</u>	**226.25**	209.19	199.95	182.04
	Mature Forest	<u>189.62</u>	**307.23**	282.05	256.16	247.01
Regeneration Regulations Enforced	*Deficit Forest*	**56.89**	13.70	15.99	10.55	<u>6.53</u>
	Normal Forest	**158.00**	132.58	120.19	98.00	<u>76.86</u>
	Mature Forest	195.74	**250.23**	229.32	181.47	<u>166.66</u>

Note: Figures in bold indicate the cover type with the highest shadow price value in that model scenario. <u>Underlined</u> figures indicate the cover type with the lowest shadow price value in that model scenario. Each row represents a distinct model scenario.

The results in Tables 5-10 and 5-11 indicate that, when the hypothetical landscape is managed for timber harvest only, the forest cover types with the highest and lowest marginal area values depend on the initial age-class structure and regulatory scenario. When no regeneration regulations are enforced, a marginal hectare of mixedwood (MW) generates the highest implicit price for normal or mature initial age-class distributions, while a hectare of white spruce (SW) has the highest marginal value for younger initial age-class distributions. When regeneration regulations are enforced, the highest shadow price for a marginal hectare of initial area switches to aspen (PO) for both the younger and normal initial age-class structures, but remains with mixedwood for more mature forests. The lowest shadow prices, meanwhile, are attributed to a marginal area of mixed coniferous (MC) forest when regeneration regulations are enforced and to a marginal area of aspen when they are not enforced. The only scenario in which this pattern does not hold is for a younger initial age-class distribution, no regeneration regulations and a 7% discount rate, which switches the lowest marginal value from aspen to mixed coniferous cover type.

Tables 5-12 and 5-13 provide the average shadow price results for model scenarios with incentives for both timber and carbon management. Table 5-12 includes results assuming a 3% discount rate, while those in Table 5-13 assume a discount rate of 7%. The values can again be interpreted as the average additional net present value (cost) from forest management that would be expected if the initial area of that cover type were expanded (reduced) by one hectare. Averages are taken across the site productivity levels and haul zones for each forest cover type, as well as over each period of age captured in the initial age-class distribution. Shadow price results are presented for the model scenario with a flexible harvest volume policy only.[78]

[78] Model scenarios which force harvested volumes to remain equal to, or within +/- 25%, of the baseline harvested volumes do not substantially change the shadow price results presented in Tables 5-12 and 5-13.

Table 5-12 Average Shadow Prices ($/ha) of the Initial Area Assumptions made for each Forest Cover Type on the Hypothetical Boreal Plains Landscape, at a Discount Rate of 3%.

Regulatory Environment	Initial Age-Class Structure	Carbon Cost ($/t C)	PO ($/ha)	MW ($/ha)	SW ($/ha)	PI ($/ha)	MC ($/ha)
No Regeneration Regulations	*Deficit Forest*	*10*	8,084	**11,303**	8,074	7,063	<u>5,119</u>
		25	20,209	**28,255**	20,180	17,619	<u>12,755</u>
		55	44,459	**62,162**	44,395	38,762	<u>28,062</u>
		110	88,918	**124,324**	88,790	77,524	<u>56,124</u>
	Normal Forest	*10*	8,600	**11,976**	8,471	7,521	<u>5,781</u>
		25	21,489	**29,924**	21,125	18,645	<u>14,289</u>
		55	47,275	**65,833**	46,475	41,020	<u>31,435</u>
		110	94,550	**131,666**	92,949	82,039	<u>62,869</u>
	Mature Forest	*10*	9,167	**13,290**	9,159	8,193	<u>6,860</u>
		25	22,880	**33,011**	22,616	20,104	<u>16,636</u>
		55	50,336	**72,625**	49,754	44,230	<u>36,586</u>
		110	100,672	**145,250**	99,508	88,459	<u>73,173</u>
Regeneration Regulations Enforced	*Deficit Forest*	*10*	8,083	**11,302**	8,072	7,048	<u>5,102</u>
		25	20,209	**28,255**	20,180	17,619	<u>12,755</u>
		55	44,459	**62,162**	44,395	38,762	<u>28,062</u>
		110	88,918	**124,324**	88,790	77,524	<u>56,124</u>
	Normal Forest	*10*	8,599	**11,970**	8,453	7,459	<u>5,715</u>
		25	21,489	**29,924**	21,125	18,645	<u>14,289</u>
		55	47,275	**65,833**	46,475	41,020	<u>31,435</u>
		110	94,550	**131,666**	92,949	82,039	<u>62,869</u>
	Mature Forest	*10*	9,165	**13,224**	9,107	8,050	<u>6,652</u>
		25	22,880	**33,011**	22,616	20,104	<u>16,630</u>
		55	50,336	**72,625**	49,754	44,230	<u>36,586</u>
		110	100,672	**145,250**	99,508	88,459	<u>73,173</u>

Note: Figures in bold indicate the cover type with the highest shadow price value in that model scenario. <u>Underlined</u> figures indicate the cover type with the lowest shadow price value in that model scenario. Each row represents a distinct model scenario.

Table 5-13 Average Shadow Prices ($/ha) of the Initial Area Assumptions made for each Forest Cover Type on the Hypothetical Boreal Plains Landscape, at a Discount Rate of 7%.

Regulatory Environment	Initial Age-Class Structure	Carbon Cost ($/t C)	PO ($/ha)	MW ($/ha)	SW ($/ha)	PI ($/ha)	MC ($/ha)
No Regeneration Regulations	*Deficit Forest*	*10*	2,727	**3,848**	2,770	2,399	<u>1,668</u>
		25	6,816	**9,617**	6,910	5,967	<u>4,149</u>
		55	14,995	**21,158**	15,202	13,128	<u>9,127</u>
		110	29,990	**42,315**	30,404	26,255	<u>18,254</u>
	Normal Forest	*10*	2,975	**4,113**	2,973	2,642	<u>1,959</u>
		25	7,388	**10,199**	7,286	6,404	<u>4,746</u>
		55	16,255	**22,438**	16,028	14,089	<u>10,441</u>
		110	32,509	**44,876**	32,056	28,179	<u>20,881</u>
	Mature Forest	*10*	3,250	**4,734**	3,320	2,970	<u>2,446</u>
		25	8,028	**11,526**	7,965	7,074	<u>5,785</u>
		55	17,662	**25,357**	17,522	15,558	<u>12,712</u>
		110	35,325	**50,714**	35,044	31,117	<u>25,425</u>
Regeneration Regulations Enforced	*Deficit Forest*	*10*	2,727	**3,847**	2,764	2,387	<u>1,659</u>
		25	6,816	**9,617**	6,910	5,967	<u>4,149</u>
		55	14,995	**21,158**	15,202	13,128	<u>9,127</u>
		110	29,990	**42,315**	30,404	26,255	<u>18,254</u>
	Normal Forest	*10*	2,975	**4,084**	2,937	2,570	<u>1,901</u>
		25	7,388	**10,199**	7,286	6,404	<u>4,746</u>
		55	16,255	**22,438**	16,028	14,089	<u>10,441</u>
		110	32,509	**44,876**	32,056	28,179	<u>20,881</u>
	Mature Forest	*10*	3,249	**4,670**	3,280	2,872	<u>2,343</u>
		25	8,028	**11,526**	7,965	7,072	<u>5,778</u>
		55	17,662	**25,357**	17,522	15,558	<u>12,712</u>
		110	35,325	**50,714**	35,044	31,117	<u>25,425</u>

Note: Figures in bold indicate the cover type with the highest shadow price value in that model scenario. <u>Underlined</u> figures indicate the cover type with the lowest shadow price value in that model scenario. Each row represents a distinct model scenario.

The shadow price results in Tables 5-12 and 5-13 can be compared to the average baseline shadow price results to evaluate the impact of carbon price on the marginal land value for each forest cover type. Interestingly, carbon incentives cause the highest marginal value for initial area to shift to mixedwood forest in all model scenarios (i.e. across all regulatory regimes, initial age-class structures and carbon prices modeled in the experimental design). Similarly, the lowest shadow prices are attributed to a marginal area of mixed coniferous forest in all model scenarios when carbon management incentives are incorporated. These observations contrast those from baseline model scenarios, in which the highest and lowest shadow prices varied between cover types depending on the initial age-class structure and regulatory scenario.

Accordingly, when incentives for both carbon and timber management are modeled, an additional hectare of mixedwood forest on the hypothetical landscape would generate the largest increase in NPV; regardless of regulatory regime, initial age-class structure, carbon price or discount rate. Conversely, the loss of a hectare of mixed coniferous cover from the initial forest area, compared against all other forest cover types, would generate the smallest loss in NPV, ceteris paribus. Interestingly, initial area shadow prices also tend to be higher for more mature age-classes of forest, as well as in model scenarios which are not subjected to regeneration constraints.

More specifically, in all model scenarios with incentives for both timber and carbon management, detailed shadow price results show that the highest marginal value for initial forest area is always attributed to mixedwood cover located on a high productivity site relatively close to the mill. In scenarios where harvest rotations for high productivity mixedwood stands are lengthened infinitely, haul zone becomes insignificant. To gain a better understanding of how implicit land values differ between forest cover types, Figure 5-9 depicts the initial area shadow prices for each species type at different incentive levels for carbon management. Results shown are for high productivity sites located relatively close to the mill, at a 3% discount rate and with no regeneration regulations enforced, as these characteristics tend to produce the highest marginal land values.

It should be noted that the temporary carbon credit values used in this study produce extraordinarily high marginal forest land values, which also explains why the model tends so quickly towards a no harvest decision.[79] This result likely implies that either the temporary carbon credit values adopted are not sufficiently discounted versus the range of permanent credit prices observed in the literature, or that the assumed range of permanent credit prices is itself too high. Mendelsohn (2005) predicts that the social cost of carbon may in fact be an order of magnitude smaller than the range applied in this study, falling somewhere between US $1/t C and US $7/t C over the next decade.[80] These carbon values would rise over time, however, due to increased concentrations of greenhouse gases in the atmosphere.

[79] Analysis of results for harvested timber volumes is presented in sub-section 5.3.2.

[80] Mendelsohn (2005) argues that many of the higher carbon values presented in the literature rely on unrealistic discount rates (below 2 percent), or, alternatively, on out-of-date climate change impact studies.

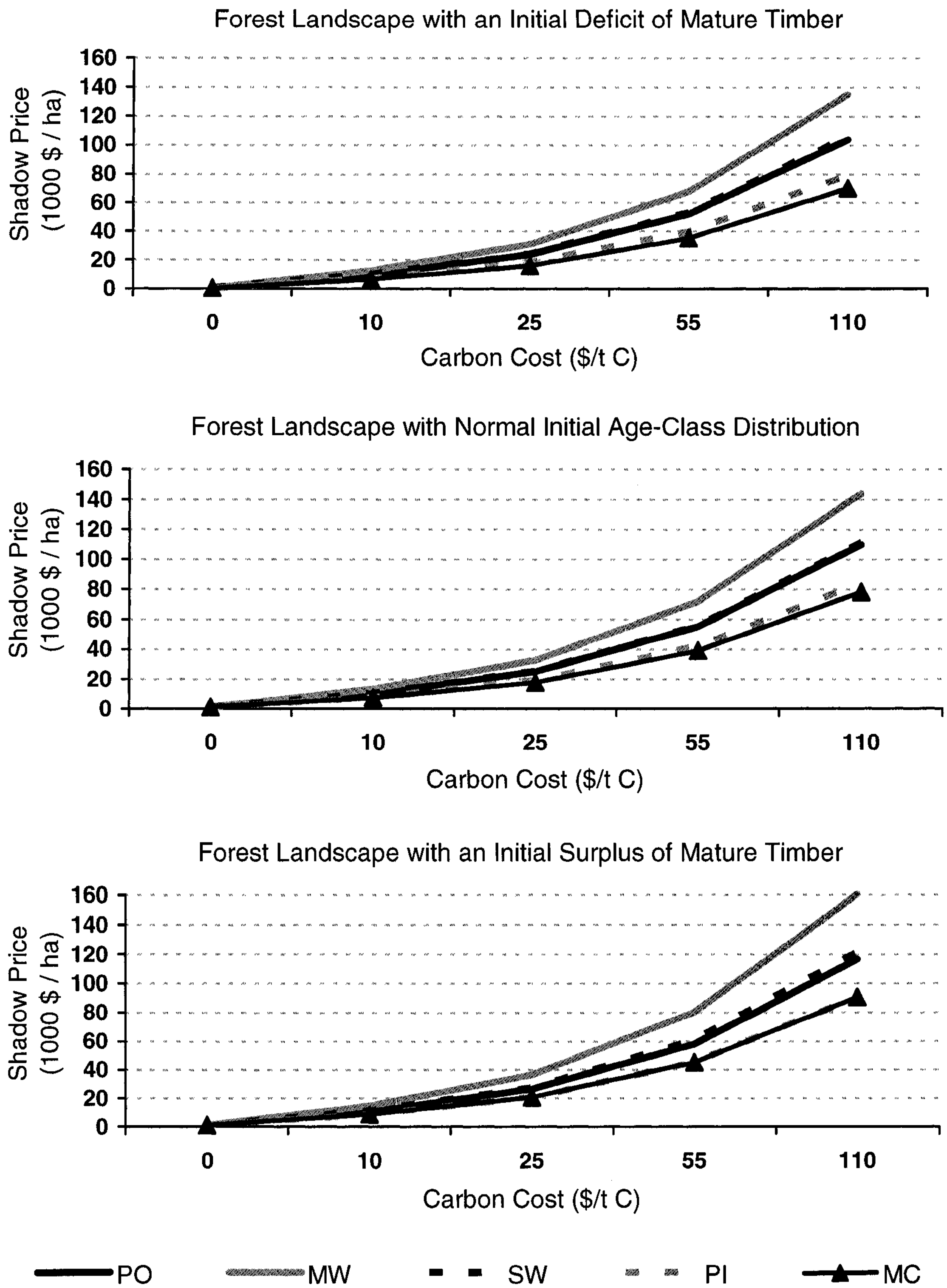

Figure 5-9 Initial area shadow prices ($/ha) at different incentive levels for carbon management, by initial age-class distribution. Results included are for each forest cover type, located on a high productivity site close to the mill, assuming a 3% discount rate and no regeneration regulations.

