University of Alberta

Economic Analysis of Carbon Supply Contracts under Risk of Fire: A Supplier Perspective

by

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Abstract

Recently there has been considerable interest by the federal and provincial governments to understand the role of carbon trading mechanisms, such as carbon supply contracts, in a strategy for meeting Canada's greenhouse gas reduction targets under the Kyoto Protocol. It is thought that carbon credits generated via forest management practices may provide cost-effective emissions offsets for other sectors. Utilizing data from the Weldwood forest management area (FMA) in Hinton, Alberta a discrete stochastic sequential programming model is used to evaluate how various contract parameters, such as carbon price, contract size, and harvest regulations, affect a credit-supplier's decision to enter into carbon credit supply contracts. The results of this research suggest that, given the particular contract structure under investigation, carbon supply contracts may not generate sufficient incentives for firms to produce carbon credits at relatively low cost, and, that alternate contract structures or credit trading mechanisms should be explored.

Dedication

To Helena and Roman Politylo

Always you are remembered

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Chapter 1: Introduction

1.1 Introduction

Recently there has been considerable interest by the federal and provincial governments to understand the role of forests in any strategy for reducing greenhouse gases. This is largely a response to Canada's desire for meeting its commitment under the 1997 Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC). Canada, along with other forested countries, has successfully argued that forestry can be used to create biological carbon sinks for sequestering atmospheric carbon and that these sinks should be counted as part of Canada's Kyoto commitments. While forest sector activities such as growing and managing forests which sequester carbon would fall outside emissions reduction targets these actions may be eligible for generating carbon credits under Articles 3.3 and 3.4 of the protocol.

The conceptual basis for this research is motivated by Article 3.4 of the Protocol, whereby carbon credits would be generated for changes in what are termed "managed" forests. These "managed" forests comprise forest lands that do not change in terms of land use but on which carbon sequestration is augmented due to the combination of forest management activities with natural growth and development processes. This is perceived to be a viable, and perhaps less costly, strategy for Canada to comply with the Protocol upon ratification vis-à-vis alternative measures, yet considerable uncertainty remains as to the specific policy directions of the federal and provincial governments and significant questions have yet to be explored with respect appropriate firm-level response to carbon sequestration projects and/or contracts. The body of economic literature that comprises forest-level optimal control models; more specifically, those which incorporate the risk of natural disturbance, is at the foundation of this research. Also important is the literature concerning forest carbon accounting and budgets. Moreover, the Saskatchewan Forest Carbon Sequestration Project provides a real-world example of carbon credit supply contracts, which are of central interest in this study.

Carbon sequestration is a potentially risky strategy for meeting Canada's Kyoto obligations. At any time forests may succumb to fire, thereby releasing "stored" carbon into the atmosphere. Empirical studies such as Amiro et al. (2001) and Weber and Flannigan (1997) have documented that fire behaviour in terms of frequency and severity is uncertain and can fluctuate greatly from year-to-year. These studies also suggest that the potential effects of climate change on the future fire regime in the boreal forest of Alberta are uncertain. It is therefore advantageous to incorporate variable, or stochastic, forest fire disturbance rates within the firm's decision-making framework for carbon sequestration activities. While there are social and ecological benefits of fire in terms of forest ecosystem renewal, composition, species diversity, and importantly carbon balance, determining the value of these benefits remains beyond the focus of this research.

Additionally, because carbon sequestration is a long-term activity with inherent risks to the supplier and buyer, the generation and trading of carbon credits will probably take place primarily through contracts between credit suppliers and buyers. Wilman and

Mahendrarajah (1999) state that a principal-agent contract and appropriate institutions are necessary because the time dimension involved will not permit arms length trades between buyers and sellers. A consequence of natural disturbance risk, which can vary significantly, is carbon credit supply uncertainty. Therefore questions about insurance, risk sharing, and the problem of moral hazard may arise with respect to carbon credits and associated supply contracts. The firm supplying carbon credits may want to insure for the possibility that large and/or consecutive fire events will threaten their credit supply potential, or alternative contract arrangements may be possible whereby some of the risk that the credit supplier would face is off-loaded onto the buyer. This could be achieved by changing the level of responsibility that the supplier has for protecting carbon stocks from fire, however a moral hazard could result.

Utilizing the Weldwood forest management area (FMA) in Hinton, Alberta as a case study, from the perspective of a carbon credit supplier a discrete stochastic sequential programming model is used to evaluate how carbon price, contract credit supply quantity, and annual allowable cut (AAC) regulations affect the credit-supplying firm's decision to enter into a carbon credit supply contract. Further to evaluating whether or not a firm would enter a particular contract, why the firm would decide to enter a contract is examined along with how the contract performs in terms of augmenting expected carbon stock levels. It will be important to establish a consistent decision criterion that the firm would use in its decision-making process and a contract baseline, which would be used to compare post-contract carbon levels with the business-as-usual scenario (no carbon contract).

1.2 Research Objective

This study advances the literature on optimal forest management or scheduling models by utilizing stochastic programming and introducing both carbon accounting and carbon contract equations. In doing so the model is capable of tracking carbon stocks and flows through time as optimal rotation decision variables respond to the state of nature as well as carbon contract parameter levels. In regard to the treatment of the risk of fire disturbance this model utilizes a stochastic programming method when the majority of previous research into forest optimal rotation decisions in the presence of fire risk relies on deterministic model formulations. As such producer decision variable levels will vary according to the state of nature that occurs. Moreover, this model incorporates carbon accounting and contract equations which permit the researcher not only to construct and evaluate potential carbon supply contract scenarios, but because of the manner with which the carbon accounting equations have been developed it enables the researcher to catalogue how carbon stock levels change as the supplier responds to stochastic fire events and particular carbon contract scenarios. While other studies at the forest level have incorporated carbon accounting equations, with the exception of Maynes (2003) there does not appear to be any other studies of forest-level optimal rotation models which integrate carbon stock calculations that are able to examine the relationship between optimal forest rotation decisions at the forest level and forest carbon stocks, whether by carbon pool or in aggregate. Thus, the objectives of this research can be summarized as the following points.

1. Develop a discrete stochastic programming model for an optimal forest rotation or forest management schedule of the Weldwood FMA that (i) utilizes the area balance network or Model III formulation of forest dynamics as in Boychuk and Martell (1996), (ii) incorporates the carbon accounting equations as developed in Maynes (2003), (iii) based on historical fire data characterizes the distribution of fire events in a stochastic manner, (iv) introduces a carbon supply contract structure that can be manipulated in order to evaluate different contractual arrangements, and (v) models forest AAC regulations given changing forest conditions (i.e. age-class structures which have been modified by fire event and harvest decisions).
2. Given the firm's objective to maximize the expected present value of timber and the carbon contract, what is the impact of changing the contract parameters of (i) carbon price, (ii) contract supply quantity, and (iii) AAC regulations on the performance of the carbon contract vis-à-vis contract baseline and credit supply targets?
3. Determine under what conditions is the firm willing to enter into a carbon credit supply contract? At what carbon price, given AAC regulations and contract size, does the firm enter the contract? That is, for each contract scenario determine the firm's break-even-price. Moreover, how does changing the set of AAC regulations or the contract size affect the firm's decisions to enter into the contract? Finally, given the circumstances when the firm decides to enter into the contract, how does the contract perform concerning the amount of carbon credits generated and the number of replacement credits the firm must purchase?

1.3 Thesis Structure

This thesis comprises five chapters subsequent to the first, providing discussion of the background issues and economic theory related to carbon supply contracts from the perspective of a carbon-supplying firm, model development and formulation, results of model scenarios under investigation, as well as conclusions and recommendations for further research. In chapter 2, information about, and the relevance to, this study is provided regarding Articles 3.3 and 3.4 of the Kyoto Protocol, forest carbon management, and firm-level issues surrounding carbon supply contracts. These include carbon ownership, contract terms such as baseline, duration and permanence, and carbon price, regulatory compatibility, natural disturbance risk, and risk management. Finally a brief overview of the Saskatchewan Forest Carbon Sequestration Project is included. Chapter 3 is concerned with the economic theory at the foundation of the model development and formulation. Optimal forest control models in the context of carbon accounting and natural disturbance are discussed, with particular emphasis on previous research at the forest-level. Chapter 4 presents the model formulation, data sources, model assumptions, and a synopsis of the model scenarios being evaluated in this study, the results of which are found in chapter 5. Chapter 5 documents the results of the model scenarios and focuses on the firm's decision of whether or not to enter a contract and describes why the firm would choose to enter a contract. Further, how the firm meets its contract obligations is discussed. Chapter 6 finalizes this study with conclusions from the model scenarios and recommendations for further research.

Chapter 2: Background

2.1 Introduction

There is increasing concern that the Earth's climate is changing due to the rising concentration of greenhouse gases in the atmosphere. The United Nations Framework Convention on Climate Change (UNFCCC), through the Kyoto Protocol, has set forth binding targets, upon Protocol ratification, for emissions of greenhouse gases from Annex I industrialised nations. Further, the UNFCCC has recognized that the stabilization of atmospheric greenhouse gas concentrations is possible through emissions reductions as well as emissions removals. Thus, there are opportunities to reduce the rate of build-up of atmospheric carbon dioxide, a principal greenhouse gas, through land management activities; or as defined in the Protocol, Land Use, Land-Use Change, and Forestry activities that may generate emissions removals. As a result, there is significant Canadian interest in exploring how forestry and forest carbon management can contribute to Canada's strategy for meeting its Kyoto emission reduction target.

While Canada committed to specific targets for reducing emissions of greenhouse gases under the Kyoto Protocol – to 6% below 1990 levels – the means by which Canada will achieve this target is flexible, residing primarily within its own jurisdiction and not that of the Protocol. However the rules and institutions, and in some instances limits, for certain emission control strategies were and continue to be negotiated in multilateral forums and therefore may constrain or restrict the manner in which Canada attempts to meet its Kyoto obligations. For example, the maximum potential contribution or ceiling of Canada's forest carbon sinks is capped under the first Kyoto commitment period. That said, under Articles 3.3 and 3.4 of the Kyoto Protocol, Canada secured recognition of the contribution that forest sinks can make towards mitigating greenhouse gas emissions, through both Removal Units (RMUs) and tradable credits. The details and concessions regarding forest sinks arose from the sixth and seventh Conference of Parties to the Kyoto Protocol, or the "Bonn Agreement", 2001, and Marrakech Accords, 2002, respectively.

2.2 Articles 3.3 and 3.4 of the Kyoto Protocol

Articles 3.3 and 3.4 of the Kyoto protocol may be of real import for Canada. Given the size of Canada's forests, it is expected that forest management will comprise an important component of Canada's strategy under Kyoto. Article 3.3 of the UNFCCC states that policies and measures to address climate change should cover all relevant sources, sinks and reservoirs of greenhouse gases, and that forestry and agricultural sinks are included as legitimate greenhouse gas emissions management strategies in the Kyoto Protocol. This article refers to the establishment of new forests on lands not forested prior to 1990 (afforestation/reforestation[1]) and the permanent removal of forests (deforestation[2]). It should be noted here that harvesting timber constitutes a removal of carbon from forests and is deducted from the carbon stock immediately under Kyoto accounting rules. This despite the reality that much of the timber is transformed into wood products, currently

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[1] Reforestation, as defined in the Kyoto Protocol, here refers to the direct human-induced conversion of non-forested land to forested land through planting, seeding and/or the human-induced promotion of natural seed sources on land that was forested but that has been converted to non-forest land. This is limited to those lands that did not contain forest on 31 December 1989. Afforestation applies to land that has not been forested for a period of at least 50 years (UNFCCC).

[2] Each party in Annex I must report on how harvesting or forest disturbance that is followed by re-establishment of a forest is distinguished from deforestation (UNFCCC).

not recognized as sinks, whereby the carbon stored within these products is not released back into the atmosphere until some decades later. Article 3.4 states that "forest management", as characterized in the protocol, is an eligible Land Use, Land-Use Change, and Forestry activity, provided the human-induced changes have occurred since 1990 on lands defined as part of the "managed forest". At this time it is pertinent to examine more closely Article 3.4, as it is inherent in the architecture of this thesis.

According to Article 3.4 each party in the Annex I group of industrialised countries, which includes Canada, shall provide data to establish its level of carbon stocks in 1990 and enable an estimate to be made of changes to carbon stocks in subsequent years for inclusion to the first Kyoto commitment period, 2008-2012. The article further stipulates that only actions commencing on or since 1 January 1990 are eligible for consideration of credit under Articles 3.3 and 3.4, commensurate with Canada's definition of its "managed forest" for Article 3.4 activities. This area, comprising the "managed forest", must be identified by 2006.

Article 3.4 is distinguished from Article 3.3 in that the latter is concerned with afforestation, reforestation, and deforestation whereas the former accounts for all emissions by sources and removals by sinks from human-induced activities involving revegetation, forest management, cropland management, and grazing land management. Here, the phrase "*human-induced changes*" is vitally important if carbon credits are sought. Canada will be required to demonstrate that carbon sequestered, for which it seeks credit, is above and beyond that which would have been sequestered naturally and/or according to baseline for the period 2008-2012. Lastly, under definition of the protocol, revegetation is restricted to areas not defined as forests, thus in this thesis the principal concern with Article 3.4 is "forest management". As a final note, because of the time dimension involved forest managers engaged in carbon sequestration projects must be concerned with subsequent commitment periods beyond the first one.

Canada, therefore, must think strategically about what it defines as "managed forest" and establishing its 1990 baseline as both of these decisions have future ramifications for forest policy and management, given that once land is included under Articles 3.3 and 3.4 all anthropogenic greenhouse gas emissions from sources and removals by sinks on this land must be accounted for throughout subsequent and contiguous commitment periods. Furthermore, this is especially concerning for forest managers who, facing uncertain environmental conditions under climate change and the potential catastrophic risk of fire to forest carbon sinks, are ultimately responsible for forest carbon management. For example, if through the effects of fire a managed forest was to become a net source of carbon with whom will the responsibility, or cost, reside for the resulting emissions; the forest firm or the province which owns the forest? As such, forest managers are, or need be, preoccupied with questions about baseline determination, incentive and regulatory structures and their compatibility with carbon management, tenure and ownership (of carbon and credits), and due to the risk of natural disturbance, of permanence, liability and insurance (of carbon sinks). Moreover, how will a shift in focus among forest managers to include carbon management affect timber supply decisions?

2.3 *Forestry and Forest Carbon Management*

"Forest Management" may be defined as a system of practices for stewardship and use of forest land aimed at fulfilling relevant ecological (including biological diversity), economic and social functions of the forest in a sustainable manner. Thus defined, forest management is essentially "sustainable forest management" (SFM). With arising concern about climate change and the development of the Kyoto Protocol, SFM may (must) now include the management of forest carbon stocks and flows. The UNFCCC process acknowledged this very issue and subsequently the Marrakech Accords were developed over concern that forest carbon management would supersede other SFM initiatives, specifying that the implementation of forest carbon management must correspond with conserving biodiversity and the sustainable use of natural resources.

"Forest Carbon Management" (FCM)[3] may then be defined as forest-related activities regarding Land Use and Land-Use Changes included in the Kyoto Protocol under Articles 3.3 and 3.4 where verifiable, human-induced changes have enhanced or augmented the rate or amount of carbon sequestered by forests. Examples of the types of activities include: lengthened rotation age; management of mature and old-growth forests; increasing pre- and commercial thinning; tree improvement; increased fire suppression; improved logging techniques; establishing protected areas; reducing primary forest conversion; and, limiting forest incursions (i.e., roads). To the degree that these

[3] In this thesis, FCM refers specifically to forest management initiatives under Article 3.4 of the Kyoto Protocol.

changes can be confirmed and accounted for, carbon credits[4] may be earned for use and trade in Canada, possibly internationally, likely facilitated through a market (or perhaps some public agent) and/or via contracts.

Traditionally forests have not been managed for the purpose of carbon storage but rather for supplying timber and/or fibre. The concept of sustainability has entered into forest management and, to some extent, policies or programmes have been initiated pursuant to forest management practices that consider the wider array of forest values however, the explicit management of forests to sequester carbon is a recent phenomenon.

Forest carbon sequestration is being considered as a strategy for meeting Canada's Kyoto obligations because it may be a relatively inexpensive means for generating greenhouse gas emissions offsets (van Kooten et al., 1995). Purchasers of carbon credits, likely from the oil and gas or energy sectors, will often require significant investment in capital stock or rely on the development of new technologies in order to comply with potential emission reduction requirements, so in the short term at least purchasing carbon credits may be an optimal alternative to capital investment in pollution abatement or other technologies. In addition, the market potential for carbon credits is estimated to be quite significant, valued at as much as US$2.2 billion annually with a price of US$50 per tonne of carbon if Canada was to fully utilize its forest management carbon credit allocation under Article 3.4 (Pollution Probe, 2002). Depending on how the government proceeds

[4] Some clarification is necessary regarding removal units (RMUs) and tradable credits. Tradable credits will be associated with specific activities or sites, whereas this is not so for RMUs. Further, while tradable credits arising from FCM will be recognised as RMUs for accounting purposes, RMUs do not necessarily yield tradable credits.

with establishing ownership of and a market for carbon credits the revenue potential from carbon sequestration for forestry firms may provide the necessary impetus for enhanced FCM. Of interest will be to evaluate under which conditions a forest manager will be willing to enter into a carbon supply contract and alter forest management to enhance forest carbon sequestration and generate carbon credits either for trade on an open market or as part of a fixed carbon supply contract.

While stated above that it is expected forest management and FCM will figure importantly into Canada's Kyoto strategy, there remains considerable uncertainty regarding the magnitude of this role since fundamental policy questions involving the federal and provincial governments remain unresolved. Provincial politics are vital given the majority of actively managed forests in Canada reside on Crown Land and are under provincial ownership and jurisdiction. This is of tremendous consequence for forest managers and forestry firms whose direct actions, or changes thereof, will determine whether or not carbon credits are granted and Canada can achieve its Kyoto targets at relatively low cost.

2.4 Firm-Level Contract Concerns and Forest Carbon Management

While forest managers have always operated under uncertainty, the concern regarding climate change and entering into a carbon supply contract is that the potential losses incurred through fire, a major source of risk along with loss to insects, may be substantially larger than in the past; that is, not limited to strictly to timber values. Under

Articles 3.3 and 3.4 a forestry firm along with provincial governments, via fire suppression, would essentially be safeguarding investments in FCM and securing not only timber but the carbon in above and below ground carbon sinks, assuming that the firm's management area is included in Canada's "managed forest". As such, a firm's losses from fire could potentially include the foregone revenue from timber and carbon management as well as any penalties for failing to meet the terms of a contract and/or carbon stock reductions, depending on the structure of any carbon contract.

Carbon sequestered through forest carbon management activities will only be realized after some time has elapsed, and while purchasing agents or buyers of carbon credits may only require assurance that carbon sequestered will remain so until the time of delivery or longer depending on the contract arrangement, society has an interest in maintaining carbon stocks over the relatively long-term, assuming there will be real costs due to climate change. As such, the trading mechanism for buyers and sellers is likely to be a long term contract because both parties will want protection from price risk that prevails in open market trades by instead securing a long term contract price. Thus along with the risk of natural disturbance arises contractual risk; this is the risk that carbon credits agreed to in contract are not secure in perpetuity, or at least for the timeframe of the contract. Given the role of provincial governments in fire suppression and carbon management (Bill 37 in Alberta), how public policy reconciles issues of carbon ownership, baseline protection, the specific incentives available (prices and contracts), compatibility of incentives with other regulatory frameworks (AAC and etcetera.), and how risk is shared among all partners to sequestration activities (and carbon credit contracts); i.e., the structure of carbon incentives, will determine whether or not forestry firms engage in enhanced carbon sequestration activities and are capable of supplying carbon credits.

2.5 Long-Term Carbon Contract Framework

The principal advantages of a long-term carbon supply contract are certainty, assurance, and recourse for the parties involved. Certainty is provided through the creation and definition of the contract. The supplier and buyer negotiate the contract terms thereby establishing some certainty regarding the transaction and the conditions signifying completion of the transaction. Assurance and recourse also originate with establishment of the contract, specifying each party's obligations to the other as well as the options available to each party should the other contravene the terms of the contract. As such the contract must outline in detail what is the purpose of the contract, when the contract starts and terminates, and how the contract operates to achieve the stated objective or purpose. Further, the rules or codes of conduct for each party are essential, especially in the case of either party failing to comply with the contract.

The purpose of the carbon supply contract is to provide a medium of exchange for carbon credits generated by a supplier and made available to the buyer. This is assuming that the supplier has the right to transfer ownership of the carbon to the buyer (see *Carbon Ownership*). Important contract parameters that must be clarified involve the timing of the contract. This includes determining when the contract begins, its duration, delivery times, the ending period, and the issues of permanence and when the credits are available for the buyer to use (see *Contract Duration*). Further there are issues surrounding the validity of the contract carbon credits. Can the supplier verify that the credits are net surplus credits? What is the baseline used in the contract and how and when are carbon stocks and flows audited? With whom does the authority rest to ensure that the credits are real and usable (see *Contract Baseline*)? Another important concern is whether or not the contract complies with current forest management legislation and policy (see *Regulatory Compatibility*). Lastly, how is risk shared in the contract? What options are available if the supplier is unable to supply the quantity of carbon credits specified in the contract (see *Risk Management*)? Details specific to the contract formulation used in this study and the contract parameters being evaluated are described in the section *Carbon Supply Contracts* of chapter three.

2.5.1 Carbon Ownership

Before forestry firms will be able, or willing, to enter into carbon credit supply contracts, elucidation of provincial policy is fundamental on the issue of carbon ownership. One important factor in setting up a carbon incentive mechanism is ownership of the carbon. Presently there is heterogeneity in property rights structures for forestry firms operating on crown lands; there are different structures for different firms, creating additional policy complexity however, this may be less the case when the discussion is limited to firms that operate under Forest Management Agreements (FMAs). In Alberta, forestry companies holding FMAs have ownership rights to the standing timber on crown land but not the land itself, which is owned by the provincial government. Further, the ownership rights that firms do have are highly attenuated by forest harvesting regulations that restrict harvest through allowable cuts, harvest quantity flexibility, and the transferability of the rights for standing timber and of trees once harvested. In addition forest management agreements impose a number of obligations on forest firms such as regeneration standards and planning requirements. Recently however there has been some clarification of ownership rights to carbon stored in forest sinks in Alberta.

The ownership structure of forest carbon is of central importance. In order for a carbon credit trading system or market to facilitate trades or permit the establishment of carbon supply contracts the forestry firm or supplier of carbon offsets must have the right to transfer ownership of the carbon to the buyer of the carbon offset (Hauer et al., 2002). Once the transfer has taken place the supplier is obligated under the terms of carbon credit supply contract to ensure that the carbon is secure. In Alberta, recently passed was Bill 37 stipulating that carbon ownership resides with the landowner, which implyies that the province owns the carbon on crown lands. However, this statement does little to clarify what this means for firms wanting to enter carbon supply contracts. Presumably the province would want carbon trades to take place, therefore the province must outline whether any action by a forest firm to increase carbon stocks above a baseline will enable it to trigger a transfer of carbon rights to a buyer, with some resulting payment landing with the firm in exchange for the right of the buyer to reduce its carbon emission reduction targets. Depending on how the province pursues the issue this could impose additional transaction costs, possibly via a sales tax, and/or constraints on the supplying firm, perhaps reducing the feasibility of a carbon supply contract (Hauer et al., 2002).

2.5.2 Contract Duration

Should the carbon ownership issue be rectified thereby permitting a carbon credit trading system to function, how the terms of the contract are defined will affect the level of adoption of carbon supply contracts as a carbon credit trading mechanism. Of particular interest here is the treatment of time in the contract. Does the contract begin immediately or some time in the future? This could have implications for the appropriate baseline. A corresponding matter is contract delivery times. Is there is a schedule of carbon sequestration targets or a single terminal credit supply quantity? This could potentially affect the cost to the firm of meeting contract targets and thus the decision to enter a contract. Regardless there must be sufficient resources allocated and employed to verify that the credits being generated are net surplus credits. Some flexibility or adjustability could be built into contract delivery times but again monitoring carbon stock levels becomes critical. With respect to the duration of the contract a longer contract period may also provide the necessary incentive for long-term sequestration activities. Forest carbon management strategies will likely involve upfront costs but yield benefits at some time in the future and thus the duration of the contract may preclude the types of management activities that are economically viable. Also important is whether contracts will contain any terminal conditions, such as a permanence clause, and if contracts are likely to be renegotiated (Hauer et al., 2002). If the contract requires the supplying firm to ensure that the credits are secured beyond the term of the contract this exposes the firm to additional risk and increases the cost of the contract, possibly reducing the likelihood that the firm would decide to enter a contract. While forestry firms may prefer the flexibility of shorter-term carbon leases buyers will opt for contracts with a relative degree of permanence, perhaps negotiating a higher price for said services (Hauer et al., 2002). A higher price may serve as a necessary risk premium for suppliers.