5.4.2 Constraints on Regeneration Practices

Regression results, presented in sub-section 5.3.4, show that incentives for carbon management can affect the silvicultural intensity applied to different forest cover types on the hypothetical boreal plains landscape.[81] By providing incentives to change management intensities, market values for stored carbon could alter the costs associated with regeneration constraints. Shadow prices derived for the constraints on regeneration practices capture how the costs of managing the forest landscape may change with incentives for carbon management.

Regeneration regulations pertain to silvicultural intensities since they constrain the use of extensive silviculture on harvested stands of all forest cover types (except aspen). Table 5-14 provides the baseline shadow price results derived from enforcing regeneration regulations on the hypothetical boreal plains landscape. Baseline scenarios include incentives for timber management only (i.e. carbon price equals \$0/t C). Shadow price results are shown for each forest cover type subjected to the regeneration regulations and cover all initial age-class structures and assumed discount rates. The values in Table 5-14 can be interpreted as the cost of forcing a marginal hectare of forest area to adhere to the regeneration constraints, and are averaged across shadow prices derived for each cover type in all periods of the planning horizon.[82]

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[81] These results, concerning changes in silvicultural intensities, are depicted in Figures 5-7 and 5-8.

[82] Conversely, the results in Table 5-14 can also be interpreted as the increase in NPV associated with removing the regeneration constraint from a marginal hectare of forest area.

Table 5-14 Average Baseline Shadow Prices ($/ha) Associated with the Regeneration Regulations Enforced on the Hypothetical Boreal Plains Landscape.

Discount Rate	Initial Age-Class Structure	MW ($/ha)	SW ($/ha)	PI ($/ha)	MC ($/ha)
3%	***Deficit Forest***	119.96	119.69	131.39	111.11
	Normal Forest	149.57	143.89	156.35	154.92
	Mature Forest	107.25	101.02	131.85	150.12
7%	***Deficit Forest***	41.64	42.49	41.00	24.77
	Normal Forest	50.70	50.48	51.10	50.58
	Mature Forest	40.46	38.50	45.12	50.27

Note: Regeneration constraints are not imposed on the aspen (PO) cover type.

Table 5-15 shows how the baseline shadow prices associated with regeneration constraints change once incentives for forest carbon management are incorporated into model scenarios. The changes in shadow price results are provided for model scenarios with a flexible harvest volume policy only, at both a 3% and a 7% discount rate. The values provided can be interpreted as the average change in cost, versus the baseline scenario, of forcing a marginal hectare of forest area to adhere to the regeneration constraints. Again, the results provided are averaged over shadow price figures provided for each forest cover type in all periods of the planning horizon.

The results displayed in Table 5-15 indicate that the effect of carbon management on the marginal cost of regeneration regulations will vary across forest cover types and depend on the initial age-class distribution of the hypothetical landscape. In almost all model scenarios, the shadow price associated with enforcing regeneration regulations declines for mixedwood (MW) and white spruce (SW) cover types once incentives for carbon management are incorporated. Conversely, the marginal cost of regeneration

Table 5-15 Change in Regeneration Constraint Average Shadow Prices (Δ $/ha), versus the Baseline Case, at Different Incentive Levels for Carbon Management.

Discount Rate	Initial Age-Class Structure	Carbon Cost ($/t C)	MW (Δ $/ha)	SW (Δ $/ha)	PI (Δ $/ha)	MC (Δ $/ha)
3%	*Deficit Forest*	***10***	(56.17)	(61.07)	(15.32)	85.54
		25	(76.66)	(107.65)	(23.30)	227.65
		55	(116.08)	(118.15)	(39.72)	501.60
		110	(33.13)	(116.93)	(106.70)	961.75
	Normal Forest	***10***	(125.92)	(71.22)	(22.82)	7.79
		25	(64.84)	(142.19)	(11.60)	423.66
		55	(128.88)	(127.45)	(7.37)	941.64
		110	(95.50)	(100.38)	57.33	1945.94
	Mature Forest	***10***	(3.03)	(23.83)	26.59	138.23
		25	(94.59)	(99.91)	12.42	427.71
		55	(60.17)	(75.77)	11.04	940.53
		110	(2.07)	(39.64)	(16.89)	1860.70
7%	*Deficit Forest*	***10***	(39.57)	(24.74)	(16.46)	(8.05)
		25	(28.93)	(32.17)	(15.38)	9.89
		55	(29.58)	(34.96)	(18.40)	24.76
		110	(16.99)	(31.99)	12.79	43.76
	Normal Forest	***10***	(15.70)	(14.76)	7.54	14.93
		25	(23.21)	(30.33)	6.76	41.49
		55	(48.98)	(49.15)	5.70	97.04
		110	41.81	(48.13)	3.19	189.03
	Mature Forest	***10***	4.07	(2.40)	13.08	15.59
		25	(9.64)	(17.13)	12.54	41.87
		55	(32.95)	(35.07)	11.30	96.58
		110	(26.78)	(31.91)	12.99	192.79

Note: Figures in parentheses indicate negative changes, or declines, in the shadow price associated with enforcing regeneration constraints on the hypothetical landscape.

constraints increases with carbon market values in almost all scenarios, versus the baseline case, for areas of mixed coniferous (MC) forest. The effect for areas of pine (PI) cover, meanwhile, appears to depend more closely on the initial age-class distribution and specific carbon price.

In the case of mixedwood and white spruce cover types, it can be inferred that resource scarcities for carbon management are similar to those which meet regeneration regulations. The costs of adhering to silviculture requirements on the hypothetical landscape are thus reduced by incentives to manage forest carbon stocks. Mixed coniferous cover, however, becomes more costly to regenerate according to regulations when also managed for carbon purposes. The resource scarcities in this case move in opposite directions. These changes in the average shadow prices associated with regeneration constraints correspond well to the changes in management intensity observed on the hypothetical landscape at different carbon values (see sub-section 5.3.4).

The general trends observed in Table 5-15 do not change substantially if harvest volume policies are constrained to be within 25% of the volume harvested in baseline scenarios. The most significant difference observed when harvest volumes are forced equal to baseline levels is that the change in average shadow price for mixedwood cover becomes positive at lower carbon prices for a mature forest and a 7% discount rate. This change for initially mature areas of mixedwood forest extends to all carbon prices when the assumed discount rate is reduced to 3%, and likely reflects increased harvest activity for mixedwood species, versus the baseline case, in these model scenarios.

5.4.3 Constraints on the Extent of Hybrid Poplar Management

Hybrid poplar plantations are constrained in the experimental design to provide no more than 17% of the total harvested volume shipped to the mill in any period of the planning horizon. This constraint is based on Alberta-Pacific Forest Industries Inc.'s stated objectives for hybrid poplar management, and is also meant to implicitly recognize that there may be regulatory and/or social issues pertaining to the establishment of hybrid plantations in Canadian forests.[83] The extent of hybrid poplar management possible on the hypothetical landscape is therefore limited by the scope of hardwood harvest and timber management in general.

Shadow price results for constraints limiting the extent of hybrid poplar management on the hypothetical landscape are presented in Figure 5-10. Results are shown for each initial age-class distribution and are specific to policies regarding the flexibility of forest managers to adjust the volume of timber harvested from the landscape. The specific scenarios modeled assume a 3% discount rate and no regulations on regeneration practices.[84] The values in Figure 5-10 may be interpreted as the marginal value of relaxing the constraint on hybrid poplar management by one cubic metre, and are averaged across shadow price results derived for every period over the planning horizon.

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[83] Alberta-Pacific is one of the few boreal forestry firms currently establishing hybrid poplar plantations on an operational basis. See Alberta-Pacific (2004) for details pertaining to their management objectives. Both Reedy (2003) and Anderson and Luckert (*in press*) provide discussions pertaining to the social and regulatory issues surrounding hybrid poplar plantations in Canada.

[84] Regeneration regulations are not directly applied to aspen cover types, and the effect of applying regeneration regulations to the landscape is not found to significantly affect the results presented in Figure 5-10. Assuming a higher discount rate (i.e. 7%) reduces the shadow price of constraining hybrid poplar management activities to a negligible level.

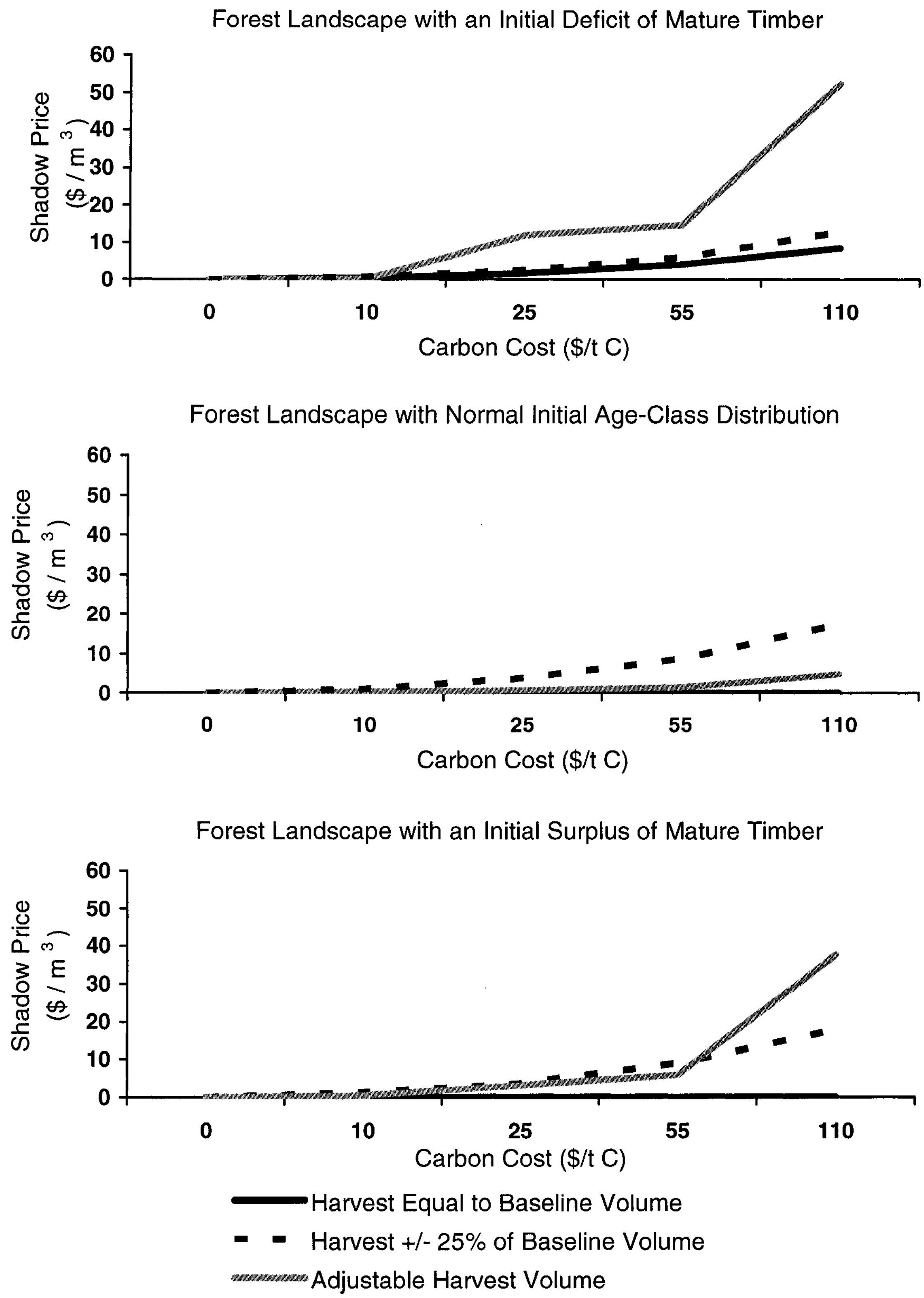

Figure 5-10 Shadow prices ($\$/m^3$) derived from constraints on the extent of hybrid poplar management permitted on the landscape, at different incentive levels for carbon management. Results are included for each harvest volume policy by initial age-class distribution, while assuming a 3% discount rate and no regulations on regeneration practices.