2.5.3 Contract Baseline

Determination of the contract baseline is critical not only in terms of the supplier's ability to meet the contract but also for monitoring the generation of credits and enforcing the terms of the contract. Carbon credits are established via comparison to an accepted and verifiable baseline however the supplying firm, and the buyer, will have an immediate incentive to negotiate the lowest baseline[5]. While this is a strategy to minimize supplier risk, it has additional benefits to the purchasing agent because a lower baseline improves the likelihood that the supplier will not renege the contract. Too high of a baseline will result in excessive supplier risk reducing participation rates among potential suppliers or resulting in a firm's decision not to enter a contract. The trajectory of the baseline also will affect the cost of meeting the contract and hence the firm's decision. However, justification of the contract baseline may be necessary to ensure that the credits generated for the contract are recognized and can in fact be used by the purchaser. At this time it is not known whether contract parties themselves or a third party will monitor and enforce the terms of the contract. Self-reporting, while less costly, presents a real problem as either firm may have an incentive to misrepresent carbon stock and flow information. An impartial authority charged with the responsibility of auditing contracts is preferable but may be expensive and difficult to administer.

[5] Many factors will influence the time-path of carbon storage. This includes age-class structure, growth rates, natural disturbance rates, harvest rates, and other disturbances. As a result, the possible carbon stock trajectories are numerous and the determination of a baseline is not straightforward (Hauer et al., 2002).

An issue relating to both contract duration and baseline enforcement is that of when the credits are available for use by the purchaser. There is some sentiment that credits could be used upon initiation of the contract, which would create problems of moral hazard by placing long-term liability on a supplier that has already recouped the value of the contract. This is especially the case if the contract operates based on a self-reporting mechanism. Even should third party monitoring be in place there are significant transactions cost associated with enforcing and validating carbon supply contracts. In contrast, if the credits cannot be applied immediately the buyer may be unwilling to wait long periods to use the credits for which they have paid. The risk to the buyer in this case is that at the date when the credits reach maturity other carbon credits may be available at a lower price via some market or they may no longer require the credits altogether because over the interim period technological innovation has facilitated emissions reductions through less costly capital investment.

2.5.4 Regulatory Compatibility

A factor that may constrain or limit the implementation and reception of market incentives for carbon sequestration is regulatory incompatibility. As mentioned, a forestry firm's ownership rights are highly attenuated given that forest management is under substantial regulation. Regulation covers all aspects of forest activities, from access through to post-harvest operations and obligations. A specific concern is regarding harvest requirements and a potential conflict with carbon sequestration incentives. Here, any trade-off between timber and carbon may be complicated by the current regulatory regime. For example, firms are required by policy to harvest within some percentage of the calculated annual allowable cut (AAC). While this restriction could be relaxed, current regulations favour harvesting the maximum allowable amount of timber. There is no regulatory assurance for firms reducing or lengthening harvest rotation decisions in order to sequester carbon that some of their AAC will not be allocated to other firms. Hence the regulations and the incentives generated therein may make it difficult for firms to limit harvest and/or lengthen harvest rotations should this be a cost effective strategy for increasing carbon stocks. In addition, forestry firms holding FMAs often do not have control of the entire cut level on an FMA area because the province grants harvest flow rights to quota holders operating on the same land base. Hence the forest firm that manages the land-base may have little flexibility for following a lower harvest rate or longer harvest rotation strategy under the current regulatory structure. By default, if harvest regulations are not compatible with carbon incentives the only available strategies or activities to enhance forest carbon sequestration are silviculture and fire suppression (Hauer et al., 2002).

2.5.5 Risk Management

For a carbon sequestration incentive mechanism to be effective there must be credits and debits for respective increases and decreases in carbon stocks, measured against a baseline, otherwise perverse incentives may result. As such, forestry firms must be concerned with risk management in instances when carbon credits are lost or debits are incurred. Given that there are risks of carbon stock losses from fire any credit taken today is therefore also a future liability. Thus, the magnitude of risk the firm faces depends on what its obligations are for failing to sequester the contracted amount of carbon above the baseline and for the amount that carbon stocks are reduced below the established baseline, if such occurs. Sedjo (2001) rightly asks whether in the case of unplanned carbon losses will the forest owner (provincial government) or forestry firm be required to recompense the purchaser of the carbon offset or credit, or does the purchaser bear the liability risk and thus go uncompensated? How this risk is shared will generate particular incentives for the credit-supplying firm. Clearly, the firm accepts additional risk if there are penalties for carbon stock reductions below an established baseline. The uncertainty of future fire conditions, in terms of frequency, magnitude and severity, further exacerbates firm-level risk. Hence, the risk is partly defined by the details of the carbon supply contract regarding the extent of penalties for carbon stock losses or for failing to meet the terms of the contract.

An option that may be available to the credit supplier to manage risk is the ability to purchase replacement carbon credits when it cannot meet the contract supply targets. It is conceivable that the firm under contract to supply a specific quantity of credits could acquire these credits from external sources however there is no guarantee that the price per replacement carbon credit is the same as the contract price per carbon credit. If the price of replacement credits is expected to be high and the risk of failing to meet the contract is also expected to be high then the firm may be less willing to enter into a contract. Conversely, there may be replacement credits available at a lower price. Alternatively, if the supplier cannot meet its supply obligations this may trigger monetary penalties that would compensate the buyer for not receiving the full amount of credits agreed to in the contract.

When a forestry firm enters into a carbon credit supply contract a key term to be negotiated is the contract price per carbon credit. From the supplier's perspective there is price risk that the market price for carbon will be higher in the future and would result in foregone revenues or that the negotiated price will not cover future costs, including the cost of replacement credits if this option is available. Thus a risk neutral firm would enter into a contract and negotiate a price whereby expectations of the future and the expected revenue stream at the contract price is greater than the expected revenue from the market. A risk averse firm would also be concerned with the variability of the price of carbon.

Aside from this, the principal risk to a supplier is that carbon stocks will decline below baseline levels, thereby resulting in net carbon debits and any ensuing cost and/or penalties. Assuming the major risk facing forest carbon stocks is from fire, a firm then has several options to manage risk and secure carbon. These include 1) fire suppression, 2) silviculture, and 3) reducing harvest levels and lengthening rotations, if a flexible regulatory regime is present. Finally, some form of insurance mechanism or risk-sharing arrangement could be established. Note, however, that in any case it will be necessary for the firm to demonstrate that its actions or combinations thereof are beyond business-as-usual levels. A further issue, beyond the terms of contract and more likely to be decided at the provincial policy level, is the inclusion or omission of firm responsibility for fire suppression along with some penalty mechanism (moral hazard problem). However this issue is dealt with another level of complexity is added to the optimization decision and new incentives, perhaps perverse ones, may result.

Whether a forestry firm accepts a contract will depend largely on its perceived ability to manage or minimize the risks of carbon sequestration. An initial strategy for risk management is when negotiating the terms of contract. Rationally a firm should argue for as much flexibility as possible in order to protect its position. This means obtaining the lowest baseline, highest carbon price, flexible terminal conditions, and omission of fire risk. While the first three points have been discussed, it could be expected that firms will argue for the omission of fire risk. However, this issue is likely beyond contract negotiations and resides instead with the authority of the provincial or federal governments. Of course the relative costs and benefits of fire suppression, silviculture, and/or reducing harvest levels or lengthening rotation ages will factor significantly into a firm's decision.

Additional risk management will involve insuring against failure to meet the carbon supply requirements of the contract, should the firm bear the risk of carbon stock decline for permanent storage type contracts. This may be achieved through either self-insurance or purchasing insurance from an external insurance agency or provider, which could be the provincial government. For example, self-insurance may be via an internal insurance fund or through including only some proportion of the total number of carbon credits sequestered in a contract, thereby producing insurance credits through a buffer stock. In the former case funds could be used to purchase credits on the open market whereas in the latter the insurance credits would be used as deemed necessary.

The ability to pursue these approaches however will likely be regulated to some extent by the provincial government, which in turn may be constrained by negotiations undertaken by the federal government at the international level. Of particular concern would be a firm's ability to omit fire risk from a contract, potentially resulting in perverse incentives. If firms are not held responsible for protecting carbon stocks against fire risk then a moral hazard problem is manifest. Under this scenario fire suppression effort may be too low and the benefits of increased or enhanced fire suppression will not be realized (Hauer et al., 2002). However carbon losses could potentially be offset by the ecological benefits of fire, whereby any penalties incurred due to carbon losses from fire could be adjusted downward to account for the aforementioned benefits. Essentially, the moral hazard problem associated with fire protection is complicated by the idea that there may be some value to maintaining natural disturbance regimes. This is another issue for which the provincial government will be required to provide clarity and policy justification.

2.6 Saskatchewan Forest Carbon Sequestration Project

Since the adoption of the Kyoto Protocol there has been growing interest in the roles of forest carbon sequestration and carbon credit trading mechanisms or carbon contracts as means for stabilizing atmospheric greenhouse gas concentrations in a cost effective manner. In 2002 a carbon trading pilot project in Saskatchewan involving Saskatchewan Environment and the Saskatchewan Power Corporation became the first carbon sequestration project reviewed and approved in Canada under the Greenhouse Gas Emission Trading (GERT) Pilot (Lemprière et al., 2002). Under this initiative Saskatchewan Environment will generate real, measurable, verifiable and surplus net carbon sequestration via establishment of white spruce plantations on 3 300 ha on lands designated "not sufficiently restocked" and from forest protection through the creation of 206 000 ha of Forest Carbon Reserves – part of the province's system of protected areas. A fifty-year contract (2000-2050) has been initiated during which the Saskatchewan Power Corporation, in order to offset emissions, will purchase net carbon sequestration from Saskatchewan Environment.

While this project involves two Crown Corporations in the province of Saskatchewan, a wider role for forestry and forest carbon management and carbon trading was envisaged when Canada negotiated the recognition of forests as carbon sinks throughout the UNFCCC process. Specifically of interest is that the Saskatchewan forest carbon sequestration project intends for carbon credits to be generated through forest carbon management. What will remain to be seen is whether or not private firms responsible for managing regulated forests will want to enter into a carbon credit supply market and what quantities of carbon these firms could potentially supply at given market or contract prices. Furthermore, how, if at all, will governments enable the necessary conditions for forest carbon management, recognizing that the regulatory environment could figure prominently in a firm's ability to enhance carbon sequestration within its management area? Will similar contract projects be initiated that include private firms as part of Canada's Kyoto strategy?

Chapter 3: Theory

3.1 Introduction

Forest management scheduling models are used extensively in forest management and across a broad spectrum of academic research, but as Boychuk and Martell (1996) indicate, few studies explicitly consider the effects of fire and/or other uncertain losses to standing forests, which can be significant. Risk and uncertainty are inherent to forest management and planning, given complex, ever-changing environments – economic, regulatory, and ecological – and forest management models are utilized to provide information and assist in decision-making. Despite the uncertainty that characterizes forestry, most planning models are deterministic and therefore may provide incomplete or inaccurate information, perhaps compromising the quality of decision-making. Furthermore, with the introduction of a carbon contract the firm faces additional risk. In the absence of a carbon supply contract fire disturbance could potentially inflict large losses to the firm via lost timber value, however once a firm is engaged in carbon credit supply there is the added risk that fire poses to carbon stocks and hence the firm's ability to meet the contract supply target, resulting in further losses to the firm (the cost of acquiring replacement credits). Thus, in examining carbon supply contracts and the firm's decision to enter into these contracts it is important to move beyond conventional forest planning models and integrate stochastic processes to arrive at a model better suited to evaluate optimal decision-making with respect to carbon contracts and the risk of natural disturbance.

The inclusion of carbon sequestration as a management objective has significant implications for how a forest is managed. Including carbon as part of the management objective or focus can effect species selection, rotation age, reforestation strategies, preferred harvesting systems, forest protection strategies and intensive management strategies. As such, there is significant additional information and/or data required for such models. Also, the merger of a forest management scheduling model with a carbon budget model, necessary to account for changes in carbon stocks over time, are essential for examining the structure of carbon supply contracts, and has seldom been completed.

3.2 Optimal Forest Rotation Models and Carbon Budgets

In the economic literature the method of determining harvesting schedules and forest rotation ages are based on the work of Faustmann – the *Faustmann model*. The Faustmann model assumes that the highest and best use for a plot of land is in growing forests for timber and then proceeds to maximize the net present value (NPV) of a stream of harvested trees on the land (Englin and Callaway, 1993). In practice however, forests often have multiple values, including ecological (carbon sequestration), recreation, and aesthetic or other non-use values, in addition to standard timber values. This spurred the development of what is termed the *Hartman model*, after Hartman (1976), where a standing forest has value. Since the traditional Faustmann model fails to provide a harvesting schedule that accounts for both the benefits of carbon sequestration and/or supply and timber supply there may exist a superior method of calculating a more desirable optimal harvest schedule/rotation.

Englin and Callaway (1993) adapted the Hartman model to carbon by deriving a complex equation to incorporate the carbon sequestered through tree/stand/forest growth, an adjustment for the carbon sequestered at the time of harvest, and the sequestered carbon that will be released into the atmosphere post-harvest. This equation is then used to determine the optimal social rotation of the forest, which is expected to be different from the traditional Faustmann rotation assuming that the carbon has a positive value, because it considers the value of both the carbon sequestered and that of timber. In comparison the Faustmann rotation includes only the values derived directly from timber. Plantinga and Birdsey (1994) state that the optimal social rotation will always be longer than the optimal private rotation; that the inclusion of carbon values in calculating the optimal rotation age will mean the optimal age is longer than the Faustmann age. Englin and Callaway (1993) also suggest that the rotation age increases under higher discount rates because one wishes to delay the costs accrued as a result of increased global warming associated with delaying timber products.

The method for integrating the value of carbon into the optimal decision-making framework in the present study is via a carbon supply contract. Here the carbon attains value, a per unit price, because a transaction between a supplier and a buyer for a specified amount at a particular price and time has been arranged. The nature of the carbon contract is of central importance because different incentives will result, and hence different timber and carbon values accruing to the firm, depending on the conditions of the contract. To review, contract conditions may include such relevant components as; baseline, duration, delivery times, carbon price, responsibility for fire, and so on, as outlined in chapter two. Thus the optimal rotation age may be affected by the introduction of a carbon supply contract because the objective of forest management is no longer only to maximize the NPV of timber but rather the NPV of timber and the carbon contract. Moreover, it should be noted that given the stochastic processes integrated within the model used herein, the objective is to maximize the *expected* NPV of timber and the carbon contract.

Determining the optimal rotation for a stand or forest requires information about production and management costs and rates of discount, biological and natural disturbance data, and when considering carbon as part of the management regime, forest carbon dynamics. Merging carbon sequestration and a carbon supply contract within the determination of the optimal rotation age requires additional information such as; price of carbon and other contract details, amount of carbon per unit volume of tree biomass, amount of carbon lost during and after harvest, the amount of carbon "stored" in wood products[6], and the amount of carbon in landfills (Englin and Callaway, 1993; van Kooten, 1995). Rotation decisions are significantly affected by long term carbon storage in wood products and therefore lifecycle analysis of forest products should be included in the analysis of optimal rotation (Hauer et al., 2001) because rotation ages affect both the amount of carbon stored in stands and the amount of carbon stored in the soil. According to Hauer et al. (2001) most rotation studies including carbon have concluded that the inclusion of carbon sequestration in the objective function lengthens the harvest rotation,

[6] Note that at present the Kyoto Protocol does not recognize wood products as carbon sinks, therefore the model formulation employed in this thesis does not include wood products as potential carbon pools.

however it should be noted that these studies failed to include the risk of natural disturbances.

3.3 Optimal Forest Rotation Models and Fire Disturbance

There are several thorough reviews of the literature relevant to the model developed in this thesis. Martell (1982) reviewed studies that examined the impact of fire on forest management. Research concerning the impact of fire and other disturbances on stand growth, timber yield, and forest management planning has been reviewed by MacLean (1990). Brumelle et al. (1990) examined and classified risks and methods of dealing with risks associated with forest management decision-making. Finally, Hof (1993) discusses the theoretical background, along with alternative model formulations, for modeling risk in forest management and planning models. Further to these reviews, the research by Reed and Errico (1986, 1989), Martell (1994), and Boychuk and Martell (1996) figure prominently in the model development process of this thesis. These studies involve optimal harvest decisions or harvest scheduling in the presence of fire risk. Mention should also be made here of the work by Maynes (2003), specifically with regard to the carbon budget component of the model as well as for appropriate yield curve data.

Four classes of timber management models are widely used in forest economics research; stand-level optimal rotation (age control), forest-level regulation (area control), forest-level simulation (volume control), and forest level optimization (Boychuk and Martell, 1996). Given that this study makes use of data at the forest level and because of the specific questions under consideration the class of models under forest-level optimization are of immediate relevance, and more specifically the research by Reed and Errico (1986) and Boychuk and Martell (1996). The research by both of these pairs of authors deals with forest-level optimal rotation models under risk of fire, thereby contributing to the model formulation used in the present study. However, this study is distinguishable from previous research, firstly, by incorporating stochastic rather than deterministic programming of fire disturbance, like Boychuk and Martell (1996). Secondly, through the use of carbon accounting equations the model formulation is capable of showing how carbon stocks change in response to optimal forest rotation decisions and demonstrates that, in response to some stimulus, a firm can modify how it is managing the forest in order to increase the amount of carbon sequestered in forest carbon sinks. A third advantage of this study is that it employs actual forest-level data rather than a hypothetical forest as in Boychuk and Martell (1996).

An important contribution by Reed and Errico (1986) concerns their treatment of fire loss in the forest-level linear model they had developed. In this model the expected burned area is subtracted from each age class in each time period and subsequently added along with the cutover area to the youngest age class in the following period. This formulation determines the dynamic structure of these forest-level optimization models, allowing for proper stand-level dynamics to be incorporated within the model structure. Although Reed and Errico described their model as stochastic, in fact they solved its equivalent mean-value problem, whereby the random proportion of area burned was replaced by its expected value. While in some cases the mean-value problem may be a fair approximation of the stochastic problem, under certain circumstances it can consistently prescribe harvest levels that are too high (Boychuk and Martell, 1996). A major result of this research was to demonstrate that planning in the presence of fire loss results in lower harvest volumes throughout the planning horizon when compared to the case without fire loss. What remains essential about this paper is the network representation of stand-level dynamics, of which Boychuk and Martell (1996) make use, extend, and provide a thorough discussion.

A major improvement upon the network representation of Reed and Errico (1986) by Boychuk and Martell (1996) was to broaden the number of strategies in preparing for and responding to stochastic fire losses. In the more simple timber management model of Reed and Errico (1986) only the decision of how much to harvest is available to the decision-maker. In contrast, under the enhanced network model formulated by Boychuk and Martell (1996) the possible strategies for managing loss to fire include various regeneration prescriptions, stand enhancement strategies to increase future yield, and rehabilitation of not-sufficiently restocked land. Incorporating a multitude of risk management options is possible through appropriate dynamic equations that can be visualized as corresponding area balance networks (see Figures 2 to 5 in Boychuk and Martell, 1996). Furthermore, in this manner a forest-level optimization model can be developed to accommodate multiple cover types, species, and regeneration types, land classes, and so forth. The model used by Boychuk and Martell (1996), and the one instituted here, falls into the Model III category of timber management models. A result, however, of these enhanced models, which characterize a wider array of management options and decision variables, is that model size and complexity can increase rapidly, which is further complicated by the inclusion of a stochastic representation of fire disturbance. Also, in a stochastic programming problem the worst case scenario, even if this state of nature occurs with a very small probability, can drive the model solution because if an optimal solution exists it must be feasible for every possible state of nature, which here includes each sequence of fire loss.

3.4 Carbon Supply Contracts – Carbon Contract Synopsis

In addition to developing a stochastic forest optimal rotation model an objective of this study is to incorporate a carbon supply contract within the model linear program. The structure of a carbon supply contract could potentially take on a number of forms however, but there are some contract parameters or components that are necessary regardless of the contract formulation and how these parameters are treated will define, in part, the contract. A single contract structure was utilized for this study but alternate formulations are possible and may be accommodated within the model program. Moreover there are a number of contractual issues that are not examined in this study (refer to the discussion *Long-term Carbon Contract* in Chapter 2).

A major issue for establishing carbon supply contracts is the determination of an appropriate carbon stock baseline necessary for verifying that supplier actions have produced real, net carbon credits. Maynes (2003) explored different baseline trajectories on carbon credit generation. Whether the baseline is downward sloping, horizontal, or upward sloping could be of significant consequence if a firm supplying carbon credits is affected by consecutive and/or large fire events. The carbon stock baseline used in this study is downward sloping and was determined from a baseline or business-as-usual model run. More detail is provided in the section *Baseline Results* of chapter four.

Corresponding matters are contract duration, delivery times and targets. The duration of a contract is related to how and when the contract is assessed vis-à-vis the baseline and also to the question of credit permanence. In the present study carbon stocks are verified in each decade of the contract; there is a schedule of carbon sequestration targets, and it is assumed that both parties to the contract walk away upon culmination of the contract (see section *Model Assumptions* of chapter four). Various alternative treatments of contract duration could be envisaged, whereby the verification process and the permanence issue could be modeled differently. Some flexibility and/or adjustability could be built into contract targets and delivery times, but this was not the case in the present study.

The responsibility a firm has for fire-related carbon losses is relative to a contract baseline and the contract amount or quantity. As part of the contract structure a firm could be responsible for replacing carbon credits if those generated fall short of the target, and depending on the degree of responsibility additionally this could require that a firm replace all credits including those when the carbon stock declines below the baseline. Suppose in period t a credit supplier's baseline is x tonnes of carbon and they have been contracted to supply $x+100$ tonnes of carbon. Further suppose that in period t the actual carbon stock is $x-20$ tonnes of carbon. Given how the carbon contract is written in this study, the firm would be responsible for replacing the 100 tonnes of carbon that it had been contracted to supply and the 20 tonnes of carbon lost below the baseline.

An alternative arrangement could have the firm be held responsible for a subset of this amount.

Contracts may also vary in the treatment of replacement credits. Conceivably the firm under contract to supply a specific quantity of credits would have to acquire these credits from external sources. While in this study it is assumed that the price per replacement carbon credit is the same as the contract price per carbon credit this need not be the case. It is possible that a penalty could be attached to the price of replacement credits. If this penalty were high enough it could influence the firm's decision of when and how much to harvest, as well as those concerning regeneration strategies and stand management. More importantly this may negatively affect the firm's decision to enter into a contract. If the price of replacement credits is expected to be high and the risk of failing to meet the contract is also expected to be high then the firm may be less willing to enter into a contract. Alternatively, the price of replacement credits may exceed the contract carbon price because at the time of purchase any available replacement credits may simply cost more than the original contract price. Conversely, there may be replacement credits available at a lower price. Furthermore a contract could stipulate that only some proportion of the contract carbon credit supply may be met by purchasing replacement credits or restrict this to a certain amount. No such restriction was instituted in the present study.

What is both interesting and valuable about this model and the particular contract formulation is that the carbon delivery times and quantities are fixed in the contract arrangement while the actual realized carbon stock fluctuates because of stochastic fire events. Thus, carbon stocks could be either above or below the baseline specified in the contract and above or below the contract target carbon stock levels. Real risk management questions can be addressed here because credits are not earned for quantities of carbon sequestered above contract targets and failure to meet these targets is penalized depending on the extent of the shortfall. These possibilities are contingent not only on forest management decisions but fire behaviour as well. Therefore, built into the decision making criterion are questions such as; should the firm attempt to get as close to the contract target as possible or to sequester even more carbon above the target level, creating a buffer against fire loss in subsequent periods? This strategy could be a form of self-insurance. Risk management strategies then can be interpreted from optimal model solutions.

3.5 Decision Criterion

When and under which contract conditions is it *expected* that the firm will decide to enter a carbon supply contract? This is the pivotal question in the present study. To determine for which contract scenarios the firm is willing to enter a contract is key, then one can assess how those contracts perform regarding the number of carbon credits generated and how reliant the firm would be on purchasing replacement credits in order to meet the contract supply target. Essentially, for each contract scenario evaluating whether or not the firm would choose to enter a contract requires comparison of a pair of objective values; the expected present value of timber under the baseline scenario when the forest is managed solely for timber with the expected present value of timber and the carbon contract for each contract scenario. This decision criterion is thus from an expected value perspective. For each contract scenario differentiated, in part, by the set of contract parameters {price of carbon, contract size, AAC regulation level}, does the expected present value of timber and the carbon contract exceed the expected present value of timber in the baseline case? If so, the firm would choose to enter the contract. If not, the firm is better off under the business-as-usual case and would not enter the contract.

As such, for each combination of contract size and AAC regulation level the break-even-price can be determined. The break-even-price is the carbon price at which the expected present value of timber and the carbon contract is equal to the expected present value of timber under the baseline scenario. Subsequently, the effect of changing either the contract size or the AAC regulation level on the break-even-price, and thus the decision to enter a contract, can be evaluated. An interesting issue, however, arises when more flexible AAC regulations are introduced.

The contract baseline is determined from a business-as-usual case that has a particular set of AAC regulations, but as more flexible AAC regulations are permitted should the contract baseline be adjusted accordingly? Likewise, should the decision criterion follow suit? To explain, under the business-as-usual case if more flexible AAC regulations were introduced this would allow the firm to increase harvest volumes, thereby reducing the total forest carbon stock which is used to calculate the contract baseline. It would be in the firm's interest to have a lower baseline. This would also result in a higher expected present value of timber, implying that for any contract scenario the objective value would need to be higher in order for the firm to decide to enter the contract, possibly driving the break-even-price up and reducing the likelihood that a firm would enter a contract.