Constraints limiting the extent of hybrid poplar management on the hypothetical landscape are non-binding in model scenarios with normal or mature initial age-class structures which force harvested volume with carbon management to equal that predicted for the baseline case. Furthermore, shadow price values in all scenarios are found to be of largely negligible value at lower levels of carbon value. However, at relatively high prices for temporary carbon credits, relaxing the constraints on hybrid poplar management generates a reasonable return in certain circumstances. Marginal values for increasing the extent of hybrid poplar management are particularly significant in scenarios with relatively young or more mature initial age-class structures which also permit forest managers to adjust their harvested volume for carbon management purposes.

Interestingly, the results in Figure 5-10 show that incentives to increase the extent of hybrid poplar management on the landscape are strongest in model scenarios which generate infinitely long harvest rotations for all other forest cover types. Accordingly, optimal land-use decisions for both timber and carbon management may involve more specialized land-use practices, when constraints on management activities do not prevent such a strategy.[85] Nevertheless, given the need to discount the value of temporary versus permanent carbon credits, results suggest that carbon prices well into the upper range of the assumed values would be needed to create strong incentives for more intensive, specialized land use.

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[85] Vincent and Binkley (1993) have also argued that economically efficient multiple use of forests may require land-use specialization.

5.5 Summary

The results presented in this chapter were intended to address several key questions concerning the effect of carbon management incentives on forest management decisions in the boreal plains ecozone of Canada. Management responses were investigated over different market assumptions, regulatory regimes and were conditioned on the forest landscape itself. The key questions are re-addressed below, with the main findings summarized for each.

1) What return will be realized from carbon management versus timber management alone?

Model scenarios incorporating returns to temporary carbon credits demonstrate the potential for significant increases in NPV when compared to timber management practices alone. The benefits of carbon management are found to be greater for landscapes with younger initial age-class distributions and in scenarios which assume a lower discount rate. However, specific combinations of harvest and carbon baseline policies, when applied to landscapes containing more mature age-classes of timber, do have the potential to generate negative returns to carbon management. Negative returns to carbon management are also found to increase with lower discount rates.

Returns from carbon management can comprise a significant proportion of the NPV derived from managing the forest landscape. When changes in harvested volume are not constrained by policy, results show that, at values greater than or equal to $25/t C for temporary carbon credits, timber management activity on the landscape will cease almost entirely. More generally, the proportion of total returns generated through carbon management increases with younger initial age-class distributions and lower discount rates.

2) How will forest policy affect the decision to manage the landscape for carbon?

As expected, returns to carbon management are generally lower when forest policies force firms to maintain harvest levels at, or near, the levels predicted for timber management only scenarios. However, results also suggest that the adoption of policies allowing fluctuations around even flow harvest levels, but constraining reductions in harvested volume, could be preferable to permitting absolute reductions in harvested volume but enforcing a strict even flow policy. Returns to carbon management were found to be greater for such policies in scenarios with mature initial age-class distributions and lower carbon values.

Regeneration regulations appear to increase incentives for forestry firms to manage for carbon when the value of carbon on the landscape is positive, but to decrease carbon management incentives when carbon values would impose a cost. Carbon market values can also affect the costs of adhering to regeneration constraints, thereby providing additional incentives or disincentives to manage the landscape for carbon. Forest areas with mixedwood and white spruce cover will generally have the costs of regeneration constraints decrease with carbon management, while areas of mixed coniferous forest will have regeneration costs increase.

Policies concerning forest carbon accounting rules may also affect the decision to manage for carbon. Forestry firms benefit from carbon management in all model scenarios which calculate temporary carbon credit values using a business-as-usual baseline. If the use of a constant carbon baseline is enforced instead, it is possible to generate negative returns to carbon management, particularly if the firm is managing a mature forest landscape and is also confronted with policies requiring the flow of timber to the mill to be maintained.

3) Which types of forest are most likely to be managed for carbon?

Results show that, all else being equal, forest managers would be most likely to manage areas of aspen cover for carbon. Analysis of potential trade-offs in management practices indicated that harvested volume and accessed area of aspen would be reduced while increasing harvest and forest access in mixedwood, pine and white spruce stands. Interestingly, however, shadow price results for the initial area of each cover type on the forest landscape suggest that a marginal hectare of mixedwood will have the highest land value with carbon management incentives. Marginal areas of mixed coniferous forest, meanwhile, are the least valuable when managing for carbon.

More generally, timber harvest activity and the area of forest accessed are found to decrease for all cover types with carbon management incentives. Harvest activity is reduced the most on landscapes with younger initial age-class distributions and when assuming a lower discount rate. This general result is illustrated in Figure 5-11, which compares the ending age-class distributions for a representative model scenario with

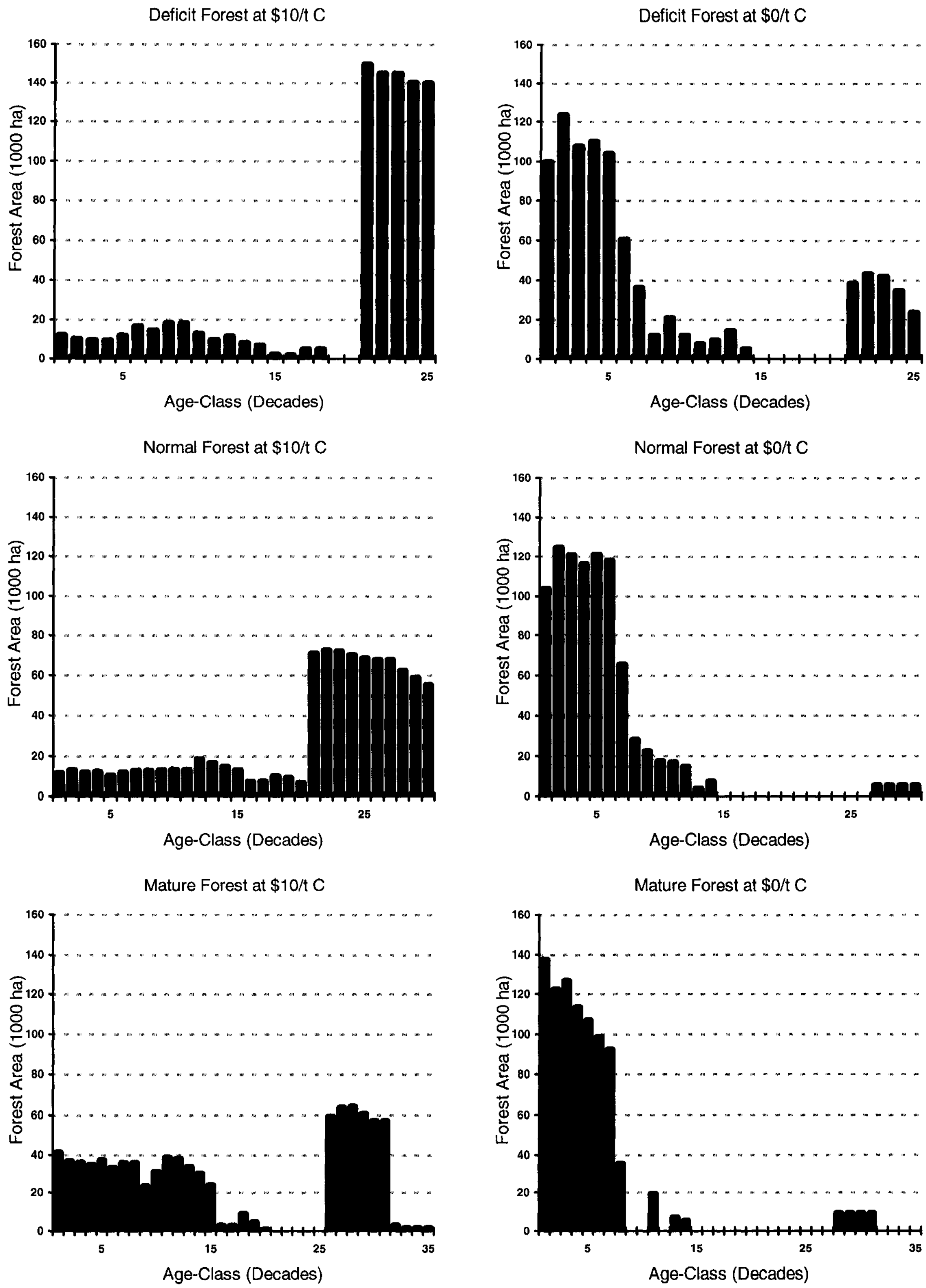

Figure 5-11 Ending age-class distributions for the $10/t C and $0/t C (baseline) model scenarios on the hypothetical boreal plains landscape, by initial age-class structure. Results shown are for a 3% discount rate, no regeneration regulations and a flexible harvest volume policy.

carbon incentives of \$10/t C versus \$0/t C (timber management only). Carbon management incentives in Figure 5-11 increase the proportion of forest area in older ending age-classes, reflecting the decisions to reduce both total harvest activity and the area of forest accessed for timber harvest over the planning horizon.

4) What intensity of silviculture is most likely to be applied?

All else being equal, results suggest that carbon management will shift expenditure on silviculture away from mixed coniferous and pine stands, in order to increase management intensity in areas of mixedwood and white spruce forest. Generally, though, in the absence of regeneration regulations, management intensity is predicted to increase for all forest cover types with positive carbon market values. Silviculture practices also tend to be more intensive on landscapes with older initial age-class distributions and when assuming lower discount rates. Model scenarios which enforce regeneration regulations still increase the intensity of silviculture applied to mixedwood, white spruce and pine stands, but maintain a more constant management intensity in areas of mixed coniferous and aspen forest. Shadow price results for hybrid poplar management suggest that more intensive, specialized land-use practices may be optimal at relatively high levels of carbon value, assuming lower discount rates.

5) Where on the forest landscape is carbon management most likely to occur?

Carbon management incentives are found to substantially reduce harvest activity in all haul zones and from all site productivity levels. In particular, the harvested volume obtained from marginal sites located furthest from the mill drops to a negligible level at all carbon prices modeled. However, if forced to maintain harvest activity on the landscape, results suggest that forest managers would prefer to reduce the volume of timber harvested in close and mid-distance haul zones, relative to what would be harvested when managing for timber values alone. Accordingly, harvest activity in more remote areas of the forest landscape would be increased. These results indicate that, ceteris paribus, the benefits of conserving younger stands and areas of aspen cover appear to outweigh the costs of harvesting further away from the mill. Surprisingly, no significant difference in carbon management is identified between sites on the landscape with different productivity characteristics.

Chapter 6: Discussion & Conclusion

6.1 Policy Discussion

The results presented in chapter 5 suggest that positive returns to forest carbon management are possible for most combinations of initial age-class structure, regulatory regime and market costs in the boreal plains ecozone of Canada. In many instances, especially when considering forest areas with relatively young initial age-class structures, significant increases in returns are observed from carbon management, versus timber management alone. However, certain model scenarios did produce negative returns to carbon management. In particular, should policies adopt carbon accounting procedures based on a constant carbon baseline, attempting to maintain harvest activity at a level similar to that undertaken when considering timber management alone generated negative returns to carbon management in several instances. Negative returns were observed in all such cases when considering a landscape with an initial surplus of mature timber.

Regulations requiring the use of intensive silviculture practices following harvest, so that forest areas return quickly to their original species composition, are found to exhibit a positive relationship with the benefits of managing for carbon. Accordingly, if the returns to forest carbon management on a particular landscape are predicted to be positive, then the benefits of managing for carbon are greater in scenarios where regeneration regulations are enforced.[86] However, if carbon management on the landscape is expected to generate negative returns, regeneration regulations will increase

[86] The benefits of carbon management, as defined here, refer to the percentage change in NPV of managing for returns to both timber and carbon management, versus timber management alone. Gross returns to carbon management may therefore be less when regeneration regulations are enforced, but the percentage change in NPV is generally larger.

the costs incurred should participation in the market for carbon be mandatory. In addition, the cost of adhering to regeneration regulations is shown to be affected by incentives for carbon management, with the effect differing depending on the forest cover type being managed. The distributional effects of combining regeneration policies with mandatory carbon accounting and market participation could therefore be significant, and need to be considered.

Yet, the very nature of regulating regeneration practices on the boreal plains may be questioned. The natural model of succession on the boreal plains usually describes a relatively pure aspen stand establishing on a site after disturbance, with spruce developing in the understory relatively quickly, or over several decades, depending on spruce seed sources and seedbeds. In most circumstances, longer-lived white spruce eventually becomes the dominant species, with mixtures of spruce and fir evolving if the site remains undisturbed over long periods (Lieffers *et al.* 1996; Cumming and Armstrong 2001). However, reforestation standards for the coniferous land base have largely been biased towards 'unmixing' the mixedwoods, mandating the rapid re-establishment of pure coniferous stands, often at great silvicultural effort and expense (Lieffers and Beck 1994; Cumming and Armstrong 2001). Such policies are not only contrary to more ecologically-based forest management practices, but may also be at odds with incentives for forest carbon management.

Results in this study indicate that, when incentives for both forest carbon and timber management are considered, a marginal area of mixedwood forest becomes more valuable than that of any other species.[87] Moreover, carbon management is generally found to reduce the cost of re-establishing both mixedwood and white spruce forest cover types, which are modeled on succession-based growth and yield characteristics developed by DMI.[88] A marginal area of mixed coniferous forest, meanwhile, has the lowest value of all cover types when managed for carbon, and become more expensive to regenerate intensively at higher carbon prices. Mixed coniferous stands are not modeled on succession dynamics, and intensive silviculture is assumed to return a harvested area to its original coniferous cover immediately. Intensive reforestation standards for the coniferous land base may therefore run contrary to incentives for forest carbon management. Furthermore, by encouraging succession-based forest management, carbon incentives could help to sustain ecosystem components on the landscape (Lieffers *et al.* 1996; Cumming and Armstrong 2001). Such characteristics could be important. As a party to the Kyoto Protocol, Canada is prevented from implementing forest carbon management activities which do not contribute to the conservation of biodiversity or the sustainable use of natural resources (UNFCCC 2002).

Should government policy or forestry firm practice not require the maintenance of timber harvest activity at some level, results show that carbon management considerations can dominate on the boreal plains landscape. Even at the minimum price for carbon observed from active trading on the European market (CAD $47.15/t C; US

[87] The implicit value of an area of forest is defined here according to the shadow price associated with its initial area constraint.

[88] DMI, referring to Daishowa-Marubeni International Ltd., utilize a landscape-level succession modeling system to develop 'ecologically reasonable' growth and yield trajectories which capture changes in the mix of coniferous and deciduous species as stands age (DMI 2002). Intensive silviculture in succession modeled stands would therefore represent quicker development of spruce in the aspen understory, as opposed to the rapid re-establishment of a pure coniferous stand.

$42.35/t C), temporary carbon credits would have to be discounted at a rate of at least 88.6%, versus permanent credit values, in order to maintain minimal harvest activity in most scenarios modeled.[89] Should intensive regeneration regulations be enforced, this discount rate would need to be increased even further. The effects of incentives for carbon management on segments of the Canadian forest industry which are dependent on the boreal forest could therefore be significant.

If market values for carbon rise high enough, hybrid poplar plantations could provide a means of mitigating the effects of carbon management on the forestry sector. Shadow price results for the supply of hybrid poplar suggest that the most efficient method for managing the forest landscape, with values accruing to both timber harvest and carbon credits, may include more intensive, specialized land use. Previous research by Vincent and Binkley (1993) has suggested that economically efficient multiple use of forests may require land-use specialization, particularly when stands differ in their innate capacity to produce each output. Proponents of priority-use zoning policies have also argued that, by allocating areas for intensive forest management, it is possible to conserve more forest in protected zones without eliminating jobs or output (Gladstone and Ledig 1990; Hunter and Calhoun 1996; Binkley 1997). It is important to note, however, that there are currently regulations in place which may constrain the use of non-native species (such as hybrid poplar) on public land in the boreal plains.[90] Reedy (2003) and Anderson

[89] See the EU Price Assessment available at http://www.pointcarbon.com (cited June 6, 2006). Market prices observed were for the period from February to June, 2006. For conversion: 1 unit of C = 3.6667 or 44/12 units of CO_2. An exchange rate of 0.898150 USD/CAD is assumed (June 6, 2006).
[90] See, for instance, the Alberta Forests Act, Timber Management Regulations 60/73 and the Standards for Tree Improvements in Alberta (Ref. T/037).

and Luckert (*in press*) discuss potential social issues which might accompany the use of hybrid species in Canadian forests as well.

Finally, the results present two interesting findings concerning the interaction of carbon markets and the forestry industry. First of all, model scenarios which force an even flow harvest of hardwood and softwood timber, at a level of production equal to that derived for timber management only, still generate benefits to carbon management in most instances. This observation is especially valid for landscapes with younger initial age-class distributions or in policy environments which permit carbon accounting using a business-as-usual baseline. These benefits from carbon management are even greater if the flow of hardwood and softwood timber to the mill is allowed to fluctuate +/- 25% from one period to the next. Secondly, firms managing for returns to both carbon and timber are predicted to favour reducing harvest in forest areas dominated by aspen versus areas of mixedwood or softwood forest types, such as pine and white spruce. Consequently, the ability of the forestry sector, and mills in particular, to adjust to variations in the flow of harvested timber from one period to the next, as well as to potential changes in the proportion of hardwood to softwood timber delivered, will be an important factor in determining the optimal balance of timber and carbon management on the landscape. Given the degree of vertical integration in the Canadian forestry sector, it may be difficult to realize the gains from carbon management that these adjustments would imply.

6.2 Limitations and Future Work

The integrated modeling framework developed herein is flexible in design and could easily be extended to incorporate additional variations in incentive mechanisms, regulatory regimes and/or forest landscape characteristics. For example, analysis in this study is limited to three hypothetical initial age-class distributions, each modeled as a fully-regulated normal forest and containing a different quantity of mature timber. This approach was meant to allow the behaviour of the model to be examined over a range of initial starting conditions. Preliminary scenarios which modeled a non-hypothetical initial age-class structure were investigated, but analysis of these formulations was limited by the timeframe of this study. Initial observations suggest that the relative age of different forest cover types on an unregulated landscape will be a significant factor in determining timber versus carbon management decisions. Further analysis of the effects associated with more 'realistic' initial age-class structures is desirable.

The model could also be easily amended to allow for analysis of alternative incentives for carbon management; such as permanent versus temporary carbon credits, carbon baseline policies different from those discussed, or the use of specified level carbon contracts versus carbon market mechanisms. Furthermore, the incorporation of timber versus carbon management incentives was limited here to an analysis of various carbon to timber price ratios, which were held constant over the planning horizon. Realistically, both carbon and timber price incentives would be expected to vary over time. Scenarios which specify increasing carbon costs through the planning horizon, or different hardwood to softwood timber price ratios, would provide a relatively simple starting point for further analysis.[91] Extending the present model to examine how price risk and uncertainty would affect carbon and timber management decisions, and the time path of management choices, may also prove interesting. The modeling framework for such an analysis, however, would likely be complex.

More in depth analysis of the trade-offs between carbon management benefits and timber harvest volumes, as the flexibility of timber yield policies is increased, would be useful as well. Model results suggest that timber yield policies which permit a variable flow of harvested timber from period to period may be able to generate significant benefits to carbon management, while also sustaining a greater degree of harvest activity for the forestry sector. However, analysis in this study was limited to the case of a +/- 25% fluctuation around the even-flow volume of timber harvested in the baseline scenario. Additional research could focus on the degree of variability from period to period required to meet forest carbon management objectives, while also maintaining an acceptable flow of harvested timber to the mill.

Notwithstanding these potential research extensions, the primary limitation of the present study concerns the potential for natural disturbance events to affect incentives for carbon versus timber management. Natural reversals, such as wildfire or insect mortality, introduce an element of risk into carbon management strategies, as at any time the forest landscape may succumb to disturbance and release large quantities of sequestered carbon back into the atmosphere. For example, both Armstrong (1999) and Amiro *et al.* (2001)

[91] The marginal impact of carbon emissions changes as the atmospheric concentrations of greenhouse gases rise. The social cost of carbon is therefore expected to increase over time if global warming unfolds in a harmful direction (Mendelsohn 2005).

have documented that the natural fire regime for the boreal forest is characterized by large interannual variability in terms of frequency and severity of disturbance. Moreover, the risk of natural reversals may increase with forest carbon management, as lengthened harvest rotations can increase the susceptibility of forests to natural disturbances like fire, insects and disease (Sedjo *et al.* 1995; Price *et al.* 1997). While such issues were beyond the scope of the current project, future extensions of the modeling framework should address the potential for carbon reversals and incorporate scenarios which evaluate management decisions under risk of natural disturbance.

Moreover, climate change impact studies report the possibility of large increases in natural disturbance rates for many parts of Canada; including forest fires, insect infestation and storm damage (Flannigan *et al.* 2001; Lemmen and Warren 2004). Climate change is also predicted to affect forest productivity rates, both domestically and internationally (Lemmen and Warren 2004; Sohngen *et al.* 2001). These effects of climate change on forested landscapes could alter the way in which forest managers would be expected to respond to incentives for carbon versus timber management. For instance, the response to climate change is not expected to be uniform across all forest cover types (Hamann and Wang 2006). Consequently, changes in the relative growth and recruitment rates between species, as well as increased reforestation failures or susceptibility to disease for one species type versus others, could be expected to affect decisions regarding the adoption of carbon or timber management practices.

In addition, the adaptation of forestry practices to climate change impacts could generate different forest management decisions. Sohngen and Mendelsohn (1998) and Volney and Hirsch (2005) have both suggested that adjusting regeneration practices and stand management techniques could reduce the susceptibility of a forest landscape to natural disturbances.[92] Spittlehouse (2005) proposes the use of faster growing species to reduce risk and aid forest managers in adjusting to continuously changing climatic conditions. Sohngen and Sedjo (2005) have also examined how these climate change impacts are expected to influence North American timber markets. Adjusting the modeling framework developed in this study to incorporate climate change impacts and adaptation strategies would be relatively straightforward, given the proper data, and could provide for more fruitful analysis of how carbon and timber management incentives on the forest landscape change through time.

Finally, the scope of this study was limited to the consideration of timber and carbon management objectives for a boreal plains forest landscape. It has been recognized that a key to making carbon mitigation activities more efficient may be to balance them with other economic, environmental and social goals of land use (Metz *et al.* 2001). Important co-benefits of forest carbon management may include providing habitat, conserving biodiversity and improving ecosystem productivity, yet the impact of carbon management incentives on non-timber values has not had substantial attention in the literature.[93] Alternative model formulations, designed to investigate the relationships and trade-offs between forest carbon management, timber harvest and a broader set of

[92] One option may be to FireSmart the landscape through regeneration practices which convert stands from coniferous to mixedwood or deciduous cover types at strategic locations (Volney and Hirsch 2005).
[93] A notable exception is Englin and Callaway (1995).

sustainable forest management values, could help to provide a more complete picture of the costs and challenges faced by forest managers in Canada. Such an approach could be based on the modeling techniques described herein, as well as in McCarney *et al.* (2006).