What is problematic about this situation is that the contract baseline, rather than being determined by the business-as-usual case, now becomes a function of the contract. Obviously this would be a serious impediment for any attempt to both benchmark and audit forest carbon sequestration projects. Further, a firm may decide to enter a contract not to supply carbon credits but instead to gain access to more flexible AAC regulations. In this case, it is possible that a firm could enter into a contract, regulated by more flexible AAC rules, to increase timber value and rely upon replacement credits to meet the contract target. The firm would decide to enter a contract whereby the increase in timber value exceeds the cost of replacement credits such that the expected present value of timber and the carbon contract is higher than the expected present value of timber in the baseline case. Essentially the contract would serve as a means for the firm to change its regulatory environment rather than a mechanism or instrument for forest carbon sequestration.

For this study the decision criterion will compare the expected present value of timber and the carbon contract under each contract scenario with the expected present value of timber for the baseline scenario. Regardless of whether the AAC regulations have been relaxed it is important to have a consistent basis for comparison, not just in terms of the monetary benefits of the contract to the firm but also for carbon stock levels. As such, for any contract scenario whereby the expected present value of timber and the carbon contract is greater than the expected present value of timber in the baseline scenario the firm would enter the contract. Equivalently, the firm will enter into a contract when the expected net present value of the contract exceeds the expected net present value of the opportunity cost of foregone timber values.

Note there are parameters in this model, which, if manipulated could also affect the firm's decision of whether or not to enter into a carbon supply contract (refer to the previous section *Carbon Supply Contracts).* In the present study there are a number of parameters held constant which through subsequent research could be varied to examine their effects on the firm's decision to enter a contract. These include replacement credit pricing and availability, contract duration and credit permanence, the timing of delivery periods, alternate baselines and target levels, the level of responsibility for carbon stock losses to fire, supplier level of risk aversion, and so on.

Chapter 4: Model Formulation

4.1 Introduction

In order to examine carbon contracts under various contractual arrangements from the perspective of a carbon credit supplying firm, it is necessary to design a model that characterizes the problem in such a way as to include stochastic fire risk and carbon pool stocks and flows at the forest level, and which also would permit one to easily vary the price of carbon, AAC regulation levels and the carbon contract quantity, holding the remaining contract parameters constant. The model, while stochastic, is in discrete time and is a finite horizon constrained optimization problem. Moreover, the model formulation is dynamic and involves sequential or multistage decision-making. Finally the decision maker has perfect knowledge of the past and present and the model objective function and constraints are linear. Thus, risk neutrality is assumed.

The optimization technique used is a discrete stochastic sequential programming method and the model objective is to maximize the expected net present value of timber in the baseline case and that of timber and the carbon contract for all other model scenarios. Discrete stochastic programming originates with Dantzig (1955) and Cocks (1968), and early applications of this method for solving mathematical programming problems were in agricultural economics (Rae 1971). However because of the dimensionality issue; model size increases exponentially with the number of decision stages, wider adoption of this type of programming has been limited (Blanco-Fonseca and Flichman, 2002). Additional problems concern data availability and handling. Thorough reviews of discrete stochastic programming are by Apland and Kaiser (1984) and Apland and Hauer (1993). In a discrete stochastic sequential problem time is discrete, the model contains knowledge of the future in terms of states of nature and probabilities, and a sequential decision process is involved whereby information available to the model is introduced in steps. State and control variables are defined as activities while the transition equations are defined as multi-period constraints that link decision stages together. Lastly, unlike dynamic programming methods, which solve problems recursively through backward induction, mathematical programming consists of solving all of the model equations simultaneously using an appropriate algorithm.

4.2 Model Description

Description of the model objective function and constraints, as well as indexes, parameters and variables follows. For the *Baseline Model*, in addition to the objective function there are (4) forest dynamics constraints, (6) market and capacity constraints, (4) harvest regulation constraints, (3) forest accounting equations, and (7) non-negativity constraints. In the *Contract Model* an augmented objective function, equation (2), is used in conjunction with all of the previous constraints and (7) carbon contract equations are added to the model formulation.

Objective Function – The Baseline Model:

$$\textbf{MAX} \sum_{e}\sum_{d''}\Bigg[\pi_{ed''} *$$

$$\left[\sum_{p}\sum_{d}\left[\sum_{w}\sum_{s}\sum_{l} VoD_{wslpd} * \left(P_{lp}^{rw} - C_{sl}^{t}\right) * \beta_p\right]\right.$$

$$+\left[\sum_{l^0}\sum_{l'}\sum_{q'} It_{l^0 l' pd} * \left(P_{l'q'p}^{ip} - C_{l^0 l'}^{tsp}\right) * \beta_p\right]$$

$$-\left[\sum_{h}\sum_{c}\sum_{s}\sum_{m'} H_{hscpd}^{m'} * \left(\sum_{w} V_{hw}\right) * C_{hsp}^{h} * \beta_p\right]$$

$$-\left[\sum_{h}\sum_{c}\sum_{s}\sum_{m'} H_{hscpd}^{m'} * C_{jksm''}^{r} * \beta_p\right]$$

$$\left.+\left[\sum_{h}\sum_{c}\sum_{s}\sum_{e} E_{hsc} * X_{hcsed''} * \beta_p\right]\right]\Bigg] = \text{EXPVTimber} \qquad (1)$$

Objective Function – The Carbon Contract Model:

$$\mathbf{MAX} \sum_{e}\sum_{d''}\Bigg[\pi_{ed''} *$$

$$\left[\sum_{p}\sum_{d}\left[\sum_{w}\sum_{s}\sum_{l} VoD_{wslpd} * \left(P_{lp}^{rw} - C_{sl}^{t}\right) * \beta_p\right]\right.$$

$$+\left[\sum_{l^0}\sum_{l'}\sum_{q'} It_{l^0 l' pd} * \left(P_{l'q'p}^{ip} - C_{l^0 l'}^{tsp}\right) * \beta_p\right]$$

$$-\left[\sum_{h}\sum_{c}\sum_{s}\sum_{m'} H_{hscpd}^{m'} * \left(\sum_{w} V_{hw}\right) * C_{hsp}^{h} * \beta_p\right]$$

$$-\left[\sum_{h}\sum_{c}\sum_{s}\sum_{m'} H_{hscpd}^{m'} * C_{jksm''}^{r} * \beta_p\right]$$

$$\left.+\left[\sum_{h}\sum_{c}\sum_{s}\sum_{e} E_{hsc} * X_{hcsed''} * \beta_p\right]\right]\Bigg]$$

$$+\left[CV - \left[\sum_{e}\sum_{d''} NPVCr_{d''}^{r} * \pi_{ed''}\right]\right] = \text{EXPVTCcon} \qquad (2)$$

where $CV = \left(\tau_{v'}^{i} * P_{v'}^{cc} * \beta_{v'}\right)$

subject to

Forest Dynamics Constraints:

$$X_{hcs't-1"I'} = AC_{hcs} \quad (3)$$

$$X_{h'scp+1d'} = X_{hscpd} * (1 - \delta_{hpd'})) - \sum_{m'} H^{m'}_{h'scp+1d'} \quad (4)$$

$$X_{h^c scp1d} = \sum_m \sum_a \sum_c H^{m'}_{hscp1d} * \alpha^{m'c}_{hc} \quad (5)$$

$$X_{h^f scpd'} = \sum_m \sum_a \sum_c X_{hscp-1d} * \alpha^{mc}_{m^0 jkac} * \delta_{hp-1d'} \quad (6)$$

Market and Capacity Constraints:

$$Vo_{wsp2d} = \sum_h \sum_c \sum_{m'} H^{m'}_{hscp2d} * V_{hw} \quad (7)$$

$$\sum_l VoD_{lwsp2d} \le Vo_{wsp2d} \quad (8)$$

$$I_{l^0 p2d} \le \sum_w \sum_s VoD_{l^0 wsp2d} * \eta_{l^0 q'} \quad (9)$$

$$\sum_{l'} It_{l^0 l' p2d} \le I_{l^0 p2d} \quad (10)$$

$$TVoD_{lp2d} = \sum_w \sum_s VoD_{lwsp2d} + \sum_{l^0} It_{l^0 lp2d} \quad (11)$$

$$\sum_w TVoD_{lp2d} \le M_l \quad (12)$$

Harvest Regulation Constraints:

$$AAC_{j^*p+1d'} = \sum_h \sum_s \sum_c \sum_w X_{hcspd} * (1-\delta_{hpd'}) * V_{h'w} / BR_{mjkw} + \sum_h \sum_s \sum_c \sum_w X_{hcspd} * (1-\delta_{hpd'}) * AI_{h'w} \quad (13)$$

$$AACV_{j^*pd} = \sum_h \sum_s \sum_c \sum_w \sum_{m'} H_{hcspd}^{m'} * V_{hw} \quad (14)$$

$$AACV_{j^*p2d} \leq \lambda^u * AAC_{j^*p2d} * PL \quad (15)$$

$$AACV_{j^*p2d} \geq \lambda^l * AAC_{j^*p2d} * PL \quad (16)$$

Forest Carbon Accounting Equations:

$$FC_{zp+1d'} = \sum_h \sum_s \sum_c X_{hcspd} * \gamma_{h'cz} + \sum_j \sum_k \sum_s \sum_{c'} X_{h^f sc'p+1d'} * \gamma_{h^f c'z} \quad (17)$$

$$TFC_{pd'} = \sum_z FC_{zpd'} \quad (18)$$

$$\Delta TFC_{zpd}^{p+1d'} = FC_{zp+1d'} - FC_{zpd} \quad (19)$$

Carbon Contract Equations – omitted from the Baseline Model:

$$Cr_{v'd}^a \leq \sum_z FC_{zv'd} * \iota_z - \tau_{v'}^b \quad (20)$$

$$Cr_{v'd}^a \leq \tau_{v'}^c \quad (21)$$

$$Cr_{v+1d'}^i \leq Cr_{v+1d'}^a - Cr_{vd}^a \quad (22)$$

$$Cr_{v'd}^r \geq \tau_{v'}^i - Cr_{v'd}^i \quad (23)$$

$$Cr_{v'd}^r \leq \tau_{v'}^i \quad (24)$$

$$Cr_{v+1d'}^{ar} \leq Cr_{vd}^{ar} + Cr_{v+1d'}^r \quad (25)$$

$$NPVCr^{r}_{d''} \geq \sum_{v'} \sum_{d} Cr^{r}_{v'd} * P^{rc}_{v'} * \beta_{v'} \quad (26)$$

Non-Negativity Constraints:

$$X_{hcspd} \geq 0 \quad (27)$$

$$H^{m'}_{hcspd} \geq 0 \quad (28)$$

$$Vo_{wsp2d} \geq 0 \quad (29)$$

$$VoD_{lwspd} \geq 0 \quad (30)$$

$$I_{lpd} \geq 0 \quad (31)$$

$$It_{l^0 lpd} \geq 0 \quad (32)$$

$$TVoD_{lpd} \geq 0 \quad (33)$$

Definition of indexes:

j	An index over yield groups: mixed conifer (MC), pine (PI), black spruce (SB), aspen (AW), other hardwood (OH)
*j**	Species grouping for annual allowable cut calculations: {ACSW, ACHW}
k	Site classes: good (G), medium (M), fair (F)
m	Management regime: FIRE, LOW, REGEN, INTENSIVE
m^0	Previous management types: FIRE
m'	Future management types: REGEN, LOW, INTENSIVE
a	Stand age: {0…350}
h	An index over yield groups *j*, site classes *k*, management regime *m*, and stand age *a*
h'	An index over yield groups *j*, site classes *k*, management regime *m*, and stand age $a+1$

h^c	An index over yield groups j, site classes k, management regime m', and age class zero – cutover effect
h^f	An index over yield groups j, site classes k, management regime m^0, and age class zero – fire effect
s	Supply locations: north (N), south (S)
w	Index over two types of wood: softwood (SW), hardwood (HW)
l	Market locations: DemSWplp,DemSWsaw, DemSWSawO, DemHWOut, DemSWplpO
$l^0(l)$	Markets supplying chips: {DemSWSaw, DemSWSawO}
$l'(l)$	Markets demanding chips: {DemSWplp, DemSWplpO}
t=1,...,T	Time periods: {T-1...T20}
$p(t)$	Planning periods: {T-1...T7}
$p1(t)$	Planning periods minus the first period: {T0...T7}
$p2(p)$	Planning periods minus the first period: {T0...T7}
$p3(p)$	Planning periods T5 through T7: {T5, T6, T7}
v	Planning periods for carbon increment verification including the initial contract period: {T0...T7}
v'	Planning periods for carbon increment verification excluding the initial contract period: {T1...T7}
$e(p)$	Ending period of the planning horizon: {T7}
$e'(t)$	Periods beyond the planning horizon for ending inventory valuation: {T7...T20}
$e''(t)$	Last period: {T20}
q	Products including bi-products: Pulpwood, Construction lumber, other lumber, woodchips, bioenergy, waste, emissions
q'	Intermediate products: woodchips
z	Carbon source pools: SOIL, MERCHC, BELOW, ABOVE
c	Carbon classes: 0, 1, 2, 3
c'	Carbon classes: 1, 2, 3
d	Disturbance states or states of nature: {I, IN, INL, INS,..., INLLLLL,..., INSSSSS}
$d'(d)$	Subset of disturbance states: {IN, INL, INS,..., INLLLLL,..., INSSSSS}
$d''(d)$	Disturbance states for period T7: {INLLLLL,..., INSSSSS}

Definition of Parameters:

PL	Period length – ten years
AC_{hsc}	Initial age-class distribution (ha) at location s for yield group j, site class k, management type m, age a, and carbon class c
$\delta_{hpd'}$	Disturbance rates (%) for management type m, yield group j, site class k, by age k in period p for state of nature d'
π_{pd}	Probability of a state of a nature d in period p
$\alpha_{hc}^{m'c}$	Alpha transfers proportion of area (ha) of yield group j, site class k by age a for management type m and carbon class c to c for management type m'
V_{hw}	Volume of merchantable timber (m^3/ha) by management type m, yield group j, wood type w, site class k, by age a
η_{lq}	Wood to product flows per m^3 at market l by product type q
BR_{ljkw}	Biological rotation age by management type m, yield group j, wood type w, and site class k
AI_{hw}	Annual increment by management type m, yield group j, wood type w, site class k, for age a
λ^u	Upper bound on annual allowable cut
λ^l	Lower bound on annual allowable cut
γ_{hzc}	Amount of carbon (tonnes/ha) by carbon pool z for management type m, yield group j, site class k, carbon class c, for age a
P_t^{rc}	Penalty or replacement price of carbon at time t
P_p^{cc}	Contract price of carbon in period p
τ_p^b	Contract carbon baseline in period p
τ_p^c	Contract cumulative carbon target in period p
τ_v^i	Contract incremental carbon target for verification periods v
ι_z	Carbon pools z included in carbon contract
β_p	Discount rate (0.04) in period p

P_{lp}^{rw}	Mill prices for roundwood at market *l* in period *p*
$P_{l'q'p}^{ip}$	Mill prices for chips at market *l'* in period *p*
C_{sl}^{t}	Travel costs from location *s* to mill/market *l*
$C_{l^0l'}^{tsp}$	Trans-shipment costs from chip supply market l^0 to chip demand market *l'*
C_{hsp}^{h}	Harvest costs ($/ha) by age *a*, yield group *j*, for site class *k*, management type *m*, and supply location *s* in period *p*
$C_{jkm's}^{r}$	Regeneration costs ($/ha) for yield group *j*, site class *k*, management type *m'*, and location *s*
E_{hsc}	Ending inventory value ($/ha) by age *a*, yield group *j*, site class *k*, location *s*, and carbon class *c*
M_l	Ten year mill capacity by mill/market *l*

Definition of variables:

X_{hscpd}	The area of forest in ha by species *j*, carbon class *c*, age class *a*, and site class *k* from location *s* for management type *m* in period *p* for state of nature *d*
$H_{hscpd}^{m'}$	The area of forest in ha harvested by species *j*, carbon class *c*, age class *a* and site class *k* from location *s* for management types *m* and *m'* in period *p* for state of nature *d*
Vo_{wsp2d}	Volume harvested in period *p2* for state of nature *d* by wood type *w* from location *s*
VoD_{lwspd}	Volume delivered to market *l* in period *p* for state of nature *d*, by wood type *w* from location *s*
I_{lpd}	Chips supplied by market *l* in period *p* for state of nature *d*
It_{l^0lpd}	Chips trans-shipped to market *l* from supply market l^0 in period *p* for state of nature *d*
$TVoD_{lpd}$	Total volume of roundwood and intermediate product delivered to market *l* in period *p* given state of nature *d*
AAC_{j^*pd}	Annual allowable cut (ha) in period *p* for state of nature *d* by species grouping *j**

$AACV_{j*pd}$	Annual allowable cut volume (m^3) in period p for state of nature d by species grouping $j*$
FC_{zpd}	Forest carbon stock in period p for state of nature d by carbon pool q
$TFC_{pd'}$	Total forest carbon stock in period p for state of nature d'
$\Delta TFC_{zpd}^{pd'}$	Change in total forest carbon stock from period p to $p+1$ for states of nature d to d' by carbon pool z
Cr_{vd}^{a}	Accumulated carbon credits for carbon verification period v and state of nature d
Cr_{vd}^{i}	Incremental carbon credits for carbon verification period v and state of nature d
Cr_{vd}^{r}	Replacement carbon credits for carbon verification period v and state of nature d
Cr_{vd}^{ar}	Accumulated replacement carbon credits for carbon verification period v and state of nature d
$NPVCr_{d''}^{r}$	Net present value of replacement carbon credits by state of nature d''
CV	The maximum value of the carbon supply contract
$PVCarbCon_{d''}$	Present value of carbon contract by state of nature d''
$EXPVCarbCon$	Expected present value of carbon contract
$PVTimber_{d''}$	Present value of timber by state of nature d''
$EXPVTimber$	Expected present value of timber
$PVTCcon_{d''}$	Present value of timber and carbon contract by state of nature d''
$EXPVTCcon$	Expected present value of timber and carbon contract

Two objective functions are presented above. In equation (1) the model objective is to maximize the expected net present value of timber, *EXPVTimber*, which is the business-as-usual scenario that is used to establish the carbon supply contract baseline. This objective function is best explained by looking at its six component parts. The first line concerns the probabilities by ending period for all possible states of nature, thus enabling the calculation of the expected value that is being maximized. Lines two through five correspond to: timber revenue P_{lp}^{rw} minus transport costs C_{sl}^{t}; intermediate product revenue $P_{l'q'p}^{ip}$ minus trans-shipment costs $C_{l^0l'}^{tsp}$; harvest costs C_{hsp}^{h}; and, regeneration costs $C_{jkm's}^{r}$, which are summed over all periods and states of nature in the planning period. These components are all discounted. Finally, line six captures the ending inventory value E_{hsc}. Together these parts comprise the expected present value of timber by state of nature. For equation (2) the objective is to maximize the expected present value of timber and the carbon contract, *EXPVTCcon.* This equation is unchanged from the previous one except for the inclusion of an additional line that is used to calculate the expected present value of the carbon contract, *EXPVCarbCon.* This value is obtained from the difference in the contract value *CV* and the expected net present value of replacement carbon credits $\left[\sum_{e}\sum_{d'} NPVCr_{d'}^{r} * \pi_{ed'}\right]$. For all model scenarios involving carbon contracts the objective function utilized is equation (2). Note here that the set of equations *Carbon Contract Equations* are not needed for the baseline model scenario.

The set of equations under *Forest Dynamics Constraints* together are responsible for controlling the movement of forest areas through time considering harvest decisions and stochastic fire loss. Equation (3) states that the initial age class distribution AC_{hsc} is given. In equation (4) the area X_{hscpd} of forest in the next period $p+1$ is the remainder of that disturbed and subsequently harvested in period p. Note, the areas that are burned cannot be harvested, and, those areas that are either burned or harvested return to the youngest age class in the following period. Equations (5) and (6) govern the transfer of forest area to different carbon classes through the parameter $\alpha_{hc}^{m'c}$ for cutover areas and fire disturbed areas, respectively. These equations constitute the area balance networks as described by Boychuk and Martell (1996) and the model III formulation of the problem.

The next set of constraints, *Market and Capacity Constraints*, determines how timber is allocated to mills or markets and the production and use of intermediate products, namely wood chips. Equation (7) determines the volume harvested Vo_{wsp2d} through appropriate harvest area variables and yield parameters and equation (8) states that the volume delivered VoD_{lwspd} cannot exceed the volume harvested. Likewise, equations (9) and (10) are companion equations for wood chips I_{lpd}. Equation (11) sums the total supply of timber and wood chips delivered to markets $TVoD_{lpd}$ and along with equation (12) stipulates that total supply delivered cannot exceed mill capacity M_l.

Equations (13) through (16), *Harvest Regulation Constraints*, are responsible for the annual allowable cut regulations imposed on the model. In equation (13) the annual allowable cut AAC_{j*pd} is determined using a Hanzlik formula (Davis et al., 2001) and through equation (14) this cut calculation is converted into an annual allowable cut volume $AACV_{j*pd}$. Together equations (15) and (16) set the upper and lower bounds on the annual allowable cut, and investigating the impact of more flexible AAC regulations is achieved through the parameters λ^u and λ^l. More information about the Hanzlik AAC calculation is provided in the section *Model Assumptions* below.

Forest carbon accounting is facilitated by equations (17), (18), and (19), *Forest Carbon Accounting Equations*. Equation (17) is used to calculate the amount of carbon by carbon pool FC_{zpd} in each period by state of nature and equation (18) simply sums across carbon pools to determine the total forest carbon stock $TFC_{pd'}$ by period. These are the carbon stock equations. Carbon flows are calculated through equation (19), which determines the change in carbon stock $\Delta TFC_{zpd}^{pd'}$ from period p to $p+1$ by carbon pool, considering the specific states of nature in each of those periods.

The next set of equations, *Carbon Contract Equations*, establishes how this particular carbon contract operates. Equation (20) states that carbon credits are accumulated Cr_{vd}^{a} when carbon stocks are above the contract baseline τ_p^b and equation (21) sets a maximum on the number of carbon credits that can be accumulated equivalent to the carbon target τ_p^c for a period. The incremental amount of carbon credits Cr_{vd}^{i} is calculated as the difference in the number of accumulated carbon credits Cr_{vd}^{a} from one period v to the next $v+1$, as stated in equation (22). Equations (23) and (24) determine the number of replacement carbon credits Cr_{vd}^{r} that are generated. Replacement carbon credits are incurred when the actual carbon stock levels are less than the contract target supply and the firm is also required to acquire replacement credits when carbon stock levels drop below the contract baseline. Then equation (25) tracks the number of replacement carbon credits incurred over the duration of the contract Cr_{vd}^{ar}. Finally, equation (26) calculates the net present value of replacement carbon credits by state of nature $NPVCr_{d'}^{r}$ and these values are subsequently used in determining the expected present value of the carbon contract, *EXPVCarbCon*, and appear in the model objective function.

The final set of constraints, *Non-Negativity Constraints*, is used to restrict certain variables to have positive values. Equations (27) through (33) necessitate, respectively, that forest areas X_{hscpd}, harvest areas $H_{hscpd}^{m'}$, harvest volumes Vo_{wsp2d}, volume delivered VoD_{lwspd}, chips supplied I_{lpd}, chips trans-shipped It_{l^0lpd}, and the total volume of timber and chips supplied $TVoD_{lpd}$ are to be greater than or equal to zero for all arguments governing these variables.

4.3 Data and Model Assumptions

4.3.1 Data

The parameters used in this model were derived from many different sources. The initial age class distribution AC_{hsc} and merchantable yield volume V_{hw} parameters were obtained from Weldwood Hinton Inc, as was mill capacity M_l. Some modification of the data was necessarily completed by Maynes (2003). Carbon stock per hectare γ_{hzc} and the parameter $\alpha_{hc}^{m'c}$, which controls the transfer of areas between carbon classes after disturbances, were obtained from Maynes (2003). The mill price for roundwood P_{lp}^{rw} and chips $P_{l'q'p}^{ip}$, as well as harvest cost C_{hsp}^{h}, regeneration cost $C_{jkm's}^{r}$, and trans-shipment costs $C_{l^0l'}^{tsp}$ were obtained from current market data and when necessary, data transformation was completed by Maynes (2003). In addition, the following assumptions were involved in the model creation.

4.3.2 Model Assumptions

The model was designed with the following assumptions:

1. A planning horizon of 70 years with 10 year planning periods, *PL*, is used and to calculate ending inventory values another 130 years elapse after the planning horizon. Initially a longer planning horizon was intended however because of the model size the planning horizon was shortened to 70 years.
2. Regeneration costs $C_{jkm's}^{r}$ were assumed to be \$1200/ha for the REGEN management type and \$1500/ha for the INTENSIVE management option. Regeneration costs are not associated with extensive management, LOW, or fire disturbance management, FIRE.
3. Harvest costs C_{hsp}^{h} were incorporated into the model as dollar per cubic metre values and were a function of age. The appropriate values were generated by Maynes (2003) utilizing data from Statistics Canada Catalogue #25-201 or via the National Forestry Database, as well as information from CANSIM matrix 11003.