6.3 Concluding Summary

The research conducted for this study has addressed how forest carbon management incentives are expected to change the practice of forestry in the boreal plains ecozone of Canada. Analysis was focused on changes to the management regime applied across specific forest landscapes under alternative market and regulatory structures. An integrated modeling approach is developed for the purposes of this research, capable of incorporating both forest carbon and timber value considerations within an optimal management framework. This modeling approach allows for considerable flexibility in the specification of alternative market conditions and regulatory scenarios, while presenting a range of possible management intensity and harvest scheduling options across the landscape. Furthermore, a key element in the model design is the detailed representation of forest carbon dynamics, and in particular the incorporation of separate biomass and dead organic matter (DOM) carbon yield curves. The carbon accounting procedure employed allows the model to capture carbon stocks and flux between pools that are specific to individual forest cover types, particular productivity and management characteristics and individual site disturbance histories. The techniques developed for this project have allowed for a more rigorous and realistic approach to carbon modeling than has previously been captured through the simpler representations of carbon incorporated into most economic analyses.

The main findings of this study pertain to the development of a market for carbon in Canada, and are intended to inform industry and government about the potential implications of forest carbon management on the boreal plains. Results suggest that, for most combinations of initial age-class structures, regulatory regimes and market costs studied, carbon management practices will be beneficial to forestry firms. Returns to carbon management, however, have the potential to dominate forestry operations. Unless temporary carbon credits are significantly discounted from the permanent rates currently observed in operating markets, carbon management could change the nature of the Canadian forest industry. Should government policy or industrial decisions intervene to mediate such effects, the ability of the forestry sector to adjust to variations in the periodic flow of harvested timber, as well as to changing proportions of delivered hardwood versus softwood timber, will be significant factors in determining the optimal balance between timber and carbon management. Moreover, shifting to a greater degree of land-use specialization may be the most efficient method of managing the forest landscape for both timber and carbon management incentives. Analysis also indicates that regeneration policies should be reviewed in conjunction with carbon management incentives. In particular, attention should be focused on regulations which encourage more ecological, or succession-based, forest management practices, as opposed to intensive reforestation standards.

Considering the general appearance of the forested landscape, incentives for carbon management, versus timber management alone, are found to decrease harvest activity and increase the area of forest conserved for all forest cover types, in all productivity classes and across all haul zones. However, regression analysis highlights that, for a given level of harvest activity, forestry firms would implement carbon management on the landscape by proportionally reducing timber management in aspen stands, while increasing the harvested volumes and relative silvicultural intensity for areas of mixedwood and white spruce. Harvested volumes would also be collected over a smaller proportion of the area for each cover type, and accordingly this area will be managed more intensively than when considering timber management incentives alone. The benefits of preserving younger stands and areas of aspen cover for carbon management may also outweigh the costs of shifting harvest activity to older stands of other cover types that are located further from the mill. Finally, results indicate that the costs of implementing carbon management can be affected by reforestation standards, with the effect differing depending on the forest cover type being managed.

In evaluating the potential for forests to contribute to Canada's national climate change strategy, the desirability of the forest management practices discussed above, their associated regulatory requirements and costs, and the resulting implications for Canada's forest landscape must all be considered. If Canada should choose to remain within the framework of the Kyoto Protocol, the results in this study could also help to identify whether the rules pertaining to forest carbon accounting, contained under Article 3.4, should be invoked for the first commitment period (2008-2012). The benefits of invoking Article 3.4 will likely depend on the forest management area defined for carbon accounting, and the findings of this study could help to evaluate the carbon management implications of the forest landscape characteristics. More generally, the conclusions drawn here could help industry and government agencies determine which boreal forest regions are candidates for carbon management, and to evaluate whether such a transition could be handled by existing forest policy frameworks and industrial structures.

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Appendix

A.1 Appendix Figures

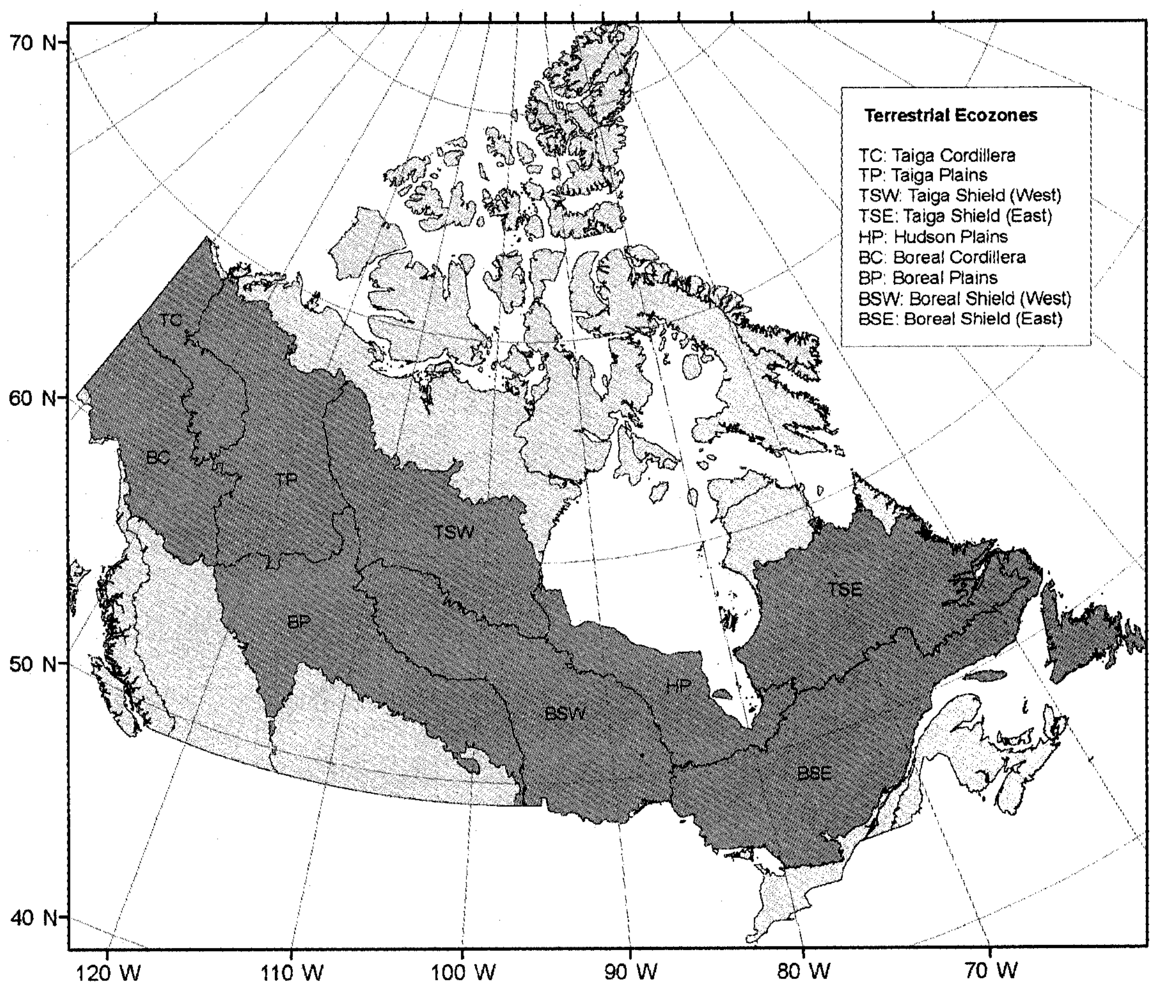
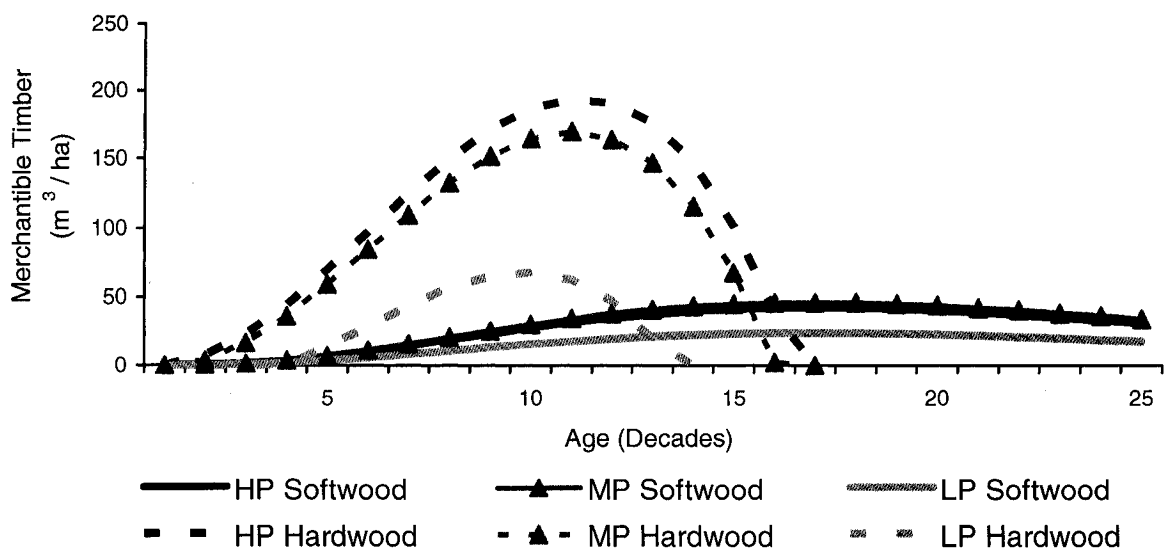


Figure A-1 Terrestrial ecozones of the Canadian boreal forest. Figure provided courtesy of Glen W. Armstrong (Armstrong, pers. comm.); GIS data for this map were obtained from Agriculture and Agri-Food Canada (2005).

Natural Growth and Yield Trajectories for Aspen (PO)



Growth and Yield Trajectory for Hybrid Poplar

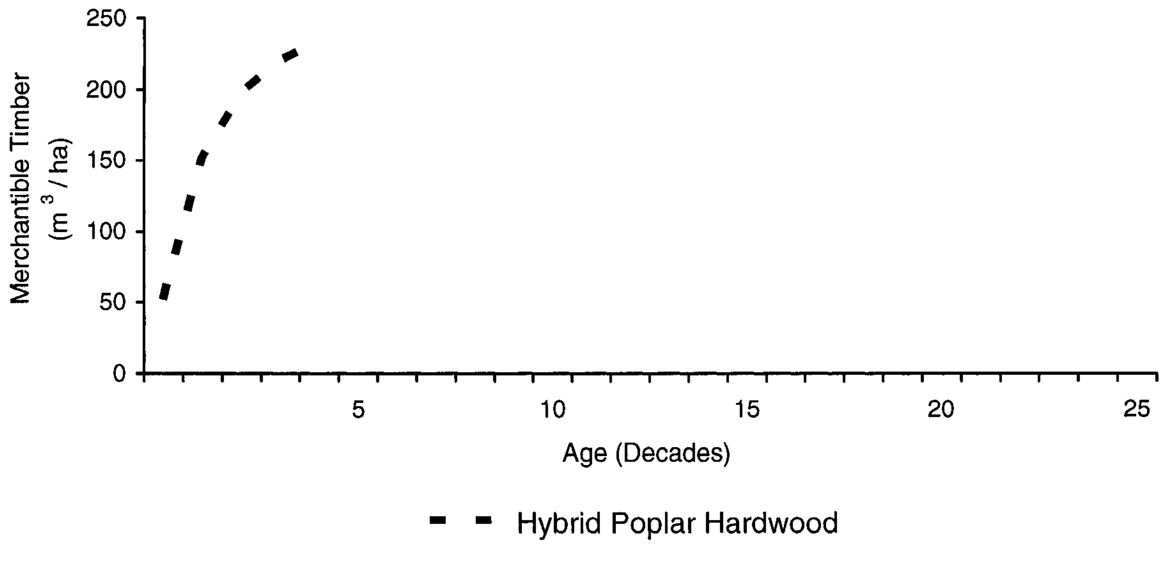
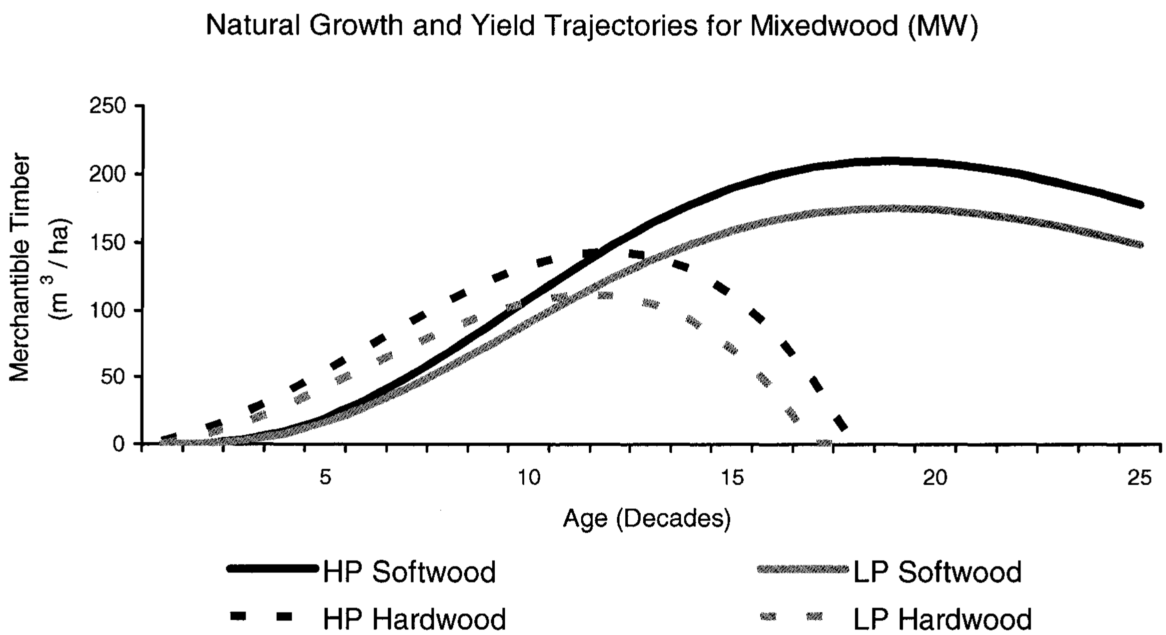


Figure A-2 Growth and yield trajectories assigned to aspen stands on the hypothetical boreal plains landscape; specific to high productivity (HP), mid-productivity (MP) and low productivity (LP) sites. Natural growth and yield trajectories are developed by DMI and summarized in their Growth and Yield Information Package (DMI 2002). Hybrid poplar growth and yield is developed in Anderson and Luckert (*in press*).



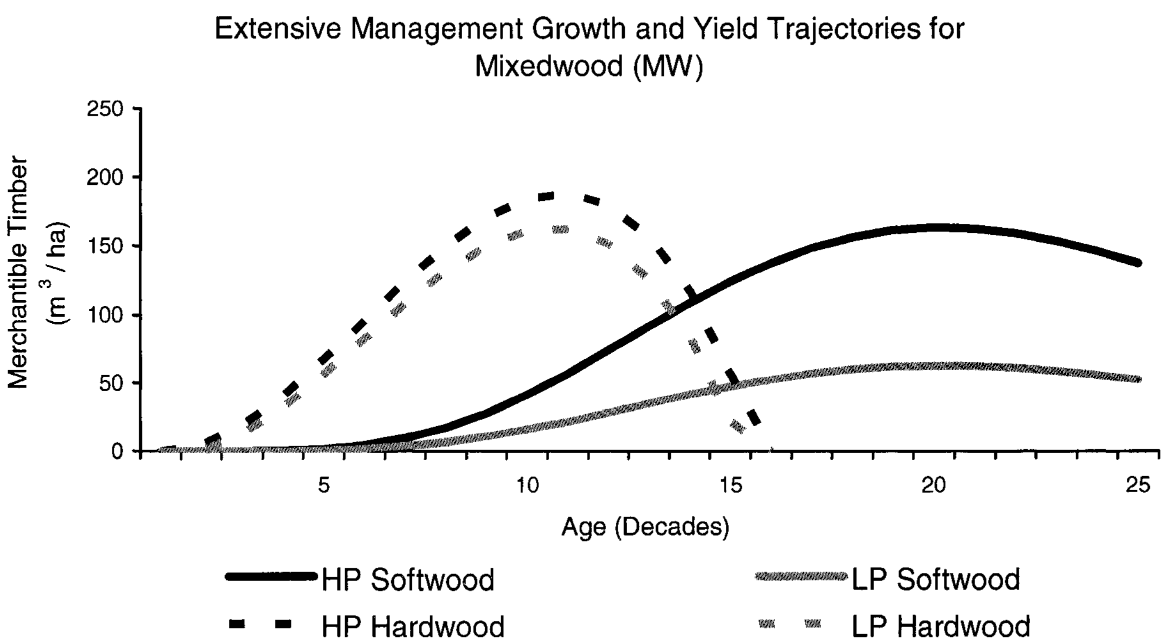
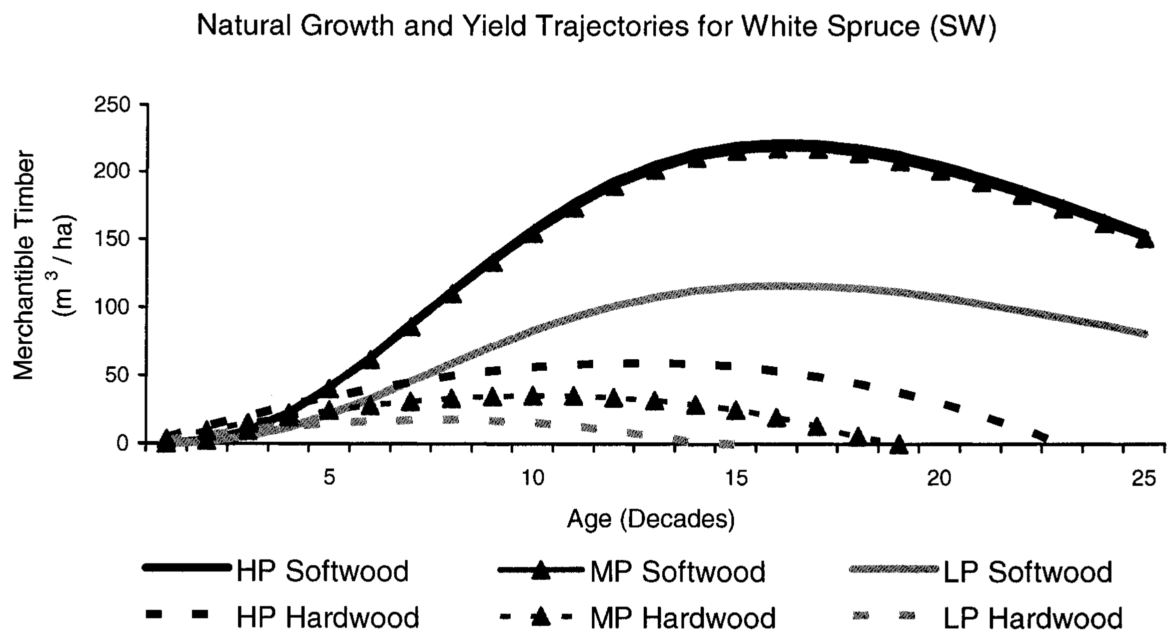


Figure A-3 Growth and yield trajectories assigned to mixedwood stands on the hypothetical boreal plains landscape; specific to high productivity (HP) and low productivity (LP) sites. Growth and yield trajectories are developed by DMI and summarized in their Growth and Yield Information Package (DMI 2002).



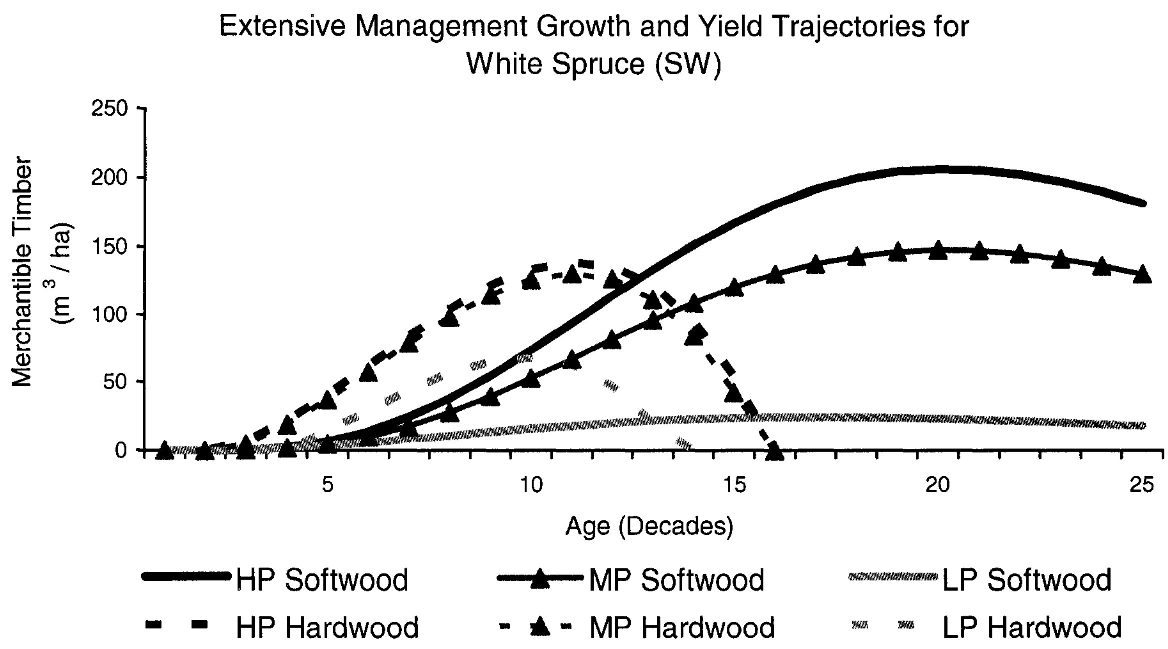
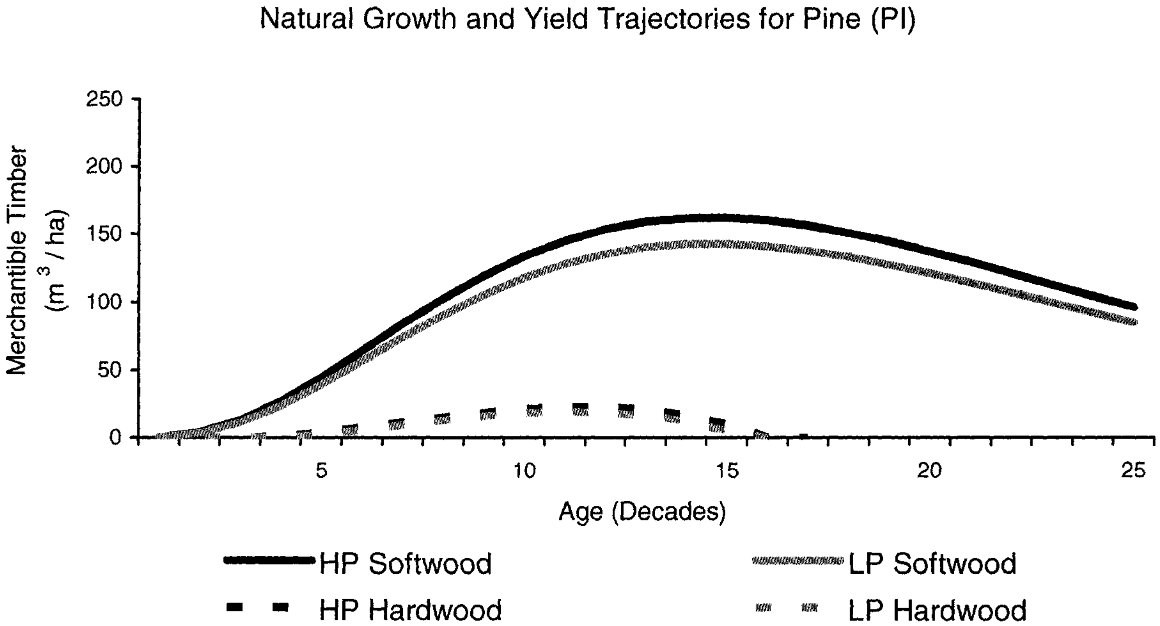


Figure A-4 Growth and yield trajectories assigned to white spruce stands on the hypothetical boreal plains landscape; specific to high productivity (HP), mid-productivity (MP) and low productivity (LP) sites. Growth and yield trajectories are developed by DMI and summarized in their Growth and Yield Information Package (DMI 2002).