4. Transport costs C_{sl}^{t} varied across location and markets and were based on an assumption that outside mills are at least 50 km away from the forest area and that it costs $0.05 per km to ship a cubic meter of wood.
5. Products included in this model are pulp, construction lumber, other lumber, and the bi-products chips, bio-energy, waste, and emissions. The products and bi-products are calculated by assuming a proportion of the input yields the products and bi-products. This is achieved using the parameter η_{lq}.
6. Site classes and the initial age distribution AC_{hsc} were obtained using forest inventory data from Weldwood. The initial age classes range from 0-10 and go to a maximum of 250 in 10 year intervals. Site classes were available only for the mixed conifer and pine yield groups, thus it was assumed that the remainder of the yield groups would be designated with a MEDIUM site class.
7. Carbon stocks are separated into the carbon pools above ground biomass (ABOVE), below ground biomass (BELOW), soil biomass (SOIL) and biomass present in the merchantable component of the tree (MERCHC). Collectively these pools are referred to as carbon stocks. Carbon that is sequestered in wood products is not included in the model because at present Kyoto accounting rules do not recognize wood products as carbon sinks.
8. Using data from the National Forestry Database it was possible to construct a stochastic representation of fire disturbance using a discrete two-point probability distribution. Based on historical data for the area burned of stocked timber productive forest land for Alberta 1970-2001, the average annual burn proportion was estimated to be 0.009085 (0.91%). Using the following equation it is possible to

estimate the ten-year burn proportion: $\left(1-(1-0.009085)^{10}\right)=0.08722\ (8.7\%)$. Next, in examining the historic fire data a two-point discretization was chosen that satisfied the ten-year mean and coefficient of variation. The decision was that a large fire event (L) would be characterized as a ten-year burn proportion of 0.224 and occurs with a probability of 0.16 and that a small fire event (S) would be associated with a ten-year burn proportion of 0.061 with the probability of 0.84. These burn proportions and probabilities were instituted in periods T1 through T5; five decades with stochastic fire events, whereas the burn proportion was fixed at zero in periods T-1 and T0 under the premise that the decision-maker has complete knowledge of the past and present, and for periods beyond T5 the model reverted to a deterministic formulation using the expected ten-year burn proportion of 0.087. The disturbance rates and corresponding probabilities are represented by the parameters $\delta_{hpd'}$ and π_{pd}, respectively.

States of nature in period T7, the final planning period, are labelled *INXXXXX* where the "*I*" indicates the "initial" disturbance rate occurring in period T-1, which is set at zero. The "*N*" disturbance state in period T0 corresponds to a "known" disturbance rate of zero as well. These statements are consistent with the model perspective that the decision-maker has perfect knowledge of the past and present. For periods T1 through T5; the "*X*'*s*", for each of these periods the state of nature may be either "*L*" or "*S*", resulting in $2^5 = 32$ possible states of nature by period T5 from *INLLLLL* to *INSSSSS*. The model adopts a deterministic formulation in periods T6 and T7 and the

GAMS program was written in such a way so that additional terms were not necessary to identify states of nature in those periods.

9. The carbon supply contract was developed under the assumption that the supplier of carbon credits is fully responsible for carbon stock declines due to fire. Thus for instances when the carbon stock drops below the contract baseline the firm supplying carbon credits would incur carbon debits and must then purchase replacement credits to cover the loss. Carbon stock verification for contract purposes occurs at the beginning of a period and utilizes pre-disturbance and pre-harvest carbon stock calculations. The contract targets are set for periods T1 through T7. The set of contract quantities under investigation is {0.5Mt, 0.67Mt, 0.83Mt, and 1Mt}. Furthermore it was assumed that the price of replacement credits would be equal to the contract price of carbon. The set of carbon prices ($/tonne) {1, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 30, 40, 50, 60, 70, 80, 90, 100, 150, 200, 300, 400, 500} was evaluated for all possible contract scenarios.

10. The Hanzlik formula used for calculating the AAC takes into account disturbance rates and thus the AAC is a post-disturbance value. This manner of AAC calculation recognizes that when there are stochastic fire events the formulation including equations (1) and (3) through (12) does not have feasible solutions if the non-declining even flow constraints (which are often used in forest management scheduling models to calculate AAC) unless harvest volumes are driven to zero. In reality if large fire events occurred in any particular forest management unit, AACs would be recalculated. Equations (13) to (16) allow the AACs to be recalculated at for each period and fire event in the planning horizon as would surely occur in real

situations although the method, which uses Hanzlik's formula, is only an approximation to what is typically done. Typically AAC levels are calculated using deterministic models approximately each decade and include changes in the forest to harvesting and natural disturbance, as well as any updated information. While it is theoretically possible to calculate a maximum AAC based on non-declining even flow constraints for each state of nature in a stochastic model, this would be extremely difficult to program and solve. As such a simplified way of calculating the AAC at each stage as described in equations (13) to (16) was utilized.

4.4 Model Scenarios

The impetus for developing the discrete stochastic sequential programming model in the present study was to examine the incentives and impacts that certain carbon contract supply parameters, or components, would generate for a credit supplying firm as evidenced primarily through changes in objective values relative to the objective function value without carbon contracts, carbon supply, or expected carbon stock, as well as volume harvested or timber supply, and secondarily through other variables, given a specific contract structure. In particular, this study is concerned with the impact of three key contract parameters: (1) different carbon contract supply quantities or contract targets; (2) relaxing the annual allowable cut constraint; and, (3) increasing the price of carbon in the contract.

These contract parameters or components under examination correspond to earlier discussion regarding firm-level issues; regulatory compatibility, and contract details, such as quantity and price. Omitted from this study are questions surrounding changing the level of responsibility for fire and contract duration. The level of responsibility for carbon loss to fire, and the contract duration and verification periods of all contracts are held constant, although these are parameters that could be investigated. Furthermore, a single carbon stock baseline is utilized in this study. It is derived from a base-case or business-as-usual model and is used to institute the numerous carbon contract scenarios. Also, in all carbon contract scenarios the contract price of carbon and the price of replacement carbon credits are set equal; there is no penalty price attached to purchasing replacement credits, and there is no restriction on the number of replacement carbon credits that the firm can purchase nor is the availability of replacement carbon credits constrained. Finally, the prices of roundwood and woodchips are held constant over the planning period, as are harvest, regeneration, and transportation cost rates.

Table 4-1 Model Scenarios

Risk Neutral Decision Criterion –Maximize Expected Present Value													
MAX:	Baseline Model	Contract Model											
	Timber	Timber and Carbon Contract											
Contract	No	Contract Quantity Q1 = 0.5Mt			Contract Quantity Q2 = 0.67Mt			Contract Quantity Q3 = 0.83Mt			Contract Quantity Q4 = 1.0Mt		
AAC Level	±10%	±10 %	±25 %	±50 %	±10 %	±25 %	±50 %	±10 %	±25 %	±50 %	±10 %	±25 %	±50 %
Carbon Price ($/tonne)	0	{1,2,4,6,8,10,12,14,16,18,20,30,40,50,60,70,80,90,100,150,200,300,400,500}											

A total of 288 scenarios (or 12 scenario groups, by carbon price set) are included in this study – (24) carbon price levels by (3) annual allowable cut levels by (4) contract quantities – as indicated in Table 4-1. Each scenario comprises of, and is thus differentiable by, the three contract parameters (components), but all contracts share a common parameter setting, which characterizes the level of responsibility for carbon loss due to fire disturbance. Given the model setup the firm is fully responsible for carbon stock decline due to fire disturbance, including that below baseline. A parameter that differentiates a contract is the quantity of carbon contracted by the supplier and purchaser. The lower and upper carbon supply quantities, 500,000 tonnes (0.5Mt) and 1,000,000 tonnes (1.0Mt) respectively, are based on the carbon quasi-supply functions derived by Maynes (2003). Two intermediate quantities, 670,000 tonnes (0.67Mt) and 830,000 tonnes (0.83Mt), were chosen to enable subsequent analysis. Table 4-2 summarizes the period carbon targets above baseline; the quantity of carbon credits to be supplied above the contract baseline, for the four possible contract quantities and Table 4-3 reports what the actual carbon supply targets would be by contract quantity type alongside the contract baseline. These values function as part of the contract verification process, in order to track the stock of carbon for the periods included in the carbon contract. A second distinguishing parameter, the annual allowable cut level, permits introducing greater flexibility in terms of harvest decisions. The initial level allows a firm to fluctuate harvest ±10 percent from the annual allowable cut, with comparison levels set at ±25 percent and ±50 percent. The hypothesis is that as the price of carbon increases perhaps allowing more flexibility regarding the AAC level will enable a firm to alter the optimal rotation and meet the carbon contract target at a lower price, or equivalently, supply more carbon at the same price. The third parameter is the price of carbon in the contract. The set of twenty-four carbon price levels range from a minimum

$1/tonne to a maximum $500/tonne. Thus, each of the 288 scenarios can be defined on the basis of contract quantity, annual allowable cut level, and carbon price.

Table 4-2 Contract Verification/Delivery Targets ('000 tonnes) above Baseline by Period

Period	Contract Quantity			
	Q1=0.5Mt	Q2=0.67Mt	Q3=0.83Mt	Q4=1.0Mt
T0	0	0	0	0
T1	50.00	67.00	83.00	100.00
T2	162.50	217.75	269.75	325.00
T3	275.00	368.50	456.50	550.00
T4	387.50	519.25	643.25	775.00
T5	500.00	670.00	830.00	1 000.00
T6	500.00	670.00	830.00	1 000.00
T7	500.00	670.00	830.00	1 000.00

Table 4-3 Contract Baseline and Target Levels (megatonnes) by Period

Period	Contract Quantity				
	Baseline	Q1=0.5Mt	Q2=0.67Mt	Q3=0.83Mt	Q4=1.0Mt
T0	142.55	142.55	142.55	142.55	142.55
T1	141.80	141.85	141.87	141.88	141.90
T2	134.73	134.89	134.95	135.00	135.06
T3	127.67	127.95	128.04	128.13	128.22
T4	120.63	121.02	121.15	121.27	121.41
T5	114.24	114.74	114.91	115.07	115.24
T6	108.50	109.00	109.17	109.33	109.50
T7	103.34	103.84	104.01	104.17	104.34

The model was developed and written using GAMS (General Algebraic Modeling System) version 19.3 and solved with the GAMS/OSL2 linear programming solver. In the baseline model, which maximized the expected present value of timber and assigned no value to carbon, there were 144,717 equations, 282,689 variables, and 1,953,874 non-zero elements. Models for which the objective was to maximize the expected present value of timber and the carbon contract consisted of 160,491 equations, 304,261 variables, and 2,078,069 non-zero elements. To improve solve times in the latter set of models various tolerance/precision levels were adjusted using an option file. These included: the absolute pivot tolerance for the Cholesky factorization (chabstol); the cut-off tolerance in the Cholesky factorization (chtinytol); the rate of change for multiplier in composite objective function (chweight); and, the primal infeasibility tolerance (tolpinf).

Chapter 5: Results

5.1 Introduction

The key objective of this study is to determine under what circumstances the firm will decide to enter into a carbon supply contract. More specifically, based on the firm's decision criterion, given which combinations of contract quantity, AAC regulation levels, and carbon price is the firm willing to enter a contract, holding all other contract parameters constant? Also, for each contract quantity and AAC regulation level pair there will be an associated break-even-price at which the firm would decide to enter into the contract. These prices are calculated and reported in section 5.3 of this chapter. In addition it is important to examine why the firm would decide to enter into a particular contract? What incentives are being generated through the contract and how is this affecting the firm's decision? Moreover, for those contracts which the firm would enter, how do these carbon contracts perform in terms of carbon sequestration relative to baseline and contract target carbon quantities? Does a carbon contract generate the proper incentives for augmenting carbon sequestration and to what extent is the firm relying upon the acquisition of replacement carbon credits in order to meet its contract obligations?

5.2 Baseline Model Results

As an initial basis, a baseline or business-as-usual (BAU) scenario was modeled to generate the expected carbon stock baseline necessary to formulate the carbon contracts. The results from this scenario are also used for implementing the firm's decision criterion by comparing the baseline objective values with those of the carbon contract scenarios. The baseline scenario corresponds with the leftmost column in Table 4-1. Under this scenario, the objective is to maximize the expected present value of timber subject to the set of AAC regulations as well as the demand constraints in the model. This characterizes the current management objective in the forest sector, to maximize profits stemming from timber production. Thus, it is often termed the BAU case. To contrast, the introduction of a carbon contract broadens the management objective to include the profit or net revenues that may result from forest carbon management. In this way the BAU scenario can be used as a baseline or reference case to evaluate the performance of carbon contract scenarios. A brief summary of the objective value and carbon stock and harvest volumes for the baseline scenario follows.

Under the BAU scenario the objective was to maximize the expected present value of timber, EXPVTimber, given stochastic risk of fire. The GAMS output reports an objective value, EXPVTimber, of $676,195,036.95. The *expected* carbon stock, presented in Table 4-3, exhibits a declining trend over time and this trajectory was used as the carbon stock baseline to model each of the carbon contract scenarios (Figure 5-1). These values, the expected carbon stock, were generated by calculating the weighted average of all carbon stocks by states of nature in each period. Recall that in each period for every state of nature there is a corresponding total forest carbon (TFC) level and a probability that the state of nature will occur. Thus, one can sum the product of the TFC level and the associated probability for all states of nature by period to calculate the expected carbon stock in that period. In this manner the expected carbon stock baseline was determined. Note that total forest carbon levels are calculated as pre-disturbance levels in each period and as Figure 5-1 shows a downward sloping carbon stock baseline will be used in modeling all carbon contract scenarios.

For comparison purposes two states of nature, INLLLLL, the state of nature whereby consecutive large fire events occur, and INSSSSS, the sequence of fire events characterized by small fire events in all periods, are included in Figure 5-1 and demonstrate the effect of fire sequence on carbon stock levels. If only small fire events are experienced over the planning period, then the carbon stock levels are higher than the expected carbon stock baseline. In contrast, a series of large fire events can lead to a significant decrease in carbon stock levels. Of note, INSSSSS is the most probable state of the thirty-two states of nature that are possible and INLLLLL the least likely, and the carbon stock levels of the remaining thirty states fall somewhere between these two states. In period T7 the probabilities associated with the states of nature INSSSSS and INLLLLL are 0.4182 and 0.0001, respectively.

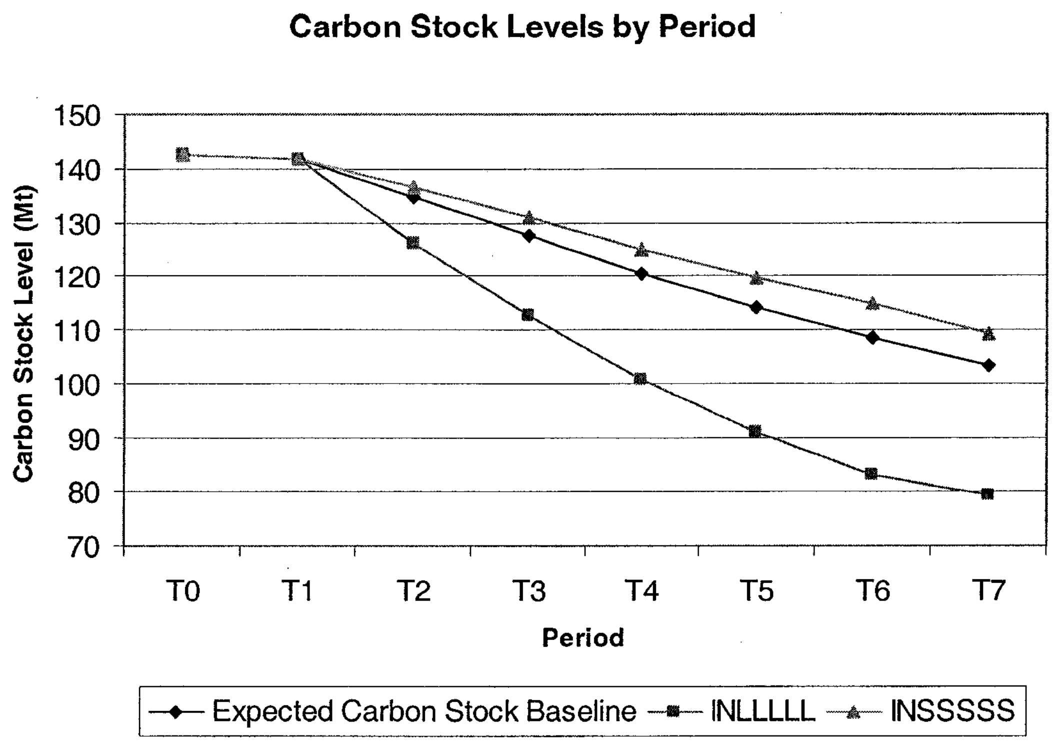

Figure 5-1 Expected Carbon Stock Baseline and Carbon Stock Levels for States of Nature INLLLLL and INSSSSS

Note: States of nature INLLLLL and INSSSSS have respective probabilities of 0.0001 and 0.4182.

5.3 Carbon Supply Contracts – Which Contracts do the Firm Enter?

Having run the series of model scenarios outlined in Table 4-1 of the preceding chapter, and based on the decision criterion being used, for which contract scenarios would the firm decide to enter a contract? Moreover, at what contract price(s) does the firm break-even? For what range of carbon prices does the firm enter a contract? Finally, given those contract scenarios for which the decision criterion states the firm will enter what is the motivation for the firm to enter the contract in those cases? Is it a result of the contract value, whereby the expected net present value of the carbon contract exceeds the expected opportunity cost of foregone timber value (see Appendices 2 and 3)?

Alternatively, does the firm agree to enter a contract because additional expected timber value can be gained from more flexible AAC regulations and which is greater than the expected cost of the carbon contract?

The criterion used in this study to evaluate the decision of the firm to enter a particular carbon contract states that the expected present value of timber and the carbon contract must be equal to or greater than the expected present value of timber for the baseline scenario, given a risk neutral decision-maker (see Appendix 1). The carbon price at which the expected present value of timber and the carbon contract equals the expected present value of timber for the baseline case is the break-even-price. Under the baseline model scenario the expected present value of timber was $676,195,036.95. When the expected present value of timber and the carbon contract equals or exceeds this amount the firm would enter the contract.

Table 5-1 Range of Carbon Prices ($/tonne) Based on the Decision Criterion that the Firm would decide to enter the Contract (where *x* represents the price of carbon)

AAC Regulations	Contract Quantity					
	0.5Mt	0.67Mt	0.83Mt	1.0Mt	2.0Mt	5.0Mt
±10%	-	-	-	-	$x \geq 464.28$	$x \geq 21.27$
±25%	$x \leq 53.24$	$x \leq 55.37$	$x \leq 57.54$	$x \leq 60.10$	$1 \leq x \leq 500$	$1 \leq x \leq 500$
±50%	$x \leq 103.44$	$x \leq 151.96$, $x \geq 478.37$	$1 \leq x \leq 500$	$1 \leq x \leq 500$	$1 \leq x \leq 500$	$1 \leq x \leq 500$

Note: (-) indicates that the firm will not enter the contract for any carbon price between $1/tonne and $500/tonne.

Table 5-1 displays the range of carbon prices over which the firm would enter a contract for each combination of contract quantity and AAC regulations. If more flexibility in terms of AAC regulations is not permitted, then for the contract quantities modelled, 0.5Mt to 1.0Mt, the firm would not enter a carbon contract. Under these scenarios the firm does better under the business-as-usual case. Additional model runs were completed to establish whether or not a larger contract size could result in the firm entering a contract without changing the AAC regulations. When the contract quantity is increased to 2.0Mt and 5.0Mt the firm would enter the contract at a carbon price ≥\$464.28/tonne and ≥\$21.27/tonne, respectively. From Table 5-1 it is apparent that if more flexible AAC regulations are introduced within the contract the firm begins to enter into contracts and with additional flexibility, from ±25 percent to ±50 percent, the firm is willing to enter the contract over a greater range of carbon prices. Therefore contract quantity and the set of AAC regulations both affect the firm's decision to enter a contract. What these results do not reveal though is why the firm decides to enter the contract for a given contract scenario.

Before turning to explanations of why the firm would decide to enter particular contract scenarios it is instructive to clarify the contract break-even-prices. As mentioned, with current AAC regulations unless the contract size is increased beyond 1.0Mt the firm would not enter the contract. These contracts may have a positive break-even-price beyond \$500/tonne for carbon. When the AAC regulations are set at ±25 percent the firm begins to enter contracts between 0.5Mt and 1.0Mt. For the contract quantity 0.5Mt the break-even-price is \$53.24/tonne, and increases to \$55.37/tonne at 0.67Mt, \$57.54/tonne at 0.83Mt, and \$60.10/tonne at 1.0Mt. What is important to note here is that above these carbon prices the firm would *not* enter the contract. This suggests that the value of the carbon contract is not influencing the decision to enter the contract but rather it is the additional timber value gained because of a relaxation of the AAC constraints. When the AAC regulations are relaxed further to ±50 percent some interesting results occur. At

0.5Mt the break-even-price increases to $103.44/tonne however this is the maximum carbon price at which the firm would enter the contract, which suggests again that increased timber values and not carbon values are what is motivating the firm's decision. With a contract size of 0.67Mt there are two break-even-prices. The firm would enter the contract at or below $151.96/tonne and at or above $478.37/tonne for carbon. At low carbon prices, less than $151.96/tonne, timber values dominate the decision to enter the contract while at higher carbon prices, greater than $478.37, the value of the carbon contract dominates. Lastly, for contract size 1.0Mt the firm would enter the contract for all carbon prices between $1/tonne and $500/tonne.

For the contracts with AAC regulations of ±10 percent the firm would not enter the contract at or below a carbon price of $500/tonne. Regardless of the contract size with these AAC regulations and for all carbon prices the expected present value of the carbon contract is negative. Furthermore, as the carbon price increases the expected value of timber decreases because the firm, in responding to a higher carbon price, is altering the forest rotation in order to sequester carbon. The net result is that for the contract quantities 0.5Mt to 1.0Mt with current AAC regulations the expected present value of timber and the carbon contract is less than the expected present value of timber in the baseline case, and so the firm would not enter a contract with these parameters.

Of note here, however, is that if the firm was subject to a specific state of nature such as *INSSSSS* whereby no large fire events were to occur then the firm would enter the contract at a carbon price of $1/tonne in the case of a 0.5Mt contract with AAC regulations of ±10 percent. In this contract scenario the expected present value of timber and the carbon contract is in excess of $693 million, or a $17.4 million gain versus the baseline scenario. In contrast, if the firm were subject to a sequence of fire disturbance that comprised five consecutive large fire events, *INLLLLL*, the firm would never enter the contract. The best the firm can do relative to the baseline case is a $98.2 million loss with a carbon contract price of $1/tonne. What this demonstrates is the possible variability in terms of outcomes that the firm could be exposed to depending on what state of nature is relevant, but a risk neutral decision-maker is concerned only with the expected value decision criterion and not with variability of possible outcomes.

When the contract size is increased to 2.0Mt with current AAC levels the firm breaks-even at a carbon price of $464.28/tonne. Below this price there is a positive expected opportunity cost of foregone timber value and because the expected present value of the contract is negative below a carbon price of $210.41/tonne the firm is worse off relative to the baseline case. For carbon prices between $210.41/tonne and $464.28/tonne the carbon contract has a positive expected value but is less than the opportunity cost of timber. At or above a carbon price of $464.28/tonne the firm would enter the contract since the expected present value of the carbon contract is equal to or greater than the expected opportunity cost of foregone timber value. What this scenario demonstrates is the impact of contract size on the firm's decision to enter the contract if AAC regulations are unchanged.

As the AAC regulations are relaxed to ±25 percent the firm will decide, based on the decision criterion, to enter contracts of size 0.5Mt through 1.0Mt, albeit for different carbon prices. Aforementioned were the break-even-prices for these contracts and it was suggested that in these contract scenarios having access to more relaxed AAC regulations would influence the firm's decision and not the expected values of the carbon contract.

In the cases of contract sizes 0.5Mt and 0.67Mt the expected present value of the contract is negative for all carbon prices but more flexible AAC regulations mean the firm can increase harvest and generate additional timber value which, up to the break-even-price, covers the cost of the carbon contract to the firm. When the expected present value of the contract is negative, recalling equation (2), the contract value is less than the expected present value of replacement credits and in terms of carbon the contract is thus a cost rather than a benefit to the firm. However, these contracts are beneficial to the firm because entering these contracts has provided the firm with access to less restrictive AAC regulations. That is, if the firm decided *not* to enter these contracts the firm would be foregoing higher timber values. Figures 5-2 and 5-3 display the results for the expected present value of the contract, the change in timber value relative to the baseline case, and the net change in timber and carbon values from the contract as the price of carbon increases. The point where the net change in timber and carbon values curve intersects the horizontal axis is the break-even-price, which equivalently states that the expected present value of timber and the carbon contract equals the expected present value of timber under the baseline case.

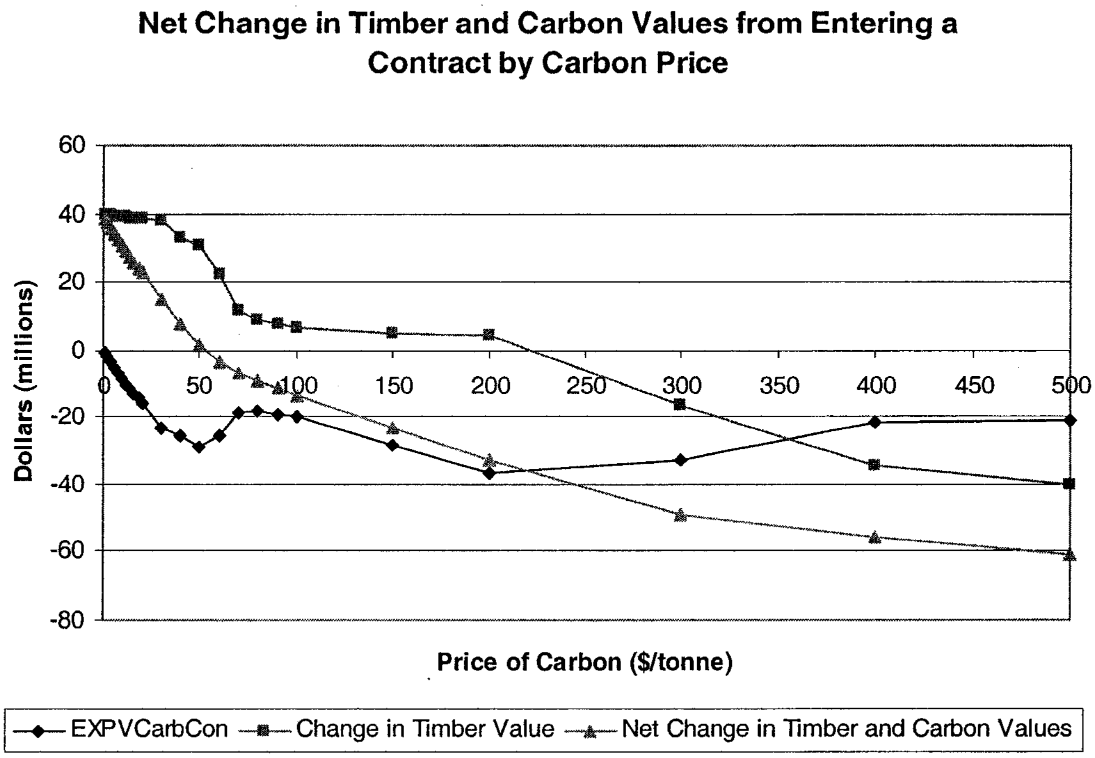

Figure 5-2 Net Change in Timber and Carbon Values from Entering a 0.5Mt Contract with AAC Regulations of ±25 Percent

Note: The break-even-price is $53.24/tonne for carbon.

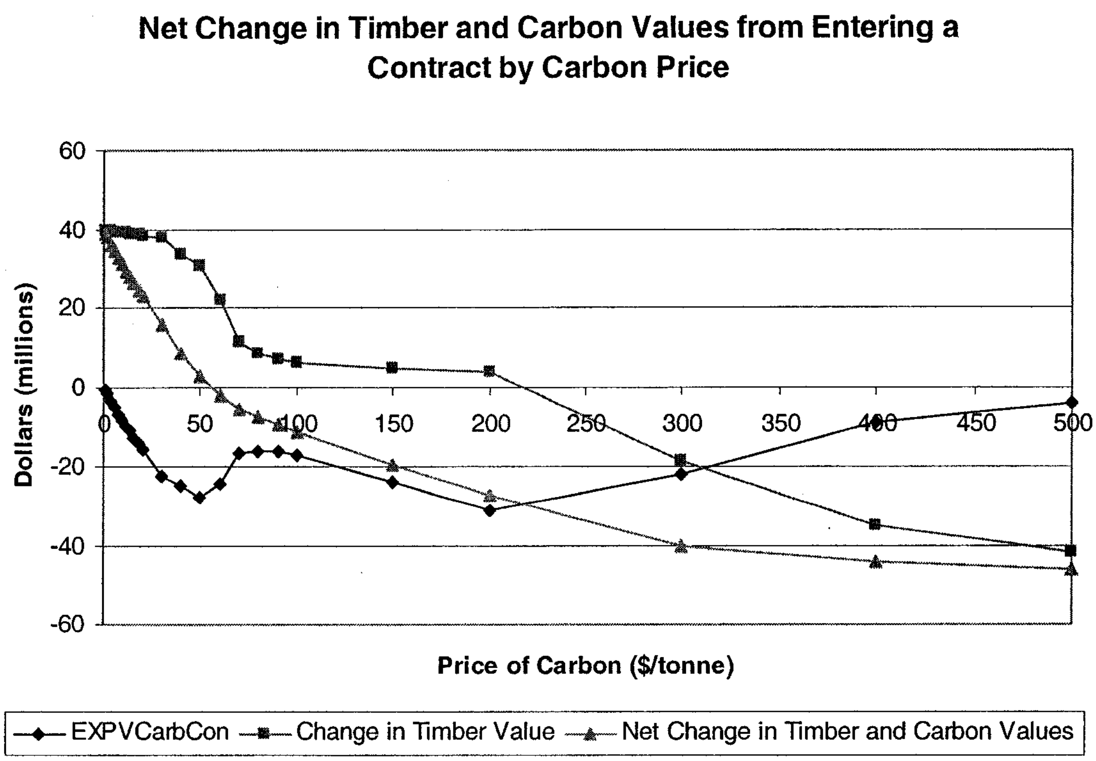

Figure 5-3 Net Change in Timber and Carbon Values from Entering a 0.67Mt Contract with AAC Regulations of ±25 Percent

Note: The break-even-price is $55.37/tonne for carbon.

With the AAC regulations at ±25 percent and increasing the contract quantity to 0.83Mt and 1.0Mt the firm likewise enters the contracts up to the break-even-price because the additional timber value that is expected exceeds the cost of the contract to the firm. How these cases differ from the previous ones is that at some higher carbon prices, above the break-even-price, the expected present value of the contract is positive but the firm would not enter the contract at those prices because the expected opportunity cost of timber dominates the firm's decision. Figures 5-4 and 5-5 display the decision criterion results for the 0.83Mt and 1.0Mt contracts.

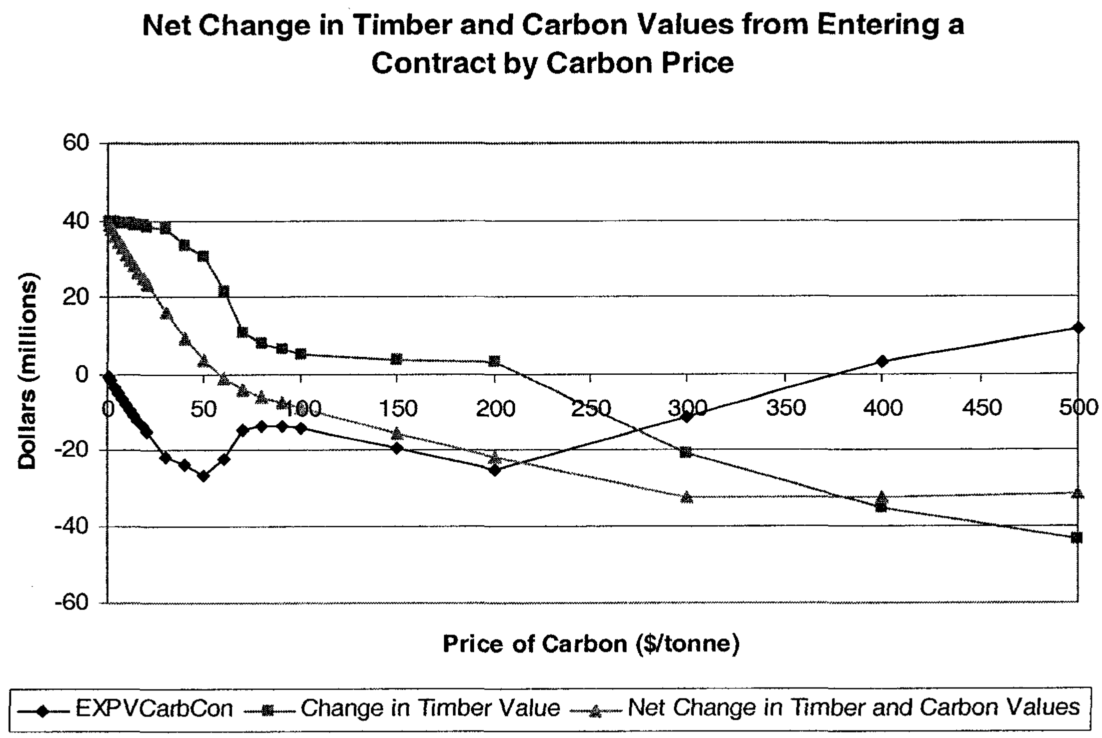

Figure 5-4 Net Change in Timber and Carbon Values from Entering a 0.83Mt Contract with AAC Regulations of ±25 Percent

Note: The break-even-price is $57.54/tonne for carbon.

The results for the contracts with ±25 percent AAC regulations confirm the supposition earlier that a firm may decide to enter a contract not to supply carbon credits but instead to gain access to more flexible AAC regulations. In the case of the 0.5Mt, 0.67Mt, 0.83Mt, and 1.0Mt contracts, it is possible for the firm to enter into a contract, regulated by more flexible AAC rules, to increase timber value and rely upon replacement credits to meet the contract target up to the break-even-prices of $53.24/tonne, $55.37/tonne, $57.54/tonne, and $60.10/tonne, respectively. For these contract scenarios the increase in timber value exceeds the cost of replacement credits such that the expected present value of timber and the carbon contract is higher than the expected present value of timber in the baseline case. Essentially the contract has served as a means for the firm to change its regulatory environment rather than a mechanism or instrument for forest carbon sequestration.

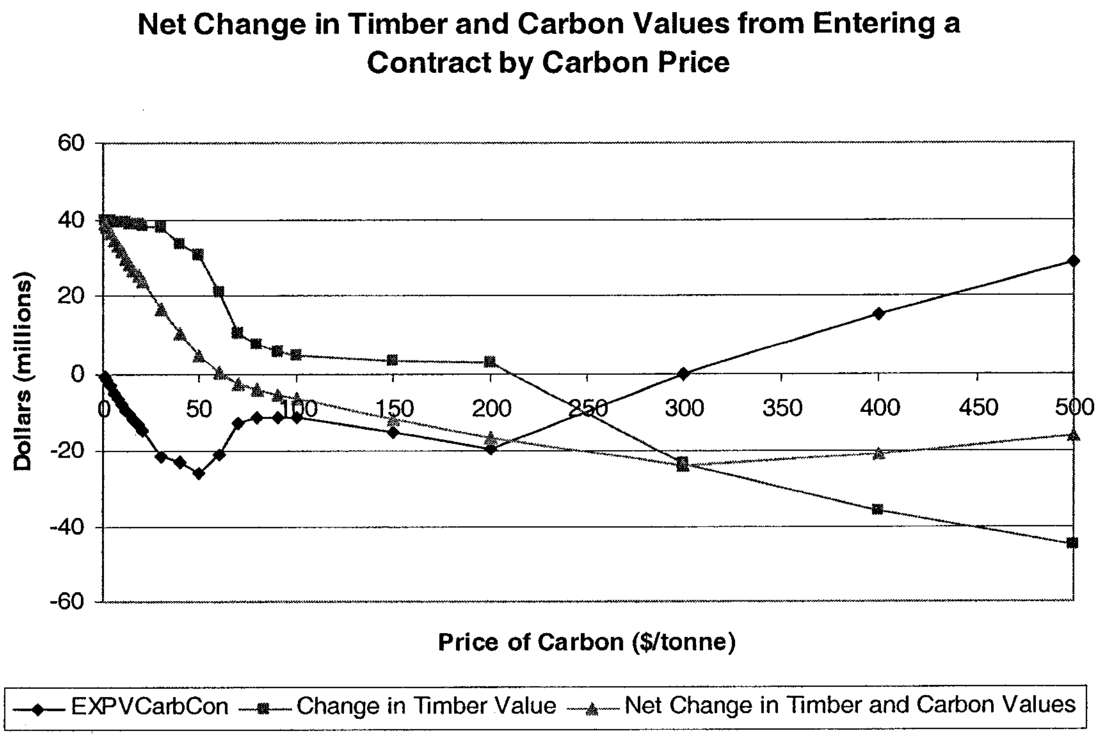

Figure 5-5 Net Change in Timber and Carbon Values from Entering a 1.0Mt Contract with AAC Regulations of ±25 Percent

Note: The break-even-price is $60.10/tonne for carbon.

As the AAC regulations are relaxed further to ±50 percent the firm will enter a contract over a greater range of carbon prices for all contract quantities. What is most interesting, however, is that for contracts above 0.5Mt the reason for entering the contract may have changed relative to the firm's decision under a set of less flexible AAC regulations. The results for the 0.5Mt contract show that, as is the case under ±25 percent AAC regulations, it is still the additional timber value arising from the AAC regulation change that is motivating the firm to enter the contract up to a carbon price of $103.44/tonne.

While above $367.27/tonne for carbon the contract attains a positive value it does not offset the expected opportunity cost of foregone timber values (Figure 5-6).

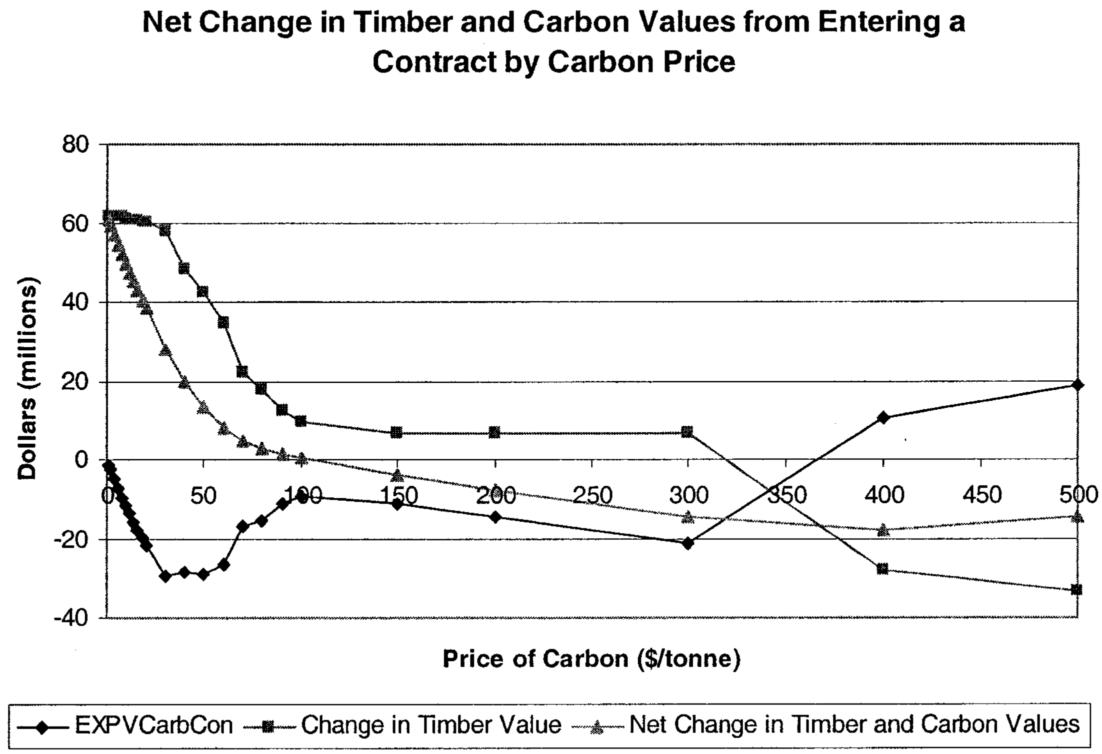

Figure 5-6 Net Change in Timber and Carbon Values from Entering a 0.5Mt Contract with AAC Regulations of ±50 Percent

Note: The break-even-price is $103.44/tonne for carbon.

Depending on the price of carbon when the contract quantity is 0.67Mt, different values are influencing the firm's decision to enter the contract. In this case there are two break-even-prices, $151.96/tonne and $478.37/tonne, but the explanation for whether or not the firm breaks-even changes at these prices. At or below a carbon price of $151.96/tonne additional expected timber values exceed the expected cost of the contract so the firm decides to enter the contract. In contrast, above $478.37/tonne for carbon the expected value of the contract is greater than the expected opportunity cost of foregone timber values. The results are illustrated in Figure 5-7.

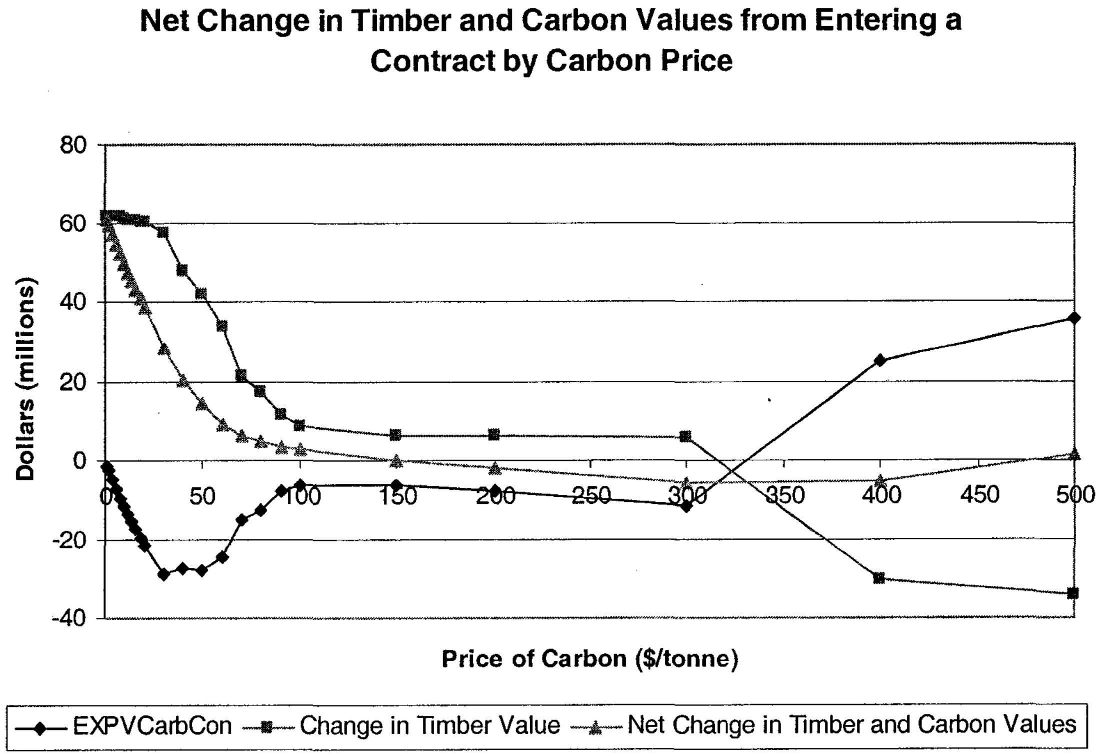

Figure 5-7 Net Change in Timber and Carbon Values from Entering a 0.67Mt Contract with AAC Regulations of ±50 Percent

Note: The break-even-prices are $151.96/tonne and $478.37/tonne for carbon.

If the contract size is increased to 0.83Mt and 1.0Mt with AAC regulations of ±50 percent the firm will enter these contracts for all carbon prices from $1/tonne to $500/tonne. In the case of the 0.83Mt contracts the additional timber value that is expected exceeds the expected cost of the contract up to about $300/tonne for carbon, above which the expected present value of the contract exceeds the expected opportunity cost of timber (Figure 5-8). Note the expected present value of the contract is positive above $306.11/tonne of carbon. With the contract quantity at 1.0Mt more flexible AAC regulations mean that the additional timber value is greater than the expected cost of the contract up to approximately $150/tonne of carbon. At a carbon price above $98.38/tonne the expected value of the contract is positive and increases with carbon price. Eventually, between $150/tonne and $200/tonne for carbon the expected present value of the contract exceeds the additional expected value of timber, and beyond $309.48/tonne for carbon the expected present value of carbon exceeds the expected opportunity cost of foregone timber values. These results are presented in Figure 5-9.

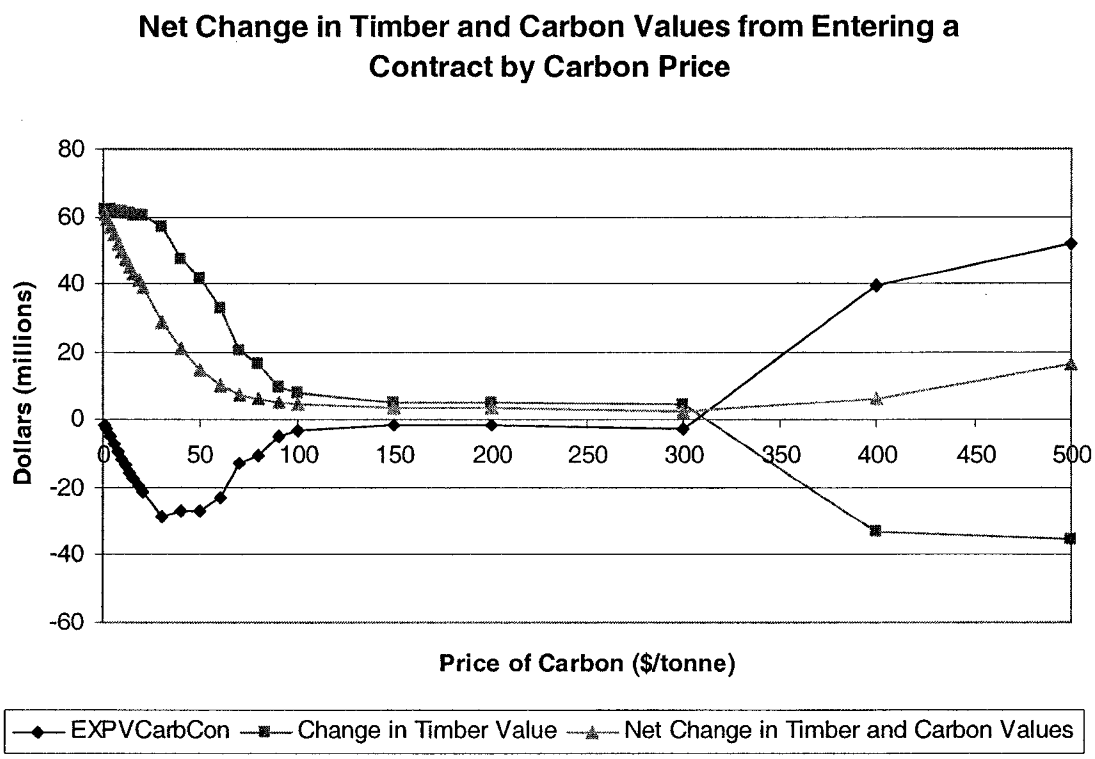

Figure 5-8 Net Change in Timber and Carbon Values from Entering a 0.83Mt Contract with AAC Regulations of ±50 Percent

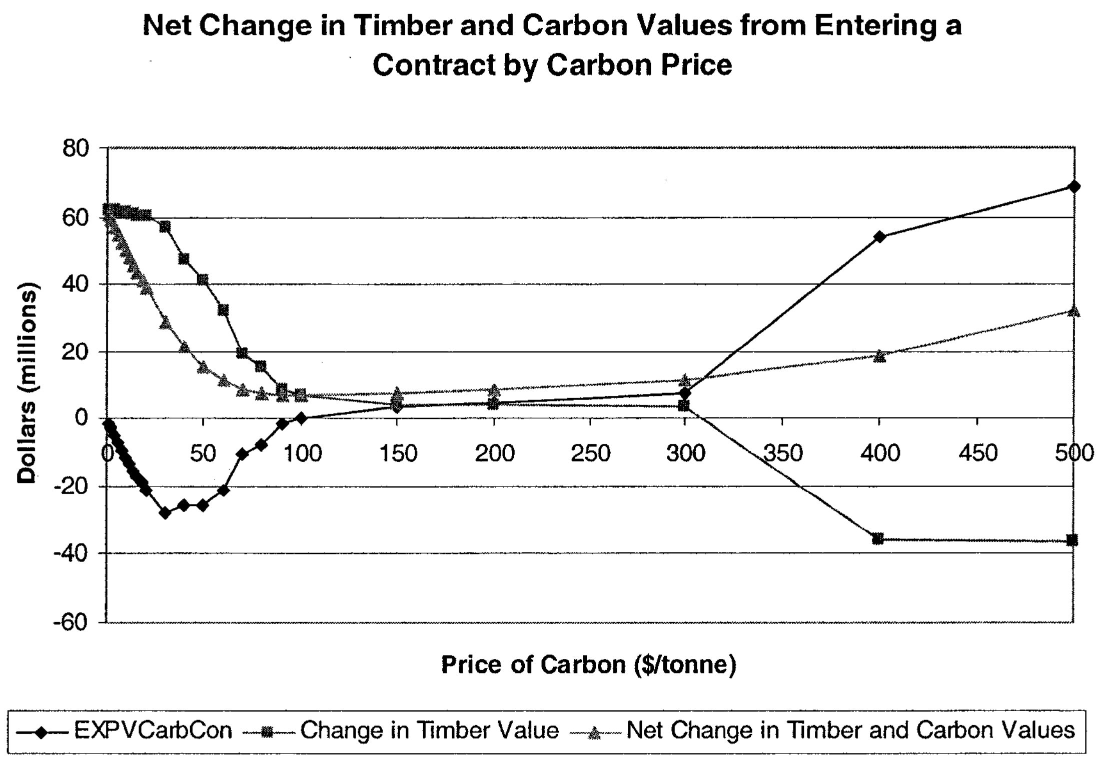

Figure 5-9 Net Change in Timber and Carbon Values from Entering a 1.0Mt Contract with AAC Regulations of ±50 Percent

5.4 Section Summary

Implicitly what has been demonstrated through the figures section 5.3 is that the contract quantity affects the firm's decision to enter a contract at each of the AAC regulation levels under examination. With the AAC regulations at ±10 percent the contract size had to be increased beyond 1.0Mt in order for the firm to enter a contact, given the decision criterion. From Table 5-1 it is apparent that increasing the size of the contract expands the range of carbon prices for which the firm would enter a carbon contract. Further, while the firm would enter contracts with more flexible AAC regulations initially to gain access to higher timber values, for the contracts greater than 0.5Mt in size if high enough carbon prices can be negotiated then the firm would enter contracts at 0.67Mt, 0.83Mt, and 1.0Mt because the expected present value of the carbon contract exceeds the expected opportunity cost of foregone timber values; or, the expected present value of timber and the carbon contract is greater than the expected present value of timber under the baseline scenario. Figures 5-10 through 5-12 illustrate the impact of contract size on the break-even-price for contracts with AAC regulations at ±10 percent, ±25 percent, and ±50 percent.