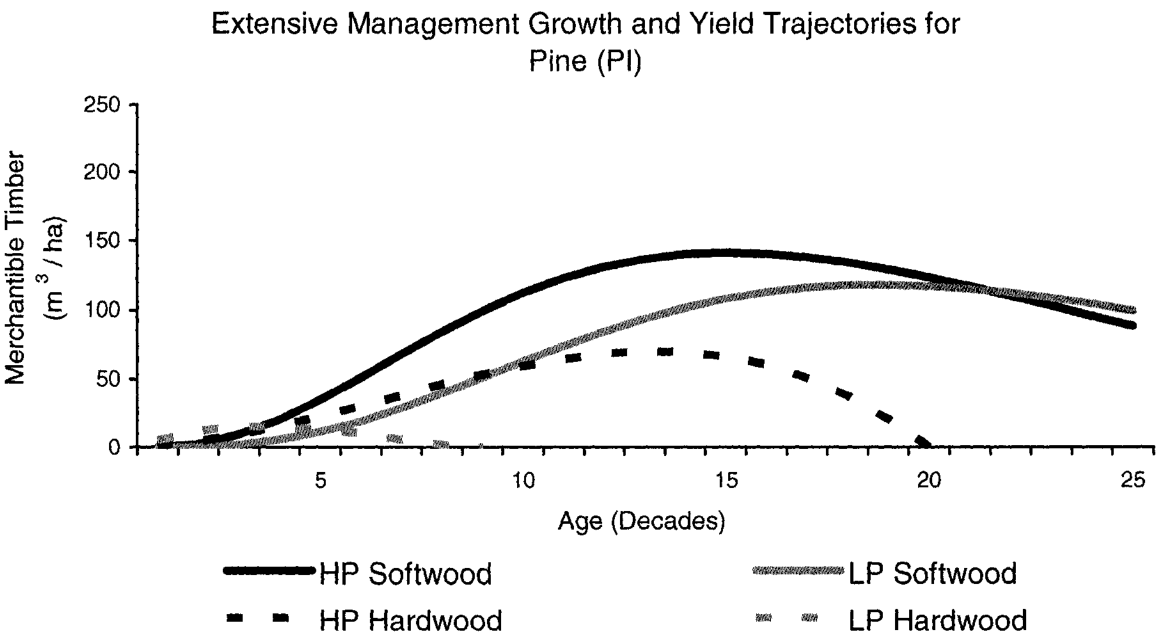
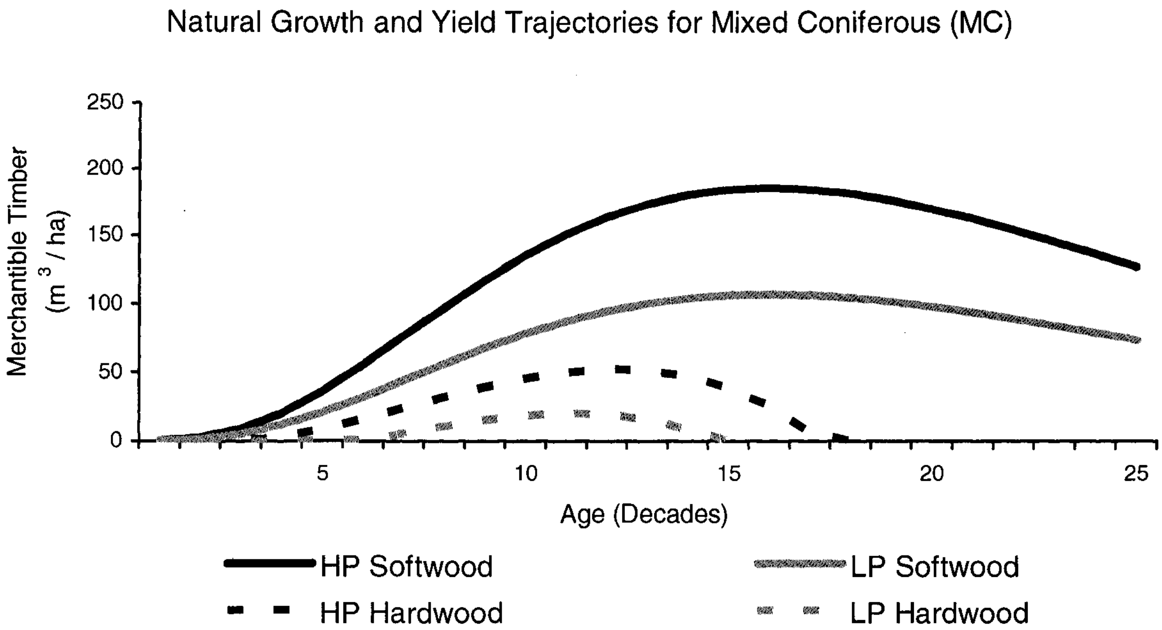


Figure A-5 Growth and yield trajectories assigned to pine stands on the hypothetical boreal plains landscape; specific to high productivity (HP) and low productivity (LP) sites. Growth and yield trajectories are developed by DMI and summarized in their Growth and Yield Information Package (DMI 2002).



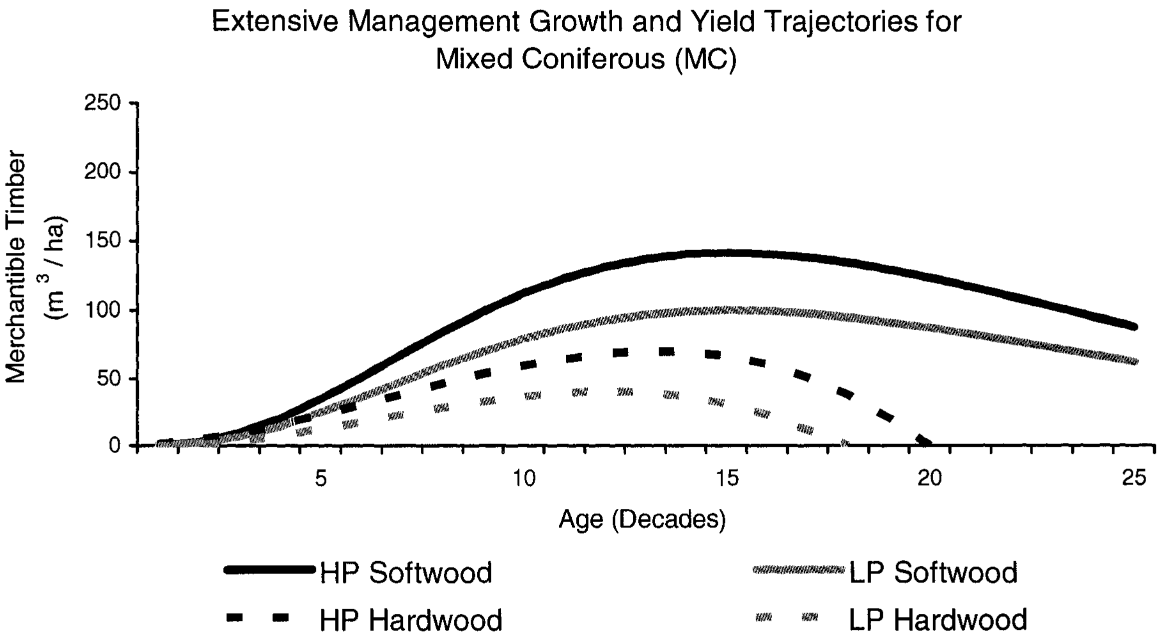


Figure A-6 Growth and yield trajectories assigned to mixed coniferous stands on the hypothetical boreal plains landscape; specific to high productivity (HP) and low productivity (LP) sites. Growth and yield trajectories are developed by DMI and summarized in their Growth and Yield Information Package (DMI 2002).

A.2 Appendix Tables

Table A-1 Regression Variable Definitions (for Tables A-2 through A-7)

Independent Variables	Variable Definitions
carbpr	Carbon Cost ($/t C)
carbpr2	Carbon Cost Squared $(\$/t\ C)^2$
dftID	Deficit Forest[d] (vs. Normal Forest)
splID	Mature Forest[d] (vs. Normal Forest)
disc7	7% Discount Rate[d] (vs. 3% Discount Rate)
regID	Regeneration Regulations Applied[d] (vs. No Regeneration Regulations)
efE	Harvest Volume Equal to Baseline Level[d] (vs. Adjustable Harvest Volume Policy)
efV	Harvest Volume +/- 25% Baseline Level[d] (vs. Adjustable Harvest Volume Policy)
mw	Mixedwood Cover Type[d] (vs. Aspen Cover Type)
sw	White Spruce Cover Type[d] (vs. Aspen Cover Type)
pine	Pine Cover Type[d] (vs. Aspen Cover Type)
mc	Mixed Coniferous Cover Type[d] (vs. Aspen Cover Type)
lp	Low Productivity Site[d] (vs. High Productivity Site)
cls	Close Haul Zone[d] (vs. Mid-Distance Haul Zone)
far	Far Haul Zone[d] (vs. Mid-Distance Haul Zone)
tot_cut	Total area of the forest landscape accessed for harvesting purposes (ha)
tot_ha	Aggregate area harvested from each cover type over the planning horizon (ha)
timbharv	Total volume of timber harvested from the landscape over the planning horizon (m^3)
tot_silv	Total expenditure on silviculture ($)

1 "d" denotes dummy variable; base case provided in parentheses.
2 Interaction terms combine the independent variables described in this table.

Table A-2 Regression Results for Figure 5-3.

```
+-----------------------------------------------------------------------+
| Ordinary    least squares regression    Weighting variable = none      |
| Dep. var. = NOT_CUT  Mean=    85264.63728    , S.D.=   115532.5732     |
| Model size: Observations =      780, Parameters =  16, Deg.Fr.=    764 |
| Residuals:  Sum of squares= .1789638298E+13, Std.Dev.=    48398.95149  |
| Fit:        R-squared=  .827885, Adjusted R-squared =           .82451 |
| Model test: F[ 15,     764] =  244.99,     Prob value =         .00000 |
| Diagnostic: Log-L =  -9512.7310, Restricted(b=0) Log-L =  -10198.9718  |
|             LogAmemiyaPrCrt.=   21.595, Akaike Info. Crt.=      24.433 |
| Autocorrel: Durbin-Watson Statistic =   2.41028,    Rho =      -.20514 |
+-----------------------------------------------------------------------+
```

Variable	Coefficient	Standard Error	b/St.Er.	P[|Z|>z]	Mean of X
Constant	295456.4171	9446.9666	31.275	.0000	
CARBPR	2581.121587	421.92727	6.117	.0000	46.153846
CARBPR2	-18.67877426	3.4604120	-5.398	.0000	3657.6923
MW	-145335.4282	12187.394	-11.925	.0000	.20000000
SW	-144862.3764	12187.394	-11.886	.0000	.20000000
PINE	-151199.1801	12187.394	-12.406	.0000	.20000000
MC	-135885.1008	12187.394	-11.150	.0000	.20000000
CARBMW	-3337.969433	592.27474	-5.636	.0000	9.2307692
CARBSW	-3293.572099	592.27474	-5.561	.0000	9.2307692
CARBPI	-3691.227503	592.27474	-6.232	.0000	9.2307692
CARBMC	-2582.838900	592.27474	-4.361	.0000	9.2307692
CARB2MW	24.12357922	4.8679166	4.956	.0000	731.53846
CARB2SW	23.48127623	4.8679166	4.824	.0000	731.53846
CARB2PI	26.34788303	4.8679166	5.413	.0000	731.53846
CARB2MC	19.44113283	4.8679166	3.994	.0001	731.53846
TOT_CUT	-.2000000000	.59182828E-02	-33.794	.0000	473676.81

(Note: E+nn or E-nn means multiply by 10 to + or -nn power.)