What this suggests is that a larger contract, and higher carbon price, is necessary to offset the liability the firm assumes with respect to fire disturbance and the level of responsibility for carbon stock losses to fire that is built into the contracts. A caveat is that this finding is premised on three key assumptions; a risk-neutral decision-maker, the price of replacement credits equals the contract carbon price, and all contract credit shortfalls are equalized with replacement credits. Any deviation from these assumptions will alter the firm's behaviour and hence its decision to enter a contract. Moreover, if the replacement credit price is greater than contract price or if there is risk aversion, there will be a point when increasing the contract size further leads to growth in liability that exceeds growth in contract value and associated with this will be some threshold contract size (for given prices) beyond which the firm will not enter. This could be the result of either a physical land constraint or the economic cost of meeting a larger contract. As the contract size increases the firm may not be able to alter forest management within regulations to generate enough carbon credits because the capacity of the forest to act as a carbon sink has been fully utilized. A higher carbon price may temporarily induce the firm to enter these larger contracts, for contract quantities less than the physical land constraint, but eventually the liability or cost of acquiring replacement credits will outweigh the expected benefits of a larger contract. That is, increasing the size of the contract will be in the firm's interest to a point, beyond which the firm will have a diminishing or no incentive to enter a contract because of the re-emergence of excessive contract liability.

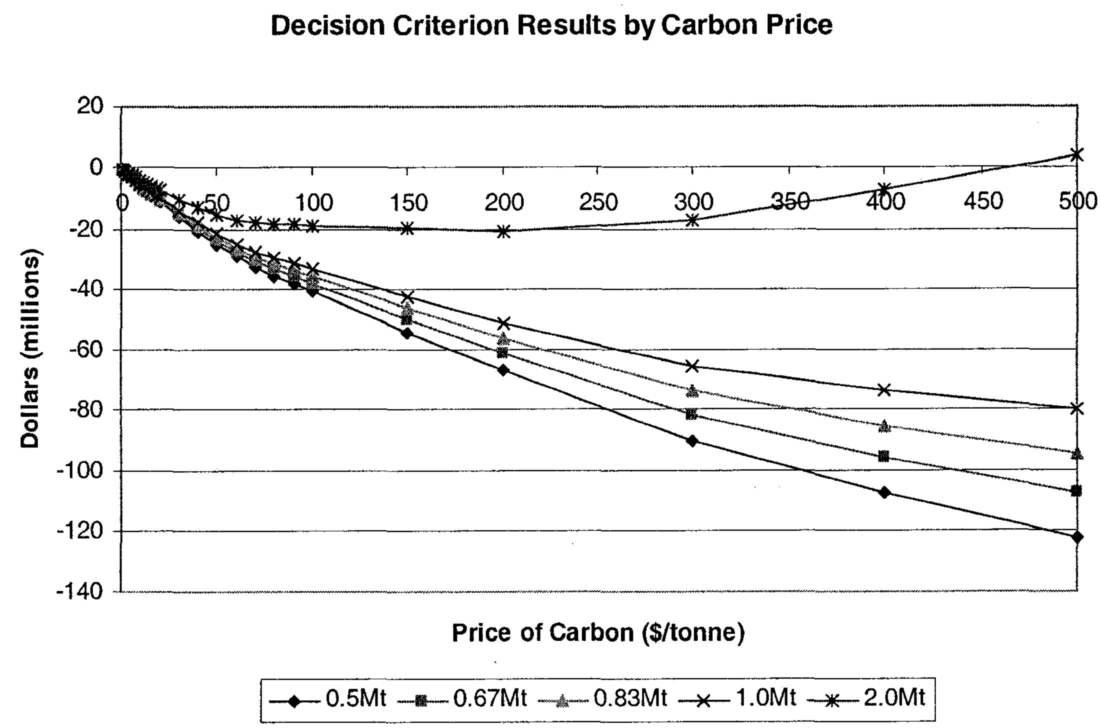

Figure 5-10 Decision Criterion Results – Expected Present Value of Timber and the Carbon Contract minus the Expected Present Value of Timber in the Baseline Case – by Carbon Price for Contracts with AAC Regulations of ±10 Percent

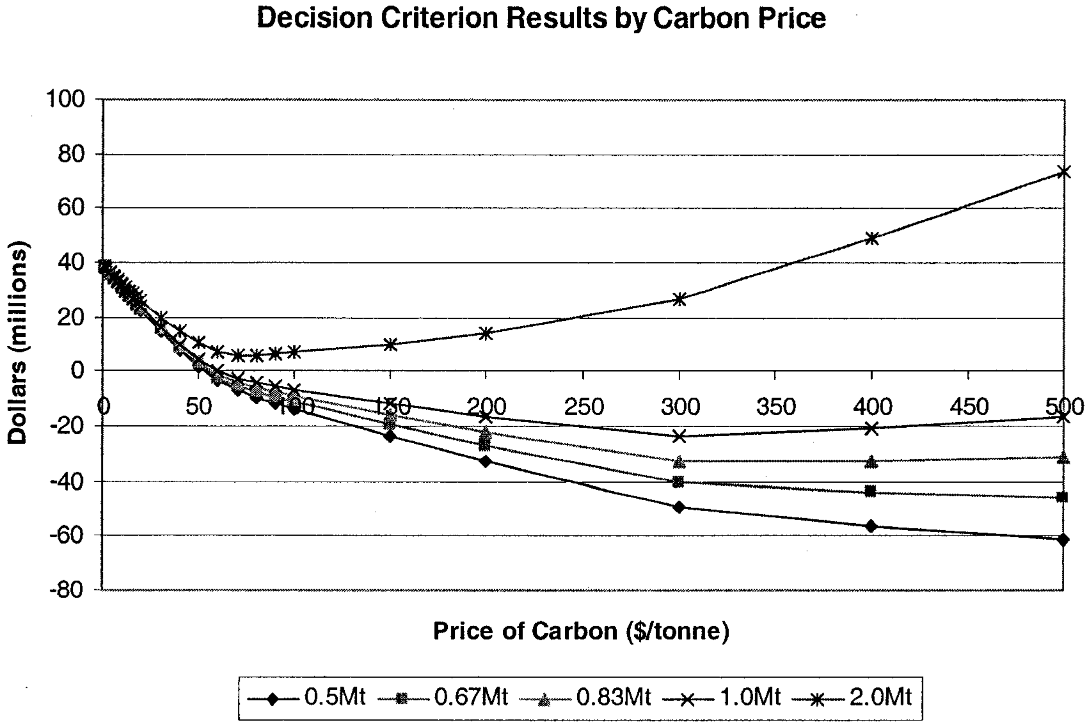

Figure 5-11 Decision Criterion Results – Expected Present Value of Timber and the Carbon Contract minus the Expected Present Value of Timber in the Baseline Case – by Carbon Price for Contracts with AAC Regulations of ±25 Percent

Decision Criterion Results by Carbon Price

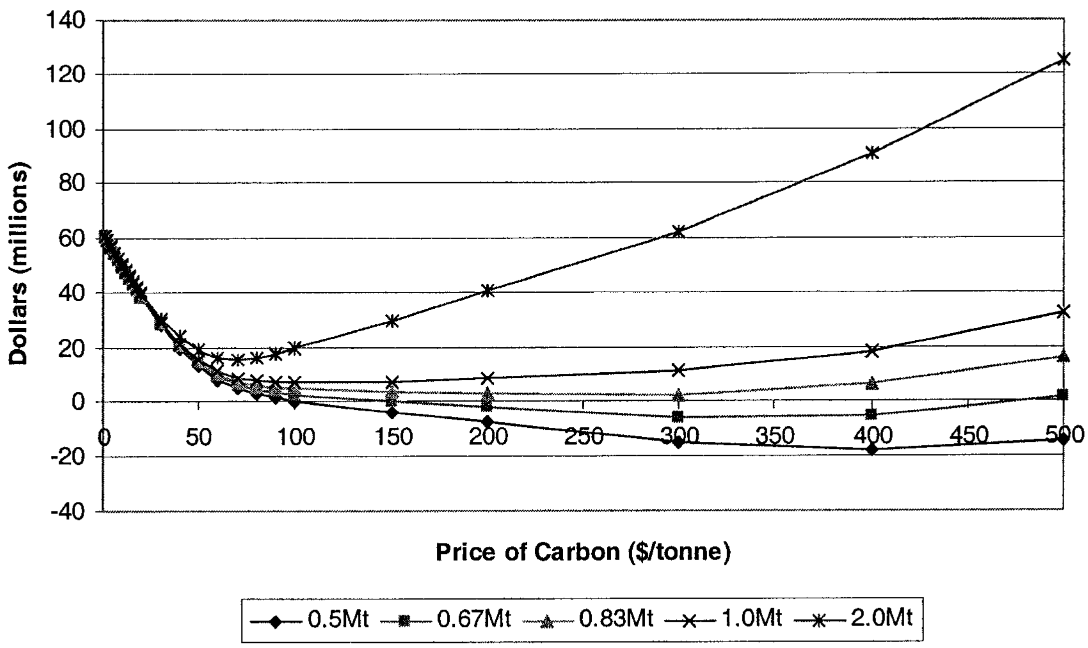

Figure 5-12 Decision Criterion Results – Expected Present Value of Timber and the Carbon Contract minus the Expected Present Value of Timber in the Baseline Case – by Carbon Price for Contracts with AAC Regulations of ±50 Percent

It has also been shown that for each contract quantity relaxing the AAC regulations impacts the decision to enter a contract. Using the information in Table 5-1, for each contract quantity as more flexible AAC regulations are introduced the firm will decide to enter a contract over a wider range of carbon prices. Figures 5-13 to 5-16 illustrate this finding for the contract quantities 0.5Mt, 0.67Mt, 0.83Mt, and 1.0Mt. Note, however, that only in the case of ±50 percent AAC regulations does the increased flexibility enable situations whereby the expected present value of the carbon contract is greater than the expected opportunity cost of foregone timber values; specifically, at high carbon prices and contracts over 0.5Mt. At ±25 percent AAC regulations there are scenarios for which the expected present value of the carbon contract are positive but they do not exceed the expected opportunity cost of foregone timber values. Therefore only in the case of ±50 percent AAC regulations does the increased flexibility influence the firm to enter a contract because of the expected present value of the contract. Of note though, this is above $478.37/tonne of carbon with a 0.67Mt contract, approximately $308/tonne at 0.83Mt, and between $150/tonne and $200/tonne at 1.0Mt. Thus, for the most part contracts with more flexible AAC regulations provide the firm with access to higher expected timber values, which are large enough to offset the cost of entering a carbon contract.

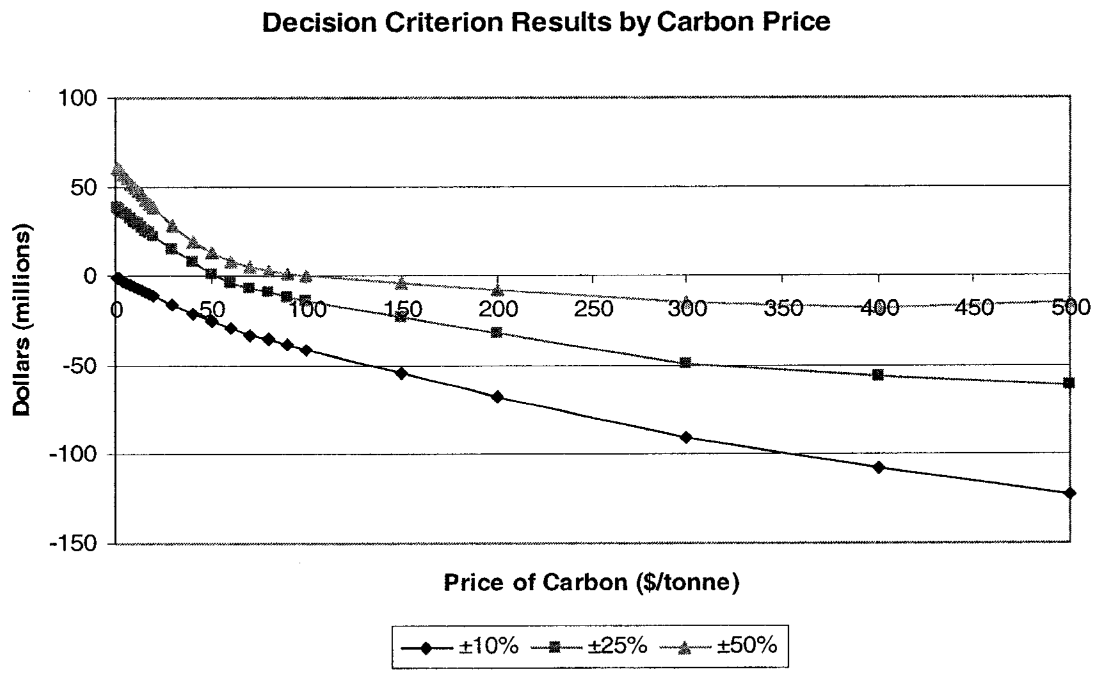

Figure 5-13 Decision Criterion Results – Expected Present Value of Timber and the Carbon Contract minus the Expected Present Value of Timber in the Baseline Case – by Carbon Price for 0.5Mt Contracts

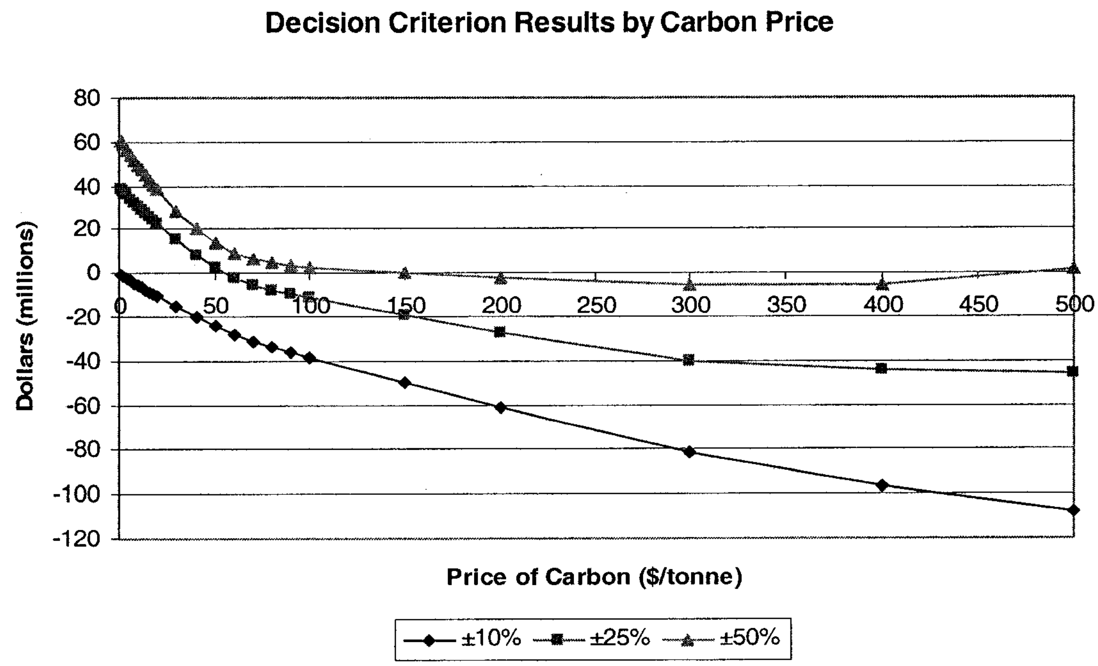

Figure 5-14 Decision Criterion Results – Expected Present Value of Timber and the Carbon Contract minus the Expected Present Value of Timber in the Baseline Case – by Carbon Price for 0.67Mt Contracts

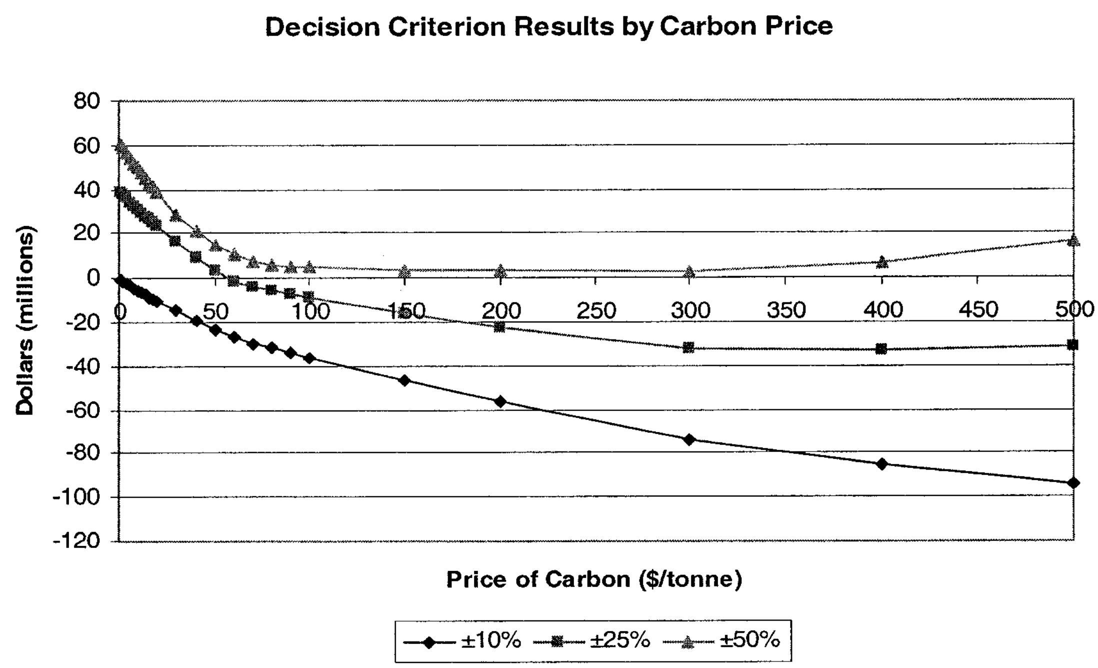

Figure 5-15 Decision Criterion Results – Expected Present Value of Timber and the Carbon Contract minus the Expected Present Value of Timber in the Baseline Case – by Carbon Price for 0.83Mt Contracts

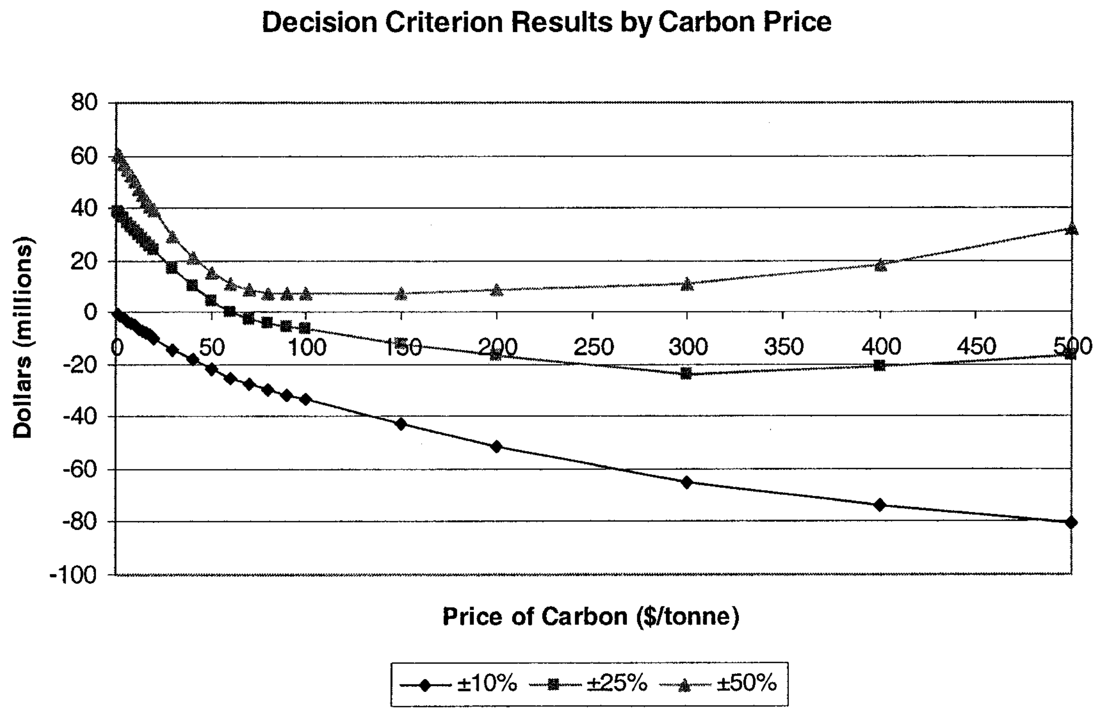

Figure 5-16 Decision Criterion Results – Expected Present Value of Timber and the Carbon Contract minus the Expected Present Value of Timber in the Baseline Case – by Carbon Price for 1.0Mt Contracts

What is also evident from Figures 5-13 to 5-16 is that the firm prefers a low price of carbon. The curves displayed in these figures summarize the net change in timber and carbon values compared to the baseline scenario. In each figure, paying attention to the curves for AAC levels ±25 percent and ±50 percent, the net increase in timber and carbon values is the greatest at a carbon price of $1/tonne. For example, when the firm enters a 1.0Mt contract with AAC regulations of ±50 percent at a carbon price of $1/tonne the expected present value of timber and the carbon contract is $736,812,245.35 whereas if the price of carbon is $500/tonne this value is $708,462,693.87 (Figure 5-16). Under either scenario the firm expects to be better off by entering the contract versus the business-as-usual scenario, however when the price of carbon is $1/tonne the firm's management decisions lead to a decrease in expected carbon stock levels. Regardless of which contract the firm would enter, in terms of the contract quantity and AAC regulation level, the firm prefers a low carbon price because the expected present value of timber and the carbon contract is highest for these scenarios (see Appendix 1). This is explained by the results which show that while at higher carbon prices the firm may experience a positive contract value that more than offsets the expected opportunity cost of timber, at lower carbon prices the additional expected timber values from more flexible AAC regulations also more than offset the expected cost of the contract but to a greater degree, thus resulting in a higher expected present value of timber and the carbon contract. However, these results are conditional upon the model assumptions of risk neutrality, that replacement credits can be used to fully cover contract credit shortfalls, and that the price of replacement credits equals the contract carbon price.

Changing the price of replacement carbon credits relative to the contract price or constraining the availability of replacement credits would alter the firm's decision to enter contracts. It is likely that both of these options would diminish the likelihood that the firm would enter into a contract, given the particular contract formulation used in this study. Increasing the price of replacement credits would reduce the expected present value of the contract thereby making the contract a more costly venture. Restricting the availability of replacement credits reduces the firm's options for supplying the target carbon quantities, which would constrain the optimization problem significantly. The firm would be required to generate a minimum number of credits in order to satisfy its contract obligations and doing so may be costly in terms of the expected opportunity cost of foregone timber value. Furthermore, it may not be possible to work with these constraints unless the firm has greater flexibility in regard to the AAC regulations.

5.5 *Carbon Supply Contracts and Expected Carbon Stock Levels*

Given that from a policy standpoint the objective of carbon supply contracts is to provide the necessary incentives for enhanced forest carbon management and to increase the stock of forest carbon, how do those contracts that the firm would enter perform in terms of expected carbon stock levels? Do these contracts result in carbon stock levels that meet the contract target quantities? If not, how significant is the firm's reliance on replacement carbon credits for meeting contract carbon supply in each case? Recall that for the contract quantities evaluated between 0.5Mt and 1.0Mt the firm would not enter a contract with AAC regulations of ±10 percent for any carbon price between $1/tonne and $500/tonne.

What is important to point out here is that in this model the supply of carbon is the contract target amount. This is because the carbon contract operates under the assumption that the supplier will purchase replacement credits when actual expected carbon stock levels are less than the target amount, including below baseline, thereby ensuring that the buyer of carbon credits receives the amount of carbon credits specified in the contract.

Already it has been demonstrated that, for the particular contract arrangement formulated in this study, when the firm decides to enter a contract it may do so for reasons other than the value of the carbon contract. When the AAC regulations are relaxed to ±25 percent the firm will enter contracts of size 0.5Mt, 0.67Mt, 0.83Mt, and 1.0Mt up to a point, the break-even-price in each scenario, because it can cover the costs of meeting the contract through higher expected timber values. Thus, over the range of prices that satisfy the decision criterion for each contract quantity the firm is purchasing replacement credits to meet the contract supply targets.

Implicitly from Figures 5-2 through 5-5 the expected present value of these contracts up to the respective break-even-prices is negative, but is less in absolute value than the expected gain in timber value vis-à-vis the baseline scenario so the decision criterion is met. If the expected present value of the contract is negative then from equation (2) it can be shown that the expected net present value of replacement carbon credits must be greater than the contract value. This suggests that the firm must be replacing credits that have a discounted value in excess of the discounted value of the contract target increments.

For the 0.5Mt, 0.67Mt, 0.83Mt, and 1.0Mt contracts the firm expects to purchase replacement credits in periods T2 through T7 for failing to meet the contract supply target in each period and additional credits to cover carbon stock losses below baseline (Tables 5-2 through 5-5). Depending on the price of carbon in period T1 the firm may expect to purchase replacement carbon credits including carbon losses below baseline or just to cover the shortfall versus the target for that period. Moreover, unless the price of carbon is above $66.91/tonne, $66.30/tonne, $65.76/tonne, and $62.28/tonne for the 0.5Mt, 0.67Mt, 0.83Mt, and 1.0Mt contracts, respectively, there is an expected net loss of carbon relative to the contract baseline. Thus, for any contract that the firm would enter with AAC regulations of ±25 percent between 0.5Mt and 1.0Mt there is a net loss of expected forest carbon relative to the contract baseline because the break-even-prices are less than those prices just listed.

Table 5-2 Expected Total Replacement Carbon Credits (thousands) by Period for 0.5Mt Contract with ±25 Percent AAC Regulations for Selected Carbon Prices (to the contract break-even-price)

Price of Carbon ($/tonne)	Period						
	T1	T2	T3	T4	T5	T6	T7
1	178.16	1371.53	2516.19	3298.62	3885.45	4244.59	4673.43
2	178.16	1371.53	2516.19	3290.22	3857.11	4203.12	4622.08
4	177.69	1364.47	2498.85	3269.11	3826.47	4171.26	4564.82
6	177.67	1344.86	2460.69	3228.67	3777.65	4113.31	4491.11
8	161.07	1313.04	2427.90	3192.32	3734.98	4063.74	4422.19
10	132.77	1232.46	2287.37	3022.85	3573.51	3917.26	4274.44
12	127.77	1210.79	2246.62	2967.59	3504.90	3844.56	4195.57
14	56.36	1032.17	2035.41	2760.24	3332.64	3689.19	4024.01
16	56.36	1028.61	2022.09	2738.20	3312.57	3663.16	3966.29
18	51.63	1016.11	2000.87	2716.20	3291.47	3635.76	3895.79
20	45.70	1001.28	1975.50	2688.87	3261.32	3609.58	3837.96
30	42.76	832.25	1706.22	2411.01	2999.40	3335.94	3543.02
40	12.65	536.01	1063.19	1645.99	2227.49	2603.59	2898.28
50	11.96	520.08	1048.38	1504.61	1925.41	2127.82	2135.20
60	0.14	505.85	912.59	825.13	914.64	869.04	937.46

Table 5-3 Expected Total Replacement Carbon Credits (thousands) by Period for 0.67Mt Contract with ±25 Percent AAC Regulations for Selected Carbon Prices (to the contract break-even-price)

Price of Carbon ($/tonne)	Period						
	T1	T2	T3	T4	T5	T6	T7
1	195.16	1426.78	2609.69	3430.37	4055.45	4414.59	4843.43
2	195.16	1426.78	2609.69	3421.97	4027.11	4373.11	4792.08
4	194.69	1419.72	2592.35	3400.86	3996.47	4341.26	4734.82
6	194.67	1400.11	2554.19	3360.42	3947.65	4283.31	4661.11
8	178.07	1368.29	2521.40	3324.07	3904.98	4233.74	4592.19
10	149.77	1287.71	2380.87	3154.60	3743.51	4087.23	4444.46
12	144.77	1266.04	2340.12	3099.34	3674.90	4014.56	4365.57
14	73.36	1087.42	2128.91	2891.99	3502.64	3859.19	4194.01
16	73.36	1083.86	2115.59	2869.95	3482.57	3833.16	4136.29
18	68.63	1071.36	2094.37	2847.95	3461.47	3805.76	4065.75
20	62.70	1056.53	2069.00	2820.62	3431.32	3779.58	4007.93
30	59.76	887.50	1799.72	2542.76	3169.39	3505.93	3713.06
40	29.65	591.26	1156.69	1777.74	2397.49	2773.59	3068.28
50	28.96	575.33	1141.88	1636.36	2095.41	2297.82	2305.20
60	17.14	561.10	987.18	934.80	1048.80	1002.36	1057.38

Table 5-4 Expected Total Replacement Carbon Credits (thousands) by Period for 0.83Mt Contract with ±25 Percent AAC Regulations for Selected Carbon Prices (to the contract break-even-price)

Price of Carbon ($/tonne)	Period						
	T1	T2	T3	T4	T5	T6	T7
1	211.16	1478.78	2697.69	3554.37	4215.45	4574.59	5003.43
2	211.16	1478.78	2697.69	3545.97	4187.11	4533.11	4952.08
4	210.69	1471.72	2680.35	3524.86	4156.47	4501.26	4894.82
6	210.67	1452.11	2642.19	3484.42	4107.65	4443.31	4821.11
8	194.07	1420.29	2609.40	3448.07	4064.98	4393.74	4752.19
10	165.77	1339.71	2468.87	3278.60	3903.51	4247.23	4604.46
12	160.77	1318.04	2428.12	3223.34	3834.90	4174.56	4525.57
14	89.36	1139.42	2216.91	3015.99	3662.64	4019.19	4354.01
16	89.36	1135.86	2203.59	2993.95	3642.57	3993.16	4296.29
18	84.63	1123.36	2182.37	2971.95	3621.47	3965.76	4225.75
20	78.70	1108.53	2157.00	2944.62	3591.32	3939.58	4167.93
30	75.76	939.50	1887.72	2666.76	3329.40	3665.94	3873.02
40	45.65	643.26	1244.69	1901.74	2557.49	2933.59	3228.28
50	44.96	627.33	1229.88	1760.36	2255.41	2457.82	2465.20
60	33.14	613.10	1055.69	1035.99	1171.88	1124.99	1169.65

Table 5-5 Expected Total Replacement Carbon Credits (thousands) by Period for 1.0Mt Contract with ±25 Percent AAC Regulations for Selected Carbon Prices (to the contract break-even-price)

Price of Carbon ($/tonne)	Period						
	T1	T2	T3	T4	T5	T6	T7
1	228.16	1534.03	2791.19	3686.12	4385.45	4744.59	5173.43
2	228.16	1534.03	2791.19	3677.72	4357.11	4703.11	5122.08
4	227.69	1526.97	2773.85	3656.61	4326.47	4671.26	5064.82
6	227.67	1507.36	2735.69	3616.17	4277.65	4613.31	4991.11
8	211.07	1475.54	2702.90	3579.82	4234.98	4563.74	4922.19
10	182.77	1394.96	2562.37	3410.35	4073.51	4417.23	4774.46
12	177.77	1373.29	2521.62	3355.09	4004.90	4344.56	4695.57
14	106.36	1194.67	2310.41	3147.74	3832.64	4189.19	4524.01
16	106.36	1191.11	2297.09	3125.70	3812.57	4163.16	4466.29
18	101.63	1178.61	2275.87	3103.70	3791.47	4135.76	4395.75
20	95.70	1163.78	2250.50	3076.37	3761.32	4109.58	4337.93
30	92.76	994.75	1981.22	2798.51	3499.39	3835.93	4043.06
40	62.65	698.51	1338.19	2033.49	2727.49	3103.59	3398.28
50	61.96	682.58	1323.38	1892.11	2425.41	2627.82	2635.20
60	50.14	668.35	1132.65	1147.68	1308.30	1258.17	1290.72
70	0.00	384.66	521.25	655.45	716.03	343.63	248.67

In the previous section it was shown that based on the decision criterion the firm would enter contracts with AAC regulations of ±50 percent. Also explained was that depending on the contract size and the price of carbon either additional expected timber values or the expected present value of the carbon contract influences the firm's decision to enter a contract. This, in turn, may have implications for expected carbon stock levels.

For the 0.5Mt contract with AAC regulations of ±50 percent the results are not altogether different from those when the contract set AAC regulations at ±25 percent. Likewise, over the range of carbon prices that the firm would decide to enter the contract, up to $103.44/tonne of carbon, the expected present value of the contract is negative and additional expected timber values offset the expected cost of the contract. What changes are the relative numbers of replacement carbon credits the firm must purchase by period at each carbon price (Table 5-6). Of note, for certain carbon prices in periods T1 and T2 the expected carbon stock meets or exceeds the associated target supply level in those periods. As with the previous scenarios at ±25 percent AAC levels unless the price of carbon reaches $97.39/tonne there will be an expected net loss of carbon over the duration of the contract. Therefore it the contract carbon price is above $97.39 the expected carbon stock will exhibit a net gain from the contract baseline.

Table 5-6 Expected Total Replacement Carbon Credits (thousands) by Period for 0.5Mt Contract with ±50 Percent AAC Regulations for Selected Carbon Prices (to the contract break-even-price)

Price of Carbon ($/tonne)	Period						
	T1	T2	T3	T4	T5	T6	T7
1	104.32	1166.73	3166.10	5083.77	6536.32	7741.69	8606.26
2	102.88	1159.54	3153.23	5061.18	6508.99	7701.35	8572.65
4	50.44	1133.19	3096.63	4944.40	6360.23	7500.81	8333.97
6	24.39	1076.52	3017.74	4843.74	6251.40	7388.54	8203.14
8	19.16	1041.61	2955.19	4768.74	6163.06	7297.72	8074.95
10	17.81	1030.25	2921.23	4705.48	6031.56	7119.85	7906.45
12	11.29	935.32	2796.47	4493.89	5795.04	6925.68	7699.06
14	11.41	934.92	2784.61	4468.82	5752.73	6878.27	7612.10
16	11.61	934.33	2762.82	4447.95	5693.56	6800.82	7319.43
18	0.00	935.51	2749.49	4441.36	5651.79	6722.26	7245.70
20	0.00	935.51	2748.14	4432.92	5640.42	6662.80	7039.84
30	0.00	908.61	2693.66	4046.82	5221.57	5748.30	5882.67
40	0.00	461.72	1715.23	3020.00	4028.14	4505.33	4566.96
50	0.00	463.31	1637.03	2788.27	3471.04	3268.16	2920.26
60	0.00	462.00	1564.37	2128.96	2316.47	2115.66	1911.95
70	0.00	210.81	916.31	1535.80	1549.07	828.52	558.91
80	-5.76	214.59	808.39	1237.07	1193.00	578.44	195.97
90	-6.58	98.10	556.69	778.78	815.87	422.40	143.01
100	-8.95	-13.73	353.08	692.64	749.29	318.57	131.31
150	-19.63	-17.26	171.98	549.81	635.87	283.44	116.62

Note: A negative value indicates the amount by which expected carbon stock is above the target.

When considering a 0.67Mt contract the decision by the firm to enter the contract is initially based on the additional expected timber values that arise from more flexible

AAC regulations, until a carbon price of $151.96/tonne is reached. At or below this carbon price the expected present value of the contract is negative and the firm can expect to purchase replacement credits in periods T2 to T7, and depending on the price of carbon in period T1 as well (Table 5-7). Note that once the price of carbon reaches $88.80/tonne there is an expected net gain in carbon stock relative to the contract baseline but the firm still expects to purchase replacement credits in some periods. Above $478.37/tonne of carbon the expected present value of the contract exceeds the expected opportunity cost of foregone timber, as the firm has altered the optimal forest rotation in order to sequester more carbon, and the firm will again enter the 0.67Mt contract with AAC regulations ±50 percent (recall Figure 5-7). Also, at or above this carbon price the contract value exceeds the expected net present value of replacement credits. From Table 5-7, only in period T7 will the firm need to purchase any replacement credits.

Table 5-7 Expected Total Replacement Carbon Credits (thousands) by Period for 0.67Mt Contract with ±50 Percent AAC Regulations

Price of Carbon ($/tonne)	Period						
	T1	T2	T3	T4	T5	T6	T7
1	121.32	1221.98	3259.60	5215.52	6706.32	7911.69	8776.26
2	119.88	1214.79	3246.73	5192.93	6678.99	7871.35	8742.65
4	67.44	1188.44	3190.13	5076.15	6530.23	7670.80	8503.96
6	41.39	1131.77	3111.24	4975.49	6421.40	7558.54	8373.10
8	36.16	1096.86	3048.69	4900.49	6333.06	7467.72	8244.95
10	34.81	1085.50	3014.73	4837.23	6201.56	7289.85	8076.45
12	28.29	990.57	2889.97	4625.64	5965.04	7095.67	7869.06
14	28.41	990.17	2878.11	4600.57	5922.73	7048.27	7782.10
16	28.61	989.58	2856.32	4579.70	5863.56	6970.82	7489.43
18	0.00	992.96	2824.82	4566.76	5829.62	6897.27	7412.75
20	0.00	992.96	2823.46	4558.12	5818.01	6838.19	7208.56
30	0.00	966.31	2701.77	4088.63	5328.85	5819.09	5983.44
40	0.00	512.49	1731.31	3067.42	4106.15	4566.86	4662.25
50	0.00	522.27	1671.17	2839.33	3563.66	3336.37	2985.50
60	0.00	505.50	1544.40	2094.05	2349.31	2128.62	1947.58
70	0.00	257.20	972.20	1610.24	1583.96	865.22	589.03
80	0.00	257.20	887.14	1318.47	1215.98	594.24	202.68
90	0.00	122.88	593.11	844.91	850.91	443.42	150.09
100	0.00	39.35	431.94	769.54	784.51	342.17	138.69
150	-2.63	37.72	252.63	649.84	662.24	307.82	121.85
200	-2.63	37.72	240.52	622.79	654.13	289.55	121.30
300	-4.76	22.06	207.29	557.84	645.28	296.51	118.56
400	-2604.01	-2847.50	-2395.79	-1747.40	-1093.20	-515.83	67.37
500	-2849.08	-3106.02	-2623.94	-1990.77	-1309.54	-626.25	61.33

With AAC regulations of ±50 percent, increasing the contract size from 0.67Mt to 0.83Mt and 1.0Mt yielded results such that given the decision criterion the firm would enter the 0.83Mt and 1.0Mt contracts regardless of whether the price of carbon is as low as $1/tonne or as high as $500/tonne. However, depending on the price of carbon there are very different consequences for the expected carbon stock levels relative to the contract baseline. In the case of the 0.83Mt contract if the price of carbon is less than $84.69/tonne there will be an expected net loss of carbon whereas above this carbon price the expected carbon stock increases relative to the contract baseline. The corresponding carbon price for the 1.0Mt contract is $80.63/tonne. In either case the firm will expect to purchase replacement credits in periods T2 to T7 below a carbon price of $400/tonne (Tables 5-8 and 5-9). However, above $306.11/tonne for carbon in the 0.83Mt contract and at carbon prices greater than $98.38/tonne for the 1.0Mt contract the contract value is greater than the expected net present value of the contract, as the expected present value of the contract is positive (refer to Figures 5-8 and 5-9).

Table 5-8 Expected Total Replacement Carbon Credits (thousands) by Period for 0.83Mt Contract with ±50 Percent AAC Regulations

Price of Carbon ($/tonne)	Period						
	T1	T2	T3	T4	T5	T6	T7
1	139.35	1272.94	3344.25	5337.14	6863.20	8068.28	8933.45
2	135.88	1266.79	3334.73	5316.93	6838.99	8031.35	8902.65
4	83.44	1240.44	3278.13	5200.15	6690.23	7830.81	8663.97
6	57.39	1183.77	3199.24	5099.49	6581.40	7718.54	8533.14
8	52.16	1148.86	3136.69	5024.49	6493.06	7627.72	8404.95
10	50.81	1137.50	3102.73	4961.23	6361.56	7449.85	8236.45
12	44.29	1042.57	2977.97	4749.64	6125.04	7255.69	8029.07
14	44.41	1042.17	2966.11	4724.57	6082.73	7208.26	7942.09
16	44.61	1041.58	2944.32	4703.70	6023.56	7130.82	7649.43
18	11.70	1045.51	2908.22	4689.16	5991.59	7058.56	7571.79
20	11.10	1044.84	2906.22	4680.11	5979.69	6998.77	7367.97
30	4.65	1015.89	2772.08	4192.69	5479.70	5909.76	6060.06
40	0.52	560.10	1810.06	3120.62	4184.45	4647.36	4750.33
50	0.14	570.55	1742.21	2897.64	3641.14	3422.40	3041.11
60	0.14	552.57	1618.96	2137.25	2399.22	2180.69	1957.98
70	0.00	300.58	1023.51	1641.09	1627.30	923.14	616.80
80	0.00	300.58	957.35	1349.63	1231.83	628.68	206.65
90	0.00	145.05	622.00	854.35	865.00	475.92	152.71
100	0.00	86.59	500.51	787.63	798.86	369.79	141.76
150	0.00	85.99	316.70	694.58	677.42	325.28	125.47
200	0.00	80.74	310.77	693.00	675.93	321.96	125.42
300	0.00	61.76	272.24	643.28	668.69	318.03	123.42
400	-2711.36	-2926.29	-2440.83	-1778.97	-1095.10	-510.92	69.92
500	-2833.08	-3053.99	-2547.76	-2006.67	-1312.99	-625.51	64.02

Table 5-9 Expected Total Replacement Carbon Credits (thousands) by Period for 1.0Mt Contract with ±50 Percent AAC Regulations

Price of Carbon	Period						
($/tonne)	T1	T2	T3	T4	T5	T6	T7
1	156.35	1328.19	3437.75	5468.89	7033.20	8238.28	9103.45
2	152.88	1322.04	3428.23	5448.68	7008.99	8201.35	9072.65
4	100.44	1295.69	3371.63	5331.90	6860.23	8000.81	8833.97
6	69.16	1228.34	3278.17	5209.96	6731.62	7868.89	8685.60
8	68.49	1200.03	3223.00	5143.82	6650.78	7785.20	8563.40
10	67.81	1192.75	3196.23	5092.98	6531.56	7619.85	8406.45
12	61.29	1097.82	3071.47	4881.39	6295.04	7425.68	8199.06
14	61.41	1097.42	3059.61	4856.32	6252.73	7378.27	8112.10
16	61.61	1096.83	3037.82	4835.45	6193.56	7300.82	7819.43
18	28.70	1100.76	3001.72	4820.91	6161.59	7228.56	7741.79
20	28.10	1100.09	2999.72	4811.86	6149.69	7168.77	7537.97
30	21.65	1071.14	2865.68	4315.94	5595.29	5999.63	6138.06
40	17.52	615.35	1903.56	3174.28	4258.05	4727.83	4843.54
50	17.14	625.80	1835.71	2951.31	3726.79	3512.16	3128.14
60	17.14	607.82	1712.46	2174.14	2440.65	2222.25	1985.57
70	0.00	337.36	1086.55	1671.63	1669.30	957.70	648.26
80	0.00	337.36	1031.84	1377.48	1251.17	640.06	213.13
90	0.00	171.14	668.68	866.42	893.30	489.85	158.58
100	0.00	123.18	566.45	806.21	812.35	378.05	146.28
150	0.00	116.89	373.89	712.55	691.59	343.74	128.75
200	0.00	116.89	373.89	712.30	690.66	342.37	128.53
300	0.00	98.42	336.22	706.51	689.60	339.19	128.12
400	-2813.16	-3001.44	-2487.30	-1819.63	-1120.42	-520.15	72.58
500	-2816.08	-3008.14	-2481.54	-2023.31	-1310.44	-622.65	67.16

5.6 Section Summary

By examining the expected carbon stock levels and the expected replacement carbon credit purchases of the firm for the contracts it would decide to enter, in the preceding section it has been shown that while the intended purpose of a carbon contract mechanism is to create the necessary incentives for augmenting forest carbon stocks this may in fact not result. Given the type of contract being evaluated, with emphasis on the degree of responsibility the firm accepts for carbon stock losses to fire and the assumption equating the price of replacement credits with the contract carbon price, only for contracts with AAC regulations of ±50 percent between 0.5Mt and 1.0Mt in size will the contract yield a net gain in the expected carbon stock over the contract/planning horizon, a sufficient carbon price permitting. In contrast for each contract the firm would enter with AAC regulations at ±25 percent the expected carbon stock exhibits a loss relative to the contract baseline. Of course these results are preconditioned on the assumption that replacement credits are readily available in the quantities the firm requires at a particular price. Perhaps one of the most interesting findings, from a policy perspective, is that if a contract provides the firm with access to more flexible AAC regulations then based on the decision criterion the firm could enter a carbon supply contract and actually reduce the expected forest carbon stock below baseline. Regardless of which contract scenario the firm would enter replacement carbon credits were required in at least one period, with the expected purchases of replacement carbon credits declining as the price of carbon increases in each case.

Chapter 6: Conclusions and Recommendations

6.1 Introduction

This study provides an analysis of optimal forest management when carbon is considered in the presence of the risk of fire disturbance. A discrete stochastic sequential programming model of optimal forest-level rotation was developed and used to examine whether or not carbon supply contracts are in the interest of the firm, and if so, why the firm would enter a particular contract, how changing the arrangement of the contract would affect the firm's decision to enter a contract, and how those contracts that the firm would enter perform regarding the potential for carbon credit generation. From the perspective of the firm this study evaluates how the decision to enter carbon supply contracts would affect the firm's economic performance and based on an appropriate decision criterion it provides an indication of the firm's willingness to enter a particular set of contracts. As carbon supply contracts may become a potential business opportunity for Canadian forestry firms this research presents a significant contribution to studying how a firm would respond to a contract. Moreover, because this research is in an emerging topic area, which at present has not received considerable study, it provides a starting point for identifying a number of contractual issues that should undergo examination.

Principal benefits of this research have been inclusiveness, merging models of forest management scheduling with carbon budget models, and flexibility in the model formulation. Through the use of carbon accounting equations the model formulation has the capacity to illustrate how carbon stocks change due to optimal forest rotation decisions, and demonstrates that in response to a carbon contract a firm may modify how it is managing the forest in order to increase the amount of carbon sequestered in forest carbon sinks. Also, because of the particular model formulation real risk management questions can be addressed due to the carbon accounting equations; i.e., carbon credits are not earned for quantities of carbon sequestered above contract targets and failure to meet these targets is penalized depending on the extent of the shortfall. These possibilities are contingent not only on forest management decisions but fire behaviour as well. Therefore, risk management strategies can be interpreted from optimal model solutions. As well, the manner with which the model has been programmed is very flexible and without major adjustments will accommodate many of the key recommendations listed subsequently.

6.2 Conclusions

From the perspective of the firm its objective is to maximize expected profits irrespective of the status of the expected carbon stock. Depending on the contract scenario the firm will alter its management decisions in order to maximize profit even at the expense of incurring the cost of replacement carbon credits in excess of the value of the contract. While society as a whole may have an interest in the amount of carbon stored in forest carbon sinks the firm's interest is to meet its contract obligations. As such, the availability of replacement credits was critical to the firm's decision in many cases to enter a contract. So long as the firm can obtain additional expected timber value, in those contracts that permit more flexible AAC regulations, offsetting the cost of the contract it will be in the interest of the firm to enter a contract. Otherwise, a large contract size and/or high carbon prices are necessary incentives for the firm to generate sufficient carbon credits so that the expected present value of the contract can offset the expected opportunity cost of foregone timber values. However, the carbon prices quoted in the economic literature may not support the contract prices needed here (see Sedjo, 2001). What the results do suggest, though, is that both the AAC regulation levels and the size of the contract affect the firm's break-even-price and that the combination of AAC regulations and contract size will create different incentives for how the firm will proceed with maximizing its objective, for the particular contract structure examined.

With the AAC regulations set at ±10 percent the firm requires a large contract quantity if it is to enter the contract. Because under these AAC regulations the firm does not have potential access to additional timber values it may only acquire additional revenue from the contract value and by not incurring the cost of replacement credits. At smaller contract quantities the liability of the contract is outweighed by the expected benefit to the firm and therefore between 0.5Mt and 1.0Mt the firm justifiably would not enter into a contract. If the contract size were increased to 2.0Mt the firm would enter a contract at a high carbon price, \$464.28/tonne. If the contract quantity is increased further yet to 5.0Mt the break-even-price drops to \$21.27/tonne of carbon. Thus at these higher contract quantities the liability of the contract is more than offset by the expected benefit of the contract. Hence, this demonstrates the importance of the contract quantity given this particular contract arrangement, particularly with respect to the firm's level of responsibility for carbon stock losses to fire, assuming replacement credits are available at the contract price and that the firm is a risk neutral decision-maker. Under the latter condition, as discussed in chapter five, it is possible that once the contract size reaches some threshold quantity the liability of replacement credits would be too great for the firm to be willing to enter the contract. What is also important to note, from a public perspective, is that for these contracts the expected carbon stock levels do not drop below baseline, as may occur with more flexible AAC regulations.