Table A-3 Regression Results for Figure 5-4

```
+-----------------------------------------------------------------------+
| Ordinary    least squares regression    Weighting variable = none     |
| Dep. var. = PCNOTCUT Mean=    .4375667113     , S.D.=    .3972805132  |
| Model size: Observations =      780, Parameters =  25, Deg.Fr.=   755 |
| Residuals:  Sum of squares= 38.14828831     , Std.Dev.=         .22478 |
| Fit:        R-squared=  .689728, Adjusted R-squared =           .67986 |
| Model test: F[ 24,     755] =   69.93,     Prob value =         .00000 |
| Diagnostic: Log-L =      70.1750, Restricted(b=0) Log-L =    -386.2439 |
|             LogAmemiyaPrCrt.=    -2.954, Akaike Info. Crt.=      -.116 |
| Autocorrel: Durbin-Watson Statistic =   1.87500,    Rho =       .06250 |
+-----------------------------------------------------------------------+
```

Variable	Coefficient	Standard Error	b/St.Er.	P[|Z|>z]	Mean of X
Constant	.9589425990	.60527556E-01	15.843	.0000	
REGID	.1454707717	.35808323E-01	4.062	.0000	.50000000
CARBPR	.7022440306E-02	.22840156E-02	3.075	.0021	46.153846
CARBPR2	-.5170228018E-04	.18402100E-04	-2.810	.0050	3657.6923
MW	-.5684782991	.66471420E-01	-8.552	.0000	.20000000
SW	-.5663580096	.65876159E-01	-8.597	.0000	.20000000
PINE	-.5728174888	.67472549E-01	-8.490	.0000	.20000000
MC	-.5188653019	.64612651E-01	-8.030	.0000	.20000000
DFTID	.1618305338	.20245087E-01	7.994	.0000	.33333333
SPLID	-.6279639118E-01	.19800149E-01	-3.172	.0015	.33333333
DISC7	-.8367347099E-01	.25233661E-01	-3.316	.0009	.50000000
EFE	-.4594018698	.22067161E-01	-20.818	.0000	.30769231
EFV	-.3917082638	.21020617E-01	-18.634	.0000	.30769231
CARBMW	.8193021437E-02	.28136755E-02	2.912	.0036	9.2307692
CARBSW	.7602316668E-02	.28105971E-02	2.705	.0068	9.2307692
CARBPI	.8309593390E-02	.28152912E-02	2.952	.0032	9.2307692
CARBMC	.8966767360E-02	.27919133E-02	3.212	.0013	9.2307692
CARB2MW	-.5376723199E-04	.22987075E-04	-2.339	.0193	731.53846
CARB2SW	-.5275958078E-04	.22966094E-04	-2.297	.0216	731.53846
CARB2PI	-.5734642557E-04	.23002568E-04	-2.493	.0127	731.53846
CARB2MC	-.5703371833E-04	.22870719E-04	-2.494	.0126	731.53846
CARBDIS7	.7572141657E-03	.41215859E-03	1.837	.0662	23.076923
CARBREG	-.5055953828E-02	.17400740E-02	-2.906	.0037	23.076923
CARB2REG	.3193563478E-04	.14300762E-04	2.233	.0255	1828.8462
TOT_HA	-.5490653073E-06	.45032258E-07	-12.193	.0000	211236.47

(Note: E+nn or E-nn means multiply by 10 to + or -nn power.)

Table A-4 Regression Results for Figure 5-5

```
+-----------------------------------------------------------------------
| Ordinary    least squares regression    Weighting variable = none
| Dep. var. = SPHARV   Mean=   32180989.88     , S.D.=   43442200.23
| Model size: Observations =      780, Parameters =  16, Deg.Fr.=    764
| Residuals:  Sum of squares= .3659566453E+18, Std.Dev.= 21886087.92523
| Fit:        R-squared=  .751075, Adjusted R-squared =          .74619
| Model test: F[ 15,    764] =  153.68,     Prob value =          .00000
| Diagnostic: Log-L = -14281.7510, Restricted(b=0) Log-L =  -14824.0864
|             LogAmemiyaPrCrt.=   33.823, Akaike Info. Crt.=     36.661
| Autocorrel: Durbin-Watson Statistic =   1.98589,    Rho =      .00705
+-----------------------------------------------------------------------
```

Variable	Coefficient	Standard Error	b/St.Er.	P[|Z|>z]	Mean of X
Constant	67992967.31	4153447.4	16.370	.0000	
CARBPR	-503307.4504	190007.32	-2.649	.0081	46.153846
CARBPR2	3780.313435	1560.2093	2.423	.0154	3657.6923
MW	-81340718.14	5511160.3	-14.759	.0000	.20000000
SW	-82448390.34	5511160.3	-14.960	.0000	.20000000
PINE	-96186537.09	5511160.3	-17.453	.0000	.20000000
MC	-79989190.96	5511160.3	-14.514	.0000	.20000000
CARBMW	631333.8740	267827.64	2.357	.0184	9.2307692
CARBSW	645686.0108	267827.64	2.411	.0159	9.2307692
CARBPI	770743.2122	267827.64	2.878	.0040	9.2307692
CARBMC	468774.1551	267827.64	1.750	.0801	9.2307692
CARB2MW	-4710.844927	2201.2801	-2.140	.0324	731.53846
CARB2SW	-4678.764792	2201.2801	-2.125	.0335	731.53846
CARB2PI	-5721.146391	2201.2801	-2.599	.0093	731.53846
CARB2MC	-3790.811066	2201.2801	-1.722	.0851	731.53846
TIMBHARV	.2000000000	.69455977E-02	28.795	.0000	.160905E+09

(Note: E+nn or E-nn means multiply by 10 to + or -nn power.)

Table A-5 Regression Results for Figure 5-6

```
+-----------------------------------------------------------------------+
| Ordinary    least squares regression    Weighting variable = none     |
| Dep. var. = PRODZONE Mean=   26817491.57     , S.D.=   32090459.78    |
| Model size: Observations =      936, Parameters =  15, Deg.Fr.=   921 |
| Residuals:  Sum of squares= .2032423297E+18, Std.Dev.= 14855157.72000 |
| Fit:        R-squared=  .788918, Adjusted R-squared =         .78571  |
| Model test: F[ 14,     921] =  245.87,    Prob value =         .00000 |
| Diagnostic: Log-L = -16777.5365, Restricted(b=0) Log-L =  -17505.5151 |
|             LogAmemiyaPrCrt.=   33.044, Akaike Info. Crt.=    35.881  |
| Autocorrel: Durbin-Watson Statistic =   2.60084,    Rho =    -.30042  |
+-----------------------------------------------------------------------+
```

Variable	Coefficient	Standard Error	b/St.Er.	P[|Z|>z]	Mean of X
Constant	22377175.48	2434842.6	9.190	.0000	
CARBPR	-229094.4393	105387.68	-2.174	.0297	46.153846
CARBPR2	1620.170658	865.16958	1.873	.0611	3657.6923
LP	-38901907.83	2559371.2	-15.200	.0000	.50000000
CLS	18941388.31	2900169.5	6.531	.0000	.33333333
FAR	-26911137.01	2900169.5	-9.279	.0000	.33333333
CLSLP	-15701383.80	2378729.0	-6.601	.0000	.16666667
FARLP	14083551.79	2378729.0	5.921	.0000	.16666667
CARBLP	185758.0186	104955.19	1.770	.0767	23.076923
CARBCLS	37720.49035	128543.32	.293	.7692	15.384615
CARBFAR	370925.7997	128543.32	2.886	.0039	15.384615
CARB2LP	-1368.374003	862.62852	-1.586	.1127	1828.8462
CARB2CLS	-604.8823517	1056.4999	-.573	.5670	1219.2308
CARB2FAR	-2203.068619	1056.4999	-2.085	.0370	1219.2308
TIMBHARV	.1666666667	.43035626E-02	38.728	.0000	.160905E+09

(Note: E+nn or E-nn means multiply by 10 to + or -nn power.)

Table A-6 Regression Results for Figure 5-7

```
Ordinary    least squares regression    Weighting variable = none
Dep. var. = SILV      Mean=     121060852.8     , S.D.=    94738034.83
Model size: Observations =         540, Parameters =  26, Deg.Fr.=     514
Residuals:  Sum of squares= .6246202664E+18, Std.Dev.= 34859927.22413
Fit:        R-squared=  .870884, Adjusted R-squared =             .86460
Model test: F[ 25,     514] =   138.68,     Prob value =          .00000
Diagnostic: Log-L = -10131.0016, Restricted(b=0) Log-L =  -10683.7045
            LogAmemiyaPrCrt.=   34.781, Akaike Info. Crt.=      37.619
Autocorrel: Durbin-Watson Statistic =   1.60807,    Rho =        .19597
```

Variable	Coefficient	Standard Error	b/St.Er.	P[|Z|>z]	Mean of X
Constant	7811712.463	15653567.	.499	.6178	
REGID	-77123125.60	8402081.6	-9.179	.0000	.50000000
CARBPR	2086205.252	379000.79	5.504	.0000	44.444444
CARBPR2	-15588.26594	3082.4197	-5.057	.0000	3522.2222
MW	-36801181.00	15728836.	-2.340	.0193	.20000000
SW	-7357639.845	15583512.	-.472	.6368	.20000000
PINE	-47220040.64	16111628.	-2.931	.0034	.20000000
MC	-30888442.19	14477190.	-2.134	.0329	.20000000
DFTID	4530829.196	5777676.4	.784	.4329	.33333333
SPLID	-496524.9612	4444061.7	-.112	.9110	.33333333
DISC7	-3057557.178	3819665.6	-.800	.4234	.50000000
EFV	1897981.248	4163171.9	.456	.6485	.44444444
CARBMW	-1287822.340	509523.98	-2.528	.0115	8.8888889
CARBSW	-1274598.990	509259.63	-2.503	.0123	8.8888889
CARBPI	-2818770.438	508847.71	-5.540	.0000	8.8888889
CARBMC	-4092855.887	502520.57	-8.145	.0000	8.8888889
CARB2MW	10842.23638	4212.4074	2.574	.0101	704.44444
CARB2SW	12610.52565	4209.1886	2.996	.0027	704.44444
CARB2PI	20829.04953	4211.1650	4.946	.0000	704.44444
CARB2MC	27353.71011	4175.9614	6.550	.0000	704.44444
REGMW	103269987.0	9488325.9	10.884	.0000	.10000000
REGSW	96138121.69	9494323.2	10.126	.0000	.10000000
REGPI	84213238.58	9488002.6	8.876	.0000	.10000000
REGMC	120168098.3	9591855.4	12.528	.0000	.10000000
TOT_SILV	.1905106216	.12439475E-01	15.315	.0000	.6053043E+09
TOT_HA	54.69658661	12.541503	4.361	.0000	289678.15

(Note: E+nn or E-nn means multiply by 10 to + or -nn power.)

Table A-7 Regression Results for Figure 5-8

```
+-----------------------------------------------------------------------+
| Ordinary    least squares regression    Weighting variable = none     |
| Dep. var. = SILVHA    Mean=    638.1727097     , S.D.=    475.6279610 |
| Model size: Observations =      540, Parameters =   21, Deg.Fr.=   519 |
| Residuals:  Sum of squares= 21146658.22     , Std.Dev.=     201.85392 |
| Fit:        R-squared=  .826572, Adjusted R-squared =          .81989 |
| Model test: F[ 20,     519] =   123.68,    Prob value =         .00000 |
| Diagnostic: Log-L =   -3621.5911, Restricted(b=0) Log-L =   -4094.6298 |
|             LogAmemiyaPrCrt.=    10.653, Akaike Info. Crt.=     13.491 |
| Autocorrel: Durbin-Watson Statistic =   1.60838,    Rho =       .19581 |
+-----------------------------------------------------------------------+
```

Variable	Coefficient	Standard Error	b/St.Er.	P[|Z|>z]	Mean of X
Constant	115.5536259	41.645983	2.775	.0055	
REGID	105.7927851	43.525537	2.431	.0151	.50000000
CARBPR	5.498063624	1.0436847	5.268	.0000	44.444444
CARBPR2	-.2920539082E-01	.76313678E-02	-3.827	.0001	3522.2222
MW	220.4371392	49.724938	4.433	.0000	.20000000
SW	357.9117627	49.724938	7.198	.0000	.20000000
PINE	-1.475669555	49.724938	-.030	.9763	.20000000
MC	-118.0725138	49.724938	-2.375	.0176	.20000000
DFTID	-60.32988163	21.277272	-2.835	.0046	.33333333
SPLID	92.37950531	21.277272	4.342	.0000	.33333333
DISC7	-35.89487551	17.372820	-2.066	.0388	.50000000
EFV	-97.91003069	17.854936	-5.484	.0000	.44444444
CARBMW	3.468749735	.69840492	4.967	.0000	8.8888889
CARBSW	3.830699760	.69840492	5.485	.0000	8.8888889
CARBPI	1.621662355	.69840492	2.322	.0202	8.8888889
CARBMC	-.5797345668	.69840492	-.830	.4065	8.8888889
REGMW	518.9418030	54.937679	9.446	.0000	.10000000
REGSW	312.2363567	54.937679	5.683	.0000	.10000000
REGPI	860.5146695	54.937679	15.663	.0000	.10000000
REGMC	978.9260496	54.937679	17.819	.0000	.10000000
CARBREG	-2.428003074	.44171005	-5.497	.0000	22.222222

(Note: E+nn or E-nn means multiply by 10 to + or -nn power.)