As with AAC regulations of ±10 percent, when more flexible AAC regulations are introduced increasing the contract quantity is important for how the firm manages the liability it faces as part of the contract level of responsibility for carbon stock losses to fire. Disregard for the moment those contracts with ±50 percent AAC regulations that the firm would enter because of additional expected timber value and instead focus only on those contracts the firm would enter whereby the expected present value of the carbon contract fully offsets the expected opportunity cost of foregone timber values. As the contract size increases the carbon price at which the expected present value of the carbon contract offsets the expected opportunity cost of foregone timber value decreases. As aforementioned, a larger contract may be necessary if the expected benefits of the contract are to offset the liability of the contract. If a larger contract cannot be negotiated, a very high carbon price in excess of $500/tonne would be necessary to influence the firm's decision to enter a contract. This conclusion should be qualified on the assumptions of risk neutrality, the price of replacement credits being equal to the contract price, and that contract shortfalls can always be met through acquisition of replacement credits. Relaxing these assumptions will alter model outcomes and lead to different conclusion about the importance of AAC regulations and contract size on the firm's decision to enter a contract. This should be an objective of subsequent research. With more flexible AAC regulations included in the contract scenarios the firm is more likely to enter a carbon contract, increasingly so as AAC regulations are further liberalized. However the impetus for the firm's decision is largely affected by additional expected timber values, which on balance exceed the expected cost of replacement credits needed to meet these contracts. So corresponding with more flexible AAC regulations are decreases in the expected carbon stock levels, at least initially at lower carbon prices. At ±50 percent AAC regulations once the price of carbon is sufficient there are contracts that the firm would enter which result in a net increase in expected carbon stock levels. Thus, policymakers should be aware that unless a sufficient carbon price can be obtained more flexible AAC regulations could actually result in a net decrease from baseline in the expected carbon stock.

What the results also suggest is that a larger contract quantity and more flexible AAC regulations are in the firm's interest. Of the four contract quantities and three AAC regulation levels the highest expected present value of timber and the carbon contract would be earned when the contract quantity is 1.0Mt, the AAC regulations are ±50 percent, and interestingly, when the price of carbon is $1/tonne (Appendix 1). At lower carbon prices the firm is relatively more reliant on replacement credits and as carbon price increases the firm changes the optimal rotation in order to increase expected carbon stocks and gradually reduce the number of replacement credits it must purchase. At the same time the expected timber value is decreasing. Because of the relative movement of the expected present value of timber and the expected present value of the contract the firm can achieve the highest profits at a low carbon price for contracts up to 1.0Mt. That even with a carbon price of $500/tonne the firm is not able under any contract scenario to achieve an expected present value of the contract which offsets the expected opportunity cost of foregone timber value more than the amount by which the additional expected timber value offsets the expected cost of the carbon contract when the carbon price is $1/tonne. Note however that above contract size 1.0Mt this result can be reversed.

In terms of public policy there are two major issues that will likely involve the provincial and federal governments regarding carbon contracts. These are one, the degree or level of responsibility a firm accepts for carbon stock losses due to fire disturbance, and two, the potential authority and responsibility to monitor and enforce contracts.

Previously it was mentioned that another set of model scenarios was completed which did not hold the firm responsible for carbon stock losses below baseline. While virtually eliminating the liability facing the firm, when the results of these model runs are compared with the corresponding model runs in this study, in each case removing this liability resulted in a reduction in the expected carbon stock levels. Because the cost of not meeting the contract was essentially capped the firm had little incentive otherwise to ensure that expected carbon stocks were above the contract baseline or in the vicinity of the contract targets. Thus governments must be cognizant of the types of incentives that different arrangements surrounding fire risk and carbon stock loss will create.

In regard to monitoring and enforcement, should a public authority assume this cost it may not be a socially responsible investment. If the contracts firms enter are of such an arrangement whereby the terms of the contract are largely met through acquisition of replacement credits and the expected carbon stock exhibits a net decline, like some model scenarios with more flexible AAC regulations, this may be socially undesirable. That is, under certain contract scenarios the firm would agree to enter a contract in order to gain access to more flexible AAC regulations thereby increasing timber values and profits. It could be argued that by having a public agency assume some of the transactions cost in these cases would essentially be tantamount to subsidizing higher profits in the forestry sector. A public agency charged with the authority of monitoring carbon contracts would have to consider the transactions cost of arbitrating against the perceived public benefit of facilitating carbon sequestration projects.

6.3 Recommendations

The number and range of additional contract scenarios that could be incorporated into the model developed in this thesis are significant, which is a credit to the versatility of how the model has been programmed. That said, while the work presented in this study focuses on a particular contract arrangement it serves as an important starting point for evaluating firm level responses to carbon credit supply contracts under risk of fire disturbance. However, if time permitted the following recommendations would go some way to further improving the amount and quality of information available to policymakers and firms engaged in forest carbon sequestration and management.

As mentioned previously a particular contract arrangement was explicitly included in this thesis. A second contract type, under which the firm was responsible only for the carbon stock between the contract baseline and targets and not for losses below baseline, was also modelled. This contract arrangement virtually removed all of the liability facing the firm and the results were thus rather trivial. The expected present value of the contract was positive for all carbon prices and regardless of carbon price, contract size or the set of AAC regulations the firm would decide to enter the contract. However, along with the results from the other contract type, what has become apparent is that the assumption that sets the contract price for carbon equal to the replacement credit price was critical for the observed results. In addition, the assumption of risk neutrality underlies these results. Extending the model to account for the supplier level of risk aversion and allowing the price of replacement credits to be higher than the contract carbon price would influence the model outcomes.

Alternate contract scenarios that are of interest would explore further the contract carbon price to replacement credit price ratio, possible restrictions on the availability of replacement credits, different contract duration and verification period setup, and changing the level of carbon credit permanence, as well as some other treatment of firm responsibility for carbon stock losses to fire and the level of risk aversion. In addition some of the assumptions used in this model could be relaxed to improve the model.

Increasing the price of replacement carbon credits relative to the contract price and/or restricting the number of replacement credits that can be purchased by the firm could operate as supplementary incentives for the firm to sequester carbon. It would be interesting to investigate how much of a penalty differential would need to be added to the price of replacement credits in order to significantly change the optimal firm level response; i.e., by how much would the replacement credit price have to increase in order to change the optimal rotation, and subsequently expected harvest volumes and carbon stocks, as compared to contract scenarios which set the contract and replacement credit prices equal. In addition, by modeling different AAC regulations, as was done here, it could be investigated whether in order to generate some change in firm response due to a penalty on replacement credits more flexible AAC regulations would be required. What would this mean for the expected value of the carbon contract and how would the firm's decision to enter a contract be altered? A second proposal could include placing a quota on the number of replacement credits available to the firm. It is likely that replacement credits would not be as readily available in all periods as assumed in this model so placing some restriction on the number of replacement credits which the firm can purchase could also prove interesting.

Further research could also be devoted to alternate contract arrangements in terms of the contract duration and verification periods, as well as the treatment of the permanence issue. In the present study the contract was for five periods and carbon stock verification occurs in each period of the contract. This condition could easily be modified to accommodate other carbon stock verification schemes, with longer or shorter durations and using a different set of periods to check carbon stocks against the baseline and contract target quantities. Caution would have to be exercised though in programming the model and its equations to consider any flux in carbon stock levels about the baseline in order to establish and certify that carbon credits generated are in fact net surplus credits. In addition this model assumed that the contract target quantities in each period would increase linearly to the final target amount. There are numerous other ways in which this could be set-up. The permanence issue could also be made less or more rigid. For the contract as modelled, the contract target quantity was to be met in the fifth and final period of the contract, but this amount of carbon was to be maintained over the two remaining planning periods. This condition of carrying over the target quantity of carbon could be dropped altogether, or, the firm could be contracted to secure the target amount of carbon for subsequent periods. Additional research should explore carbon credit rental mechanisms as an alternative to permanent storage-type contracts.

It was mentioned that while this study focussed on model scenarios in which the firm was fully responsible for carbon stock losses to fire a second type of contract for which the firm was not held responsible for carbon stock losses below baseline underwent cursory examination. Still other contract scenarios are possible for different treatments of the level of responsibility for fire, whereby the firm would be held responsible for some lesser degree of carbon stock loss than modelled here. This could be achieved for example by requiring the firm to replace carbon credits for losses below baseline but only to some predetermined level, essentially capping the firm's liability. Whether or not this type of arrangement has merit is questionable however it is possible that policymakers could be interested in ways of reducing firm liability via some role for the government.

Perhaps the government or some other agency would cover the remaining liability or this could be achieved through insurance.

Some of the model assumptions could also be relaxed should the necessary data be available. In this model carbon prices, both contract and replacement credit prices, were held constant across all of the periods. Altering this assumption would be straightforward given suitable data. Further, it could be possible to move beyond a discrete two-point representation of fire disturbance through additional discretization of the historical fire data. However valuable this may be, this would be a very costly initiative not only in terms of model size but time as well.

An additional improvement on the model formulation used in this study would incorporate expected utility maximization. Given that the objectives of the model were to maximize the expected present value of timber in the baseline scenario and the expected present value of timber and the carbon contract for all contract scenarios, as explained in chapter three this particular model structure assumed risk neutrality. Therefore it would be beneficial to integrate expected utility theory within the model framework, allowing the researcher to investigate the impact of different levels of risk aversion on the firm's decision to enter a contract. However, doing so may result in additional model complexity and increase the number of equations and variables in the model.

Due to the size and level of complexity that already exists within the discrete stochastic sequential programming model it may be necessary when integrating expected utility theory to utilize separable programming in order for GAMS algorithms to have the capacity to solve the model. This will result in the creation of additional equations and variables, increasing the size of the model, but at the benefit of retaining a linear model structure. Furthermore, it is possible that without separable programming techniques, and instead using a non-linear expected utility function, the available non-linear solvers will not be able to solve the model. Significant difficulty was encountered in trying to solve this model as a linear programming problem. Also, the researcher must decide on an appropriate functional form for the utility function, considering that the choice of functional form will impose certain assumptions on the model, and, whether to maximize the utility of the expected present value of timber and the carbon contract or the expected utility of the present value of timber and the carbon contract.

As a final recommendation, without a single additional model run there are vast amounts of data produced in the model output of the scenarios presented in this thesis that could not be investigated due to time constraints. Much of this data was evaluated during the model development stage of this research to ensure that the model was operating and behaving correctly, but this data did not undergo any analysis. For example it would be very interesting to look in greater detail at how the optimal rotation is changing as contract parameters are allowed to vary. Specifically, as contract parameters are manipulated how is the firm changing management and regeneration prescriptions; its choice of species or yield groups to plant; and where, in terms of location or site class, and when, in what periods, is the firm engaging in these activities in order to sequester additional carbon above baseline? Unfortunately because of time constraints and due to the quantity of data generated by these types of mathematical programming models one has to be selective in regard to the questions one asks and attempts to answer, knowing that considerable data will go unexamined and that many questions remain to be explored.

6.4 Final Summary

Despite the numerous recommendations just listed this study is an important introductory analysis of optimal forest management when carbon is considered in the presence of the risk of fire disturbance, providing a foundation for future research in this area. Moreover, the discrete stochastic sequential programming model of optimal forest-level rotation that was developed is of tremendous value and its flexibility can facilitate numerous additional studies that will build on the research presented herein. Given a particular set of contract scenarios the model was used to determine when the decision to enter a carbon supply contract was in the interest of the firm and to investigate why the firm would enter a particular contract. In doing so it was discovered that an unintended consequence of this particular contract could be a decline in the expected carbon stock level. Also found was that potential regulatory change concerning AAC levels, initially thought to reduce the firm's break-even-price, could be perceived by the firm as a means to increase harvest levels and subsequently its profits, at the expense of forest carbon. Further, it was shown that given the particular contract arrangement the availability of replacement credits was vital if the firm is to meet its contract credit supply obligations. As such, these conclusions suggest that the particular contract structure being examined should not be recommended as a mechanism to generate carbon credits. The conditions under which the contract actually produced carbon credits in any significant quantity may not be realized in the market. Lastly, because of the level of liability the firm assumed with respect to fire disturbance contract quantity was a critical contract parameter altering the expected present value of the contract and the firm's decision to enter a contract. This research presents a significant contribution to studying how a firm would respond to a carbon supply contract, highlighting issues of importance for both firms and government regarding forest carbon management and carbon contracts.

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Appendix 1 – Expected Present Value of Timber and the Carbon Contract

Table A1-1 Expected Present Value of Timber and Carbon Contract for 0.5Mt Contracts at Carbon Prices

Carbon Price ($/tonne)	EXPVTCcon (millions)		
	AAC±10 %	AAC±25 %	AAC±50 %
1	675.60	714.85	736.79
2	675.01	713.95	735.52
4	673.85	712.17	733.03
6	672.69	710.40	730.59
8	671.54	708.66	728.20
10	670.42	706.96	725.85
12	669.31	705.28	723.55
14	668.24	703.62	721.29
16	667.19	702.01	719.06
18	666.16	700.41	716.86
20	665.13	698.82	714.67
30	660.15	691.04	704.30
40	655.43	684.00	696.03
50	651.06	677.88	689.58
60	646.98	672.68	684.44
70	643.53	669.32	681.15
80	640.63	666.91	679.06
90	637.86	664.74	677.56
100	635.18	662.68	676.48
150	622.09	653.00	672.30
200	609.32	643.68	668.68
300	586.02	627.06	661.51
400	568.49	620.13	658.51
500	553.48	615.04	661.76

Table A1-2 Expected Present Value of Timber and Carbon Contract for 0.67Mt Contracts at Carbon Prices

Carbon Price ($/tonne)	EXPVTCcon (millions)		
	AAC±10 %	AAC±25 %	AAC±50 %
1	675.62	714.87	736.80
2	675.05	713.99	735.54
4	673.93	712.25	733.06
6	672.82	710.52	730.64
8	671.72	708.82	728.27
10	670.64	707.16	725.94
12	669.58	705.51	723.66
14	668.55	703.90	721.42
16	667.55	702.33	719.21
18	666.56	700.77	717.03
20	665.58	699.22	714.86
30	660.82	691.63	704.67
40	656.32	684.79	696.64
50	652.18	678.87	690.41
60	648.35	673.89	685.55
70	645.24	670.79	682.58
80	642.64	668.68	680.80
90	640.14	666.80	679.64
100	637.74	665.05	678.91
150	626.04	656.87	676.27
200	614.68	649.03	674.28
300	594.52	635.73	670.35
400	579.98	632.21	670.85
500	568.17	630.32	677.67

Table A1-3 Expected Present Value of Timber and Carbon Contract for 0.83Mt Contracts at Carbon Prices

Carbon Price ($/tonne)	EXPVTCcon (millions)		
	AAC±10 %	AAC±25 %	AAC±50 %
1	675.64	714.89	736.81
2	675.09	714.03	735.56
4	674.01	712.32	733.10
6	672.94	710.63	730.69
8	671.89	708.97	728.34
10	670.85	707.34	726.03
12	669.83	705.74	723.76
14	668.85	704.16	721.54
16	667.88	702.63	719.35
18	666.94	701.11	717.18
20	666.00	699.59	715.04
30	661.45	692.19	704.97
40	657.16	685.54	697.12
50	653.23	679.80	691.11
60	649.63	675.02	686.49
70	646.84	672.18	683.80
80	644.51	670.33	682.32
90	642.29	668.73	681.49
100	640.15	667.27	681.09
150	629.73	660.51	679.95
200	619.68	654.07	679.50
300	602.48	643.88	678.64
400	590.78	643.53	682.47
500	581.71	644.69	692.61

Table A1-4 Expected Present Value of Timber and Carbon Contract for 1.0Mt Contracts at Carbon Prices

Carbon Price ($/tonne)	EXPVTCcon (millions)		
	AAC±10 %	AAC±25 %	AAC±50 %
1	675.66	714.91	736.81
2	675.13	714.07	735.57
4	674.08	712.40	733.12
6	673.06	710.75	730.74
8	672.06	709.13	728.41
10	671.07	707.54	726.12
12	670.10	705.98	723.87
14	669.16	704.44	721.67
16	668.24	702.95	719.49
18	667.34	701.46	717.35
20	666.45	699.99	715.22
30	662.12	692.79	705.26
40	658.06	686.34	697.59
50	654.35	680.80	691.79
60	650.99	676.22	687.40
70	648.52	673.64	684.98
80	646.49	672.08	683.81
90	644.56	670.78	683.33
100	642.69	669.62	683.28
150	633.64	664.36	683.75
200	624.96	659.42	684.97
300	610.92	652.52	687.45
400	602.25	655.42	694.80
500	596.05	659.95	708.46

Appendix 2 – Expected Present Value of Timber

Table A2-1 Expected Present Value of Timber for 0.5Mt Contracts at Carbon Prices

Carbon Price ($/tonne)	EXPVTimber (millions)		
	AAC±10 %	AAC±25 %	AAC±50 %
1	676.19	715.75	738.06
2	676.18	715.74	738.05
4	676.17	715.72	737.94
6	676.15	715.66	737.82
8	676.10	715.57	737.68
10	675.98	715.41	737.50
12	675.86	715.32	737.14
14	675.64	714.95	737.04
16	675.53	714.86	736.78
18	675.43	714.77	736.63
20	675.32	714.68	736.42
30	674.79	714.03	733.85
40	673.56	709.46	724.49
50	672.00	706.71	718.59
60	670.57	698.39	710.95
70	665.04	688.06	698.13
80	663.37	685.09	694.26
90	662.04	683.85	688.73
100	661.92	682.70	685.65
150	660.67	681.12	683.18
200	660.22	680.62	683.12
300	639.95	659.90	682.87
400	629.66	641.63	648.12
500	627.34	635.92	642.85

Table A2-2 Expected Present Value of Timber for 0.67Mt Contracts at Carbon Prices

Carbon Price ($/tonne)	EXPVTimber (millions)		
	AAC±10 %	AAC±25 %	AAC±50 %
1	676.18	715.75	738.06
2	676.18	715.74	738.05
4	676.16	715.72	737.94
6	676.13	715.66	737.82
8	676.10	715.57	737.68
10	675.98	715.41	737.50
12	675.86	715.32	737.14
14	675.64	714.95	737.04
16	675.53	714.86	736.78
18	675.43	714.77	736.57
20	675.32	714.68	736.36
30	674.79	714.03	733.50
40	673.56	709.46	724.14
50	671.98	706.71	718.22
60	670.08	698.03	709.90
70	664.42	687.41	697.37
80	663.12	684.60	693.49
90	661.91	683.16	687.54
100	661.69	682.09	684.95
150	660.38	680.54	682.30
200	659.98	680.04	682.22
300	639.74	657.49	682.00
400	628.27	641.19	645.62
500	626.53	634.31	641.87

Table A2-3 Expected Present Value of Timber for 0.83Mt Contracts at Carbon Prices

Carbon Price ($/tonne)	EXPVTimber (millions)		
	AAC±10 %	AAC±25 %	AAC±50 %
1	676.18	715.75	738.06
2	676.18	715.74	738.05
4	676.16	715.72	737.94
6	676.10	715.66	737.82
8	676.09	715.57	737.68
10	675.98	715.41	737.50
12	675.86	715.32	737.14
14	675.64	714.95	737.04
16	675.53	714.86	736.78
18	675.43	714.77	736.55
20	675.32	714.68	736.34
30	674.79	714.03	733.31
40	673.56	709.46	723.77
50	671.98	706.71	717.78
60	669.56	697.66	709.22
70	663.93	686.87	696.58
80	662.78	684.13	692.64
90	661.73	682.52	686.17
100	661.47	681.43	684.09
150	660.22	679.98	681.32
200	659.71	679.48	681.28
300	639.33	655.17	681.04
400	628.13	640.58	643.20
500	626.48	632.78	640.91

Table A2-4 Expected Present Value of Timber for 1.0Mt Contracts at Carbon Prices

Carbon Price ($/tonne)	EXPVTimber (millions)		
	AAC±10 %	AAC±25 %	AAC±50 %
1	676.18	715.75	738.06
2	676.18	715.74	738.05
4	676.16	715.72	737.94
6	676.09	715.66	737.79
8	676.06	715.57	737.66
10	675.95	715.41	737.50
12	675.84	715.32	737.14
14	675.64	714.95	737.04
16	675.53	714.86	736.78
18	675.43	714.77	736.55
20	675.32	714.68	736.34
30	674.79	714.03	733.09
40	673.56	709.46	723.40
50	671.98	706.71	717.43
60	669.07	697.31	708.55
70	663.60	686.40	695.64
80	662.27	683.53	691.58
90	661.51	681.94	684.83
100	661.28	680.74	682.99
150	660.00	679.37	680.09
200	659.52	678.87	680.07
300	639.03	652.65	679.92
400	627.85	640.23	640.64
500	626.46	631.15	639.85

Appendix 3 – Expected Present Value of the Carbon Contract

Table A3-1 Expected Present Value of the Carbon Contract for 0.5Mt Contracts at Carbon Prices

Carbon Price ($/tonne)	EXPVCarbCon (millions)		
	AAC±10 %	AAC±25 %	AAC±50 %
1	-0.59	-0.90	-1.27
2	-1.17	-1.79	-2.53
4	-2.32	-3.55	-4.92
6	-3.46	-5.26	-7.23
8	-4.55	-6.91	-9.48
10	-5.56	-8.45	-11.65
12	-6.54	-10.04	-13.59
14	-7.40	-11.32	-15.75
16	-8.34	-12.85	-17.72
18	-9.27	-14.36	-19.77
20	-10.19	-15.86	-21.75
30	-14.65	-22.99	-29.55
40	-18.13	-25.46	-28.45
50	-20.94	-28.83	-29.01
60	-23.59	-25.71	-26.52
70	-21.51	-18.74	-16.98
80	-22.74	-18.18	-15.20
90	-24.18	-19.11	-11.17
100	-26.74	-20.02	-9.17
150	-38.59	-28.12	-10.88
200	-50.90	-36.94	-14.44
300	-53.92	-32.84	-21.36
400	-61.16	-21.51	10.39
500	-73.86	-20.88	18.91

Table A3-2 Expected Present Value of the Carbon Contract for 0.67Mt Contracts at Carbon Prices

Carbon Price ($/tonne)	EXPVCarbCon (millions)		
	AAC±10 %	AAC±25 %	AAC±50 %
1	-0.57	-0.88	-1.26
2	-1.13	-1.75	-2.51
4	-2.23	-3.47	-4.88
6	-3.31	-5.14	-7.18
8	-4.38	-6.75	-9.41
10	-5.34	-8.25	-11.56
12	-6.27	-9.80	-13.48
14	-7.09	-11.05	-15.62
16	-7.98	-12.53	-17.57
18	-8.87	-14.01	-19.54
20	-9.75	-15.46	-21.49
30	-13.98	-22.39	-28.83
40	-17.24	-24.66	-27.51
50	-19.80	-27.84	-27.81
60	-21.74	-24.14	-24.35
70	-19.18	-16.61	-14.79
80	-20.48	-15.93	-12.69
90	-21.76	-16.36	-7.90
100	-23.95	-17.04	-6.04
150	-34.34	-23.66	-6.03
200	-45.30	-31.01	-7.95
300	-45.22	-21.76	-11.66
400	-48.29	-8.98	25.23
500	-58.36	-3.99	35.80

Table A3-3 Expected Present Value of the Carbon Contract for 0.83Mt Contracts at Carbon Prices

Carbon Price ($/tonne)	EXPVCarbCon (millions)		
	AAC±10 %	AAC±25 %	AAC±50 %
1	-0.55	-0.86	-1.25
2	-1.09	-1.71	-2.50
4	-2.16	-3.40	-4.85
6	-3.16	-5.03	-7.13
8	-4.20	-6.60	-9.34
10	-5.13	-8.06	-11.47
12	-6.02	-9.58	-13.37
14	-6.79	-10.79	-15.50
16	-7.65	-12.23	-17.43
18	-8.49	-13.67	-19.37
20	-9.33	-15.09	-21.30
30	-13.34	-21.83	-28.33
40	-16.40	-23.92	-26.65
50	-18.75	-26.91	-26.67
60	-19.93	-22.64	-22.73
70	-17.09	-14.69	-12.79
80	-18.27	-13.81	-10.32
90	-19.44	-13.79	-4.69
100	-21.32	-14.16	-3.00
150	-30.48	-19.48	-1.37
200	-40.03	-25.40	-1.79
300	-36.85	-11.29	-2.40
400	-37.35	2.95	39.28
500	-44.77	11.91	51.70

Table A3-4 Expected Present Value of the Carbon Contract for 1.0Mt Contracts at Carbon Prices

Carbon Price ($/tonne)	EXPVCarbCon (millions)		
	AAC±10 %	AAC±25 %	AAC±50 %
1	-0.53	-0.84	-1.25
2	-1.05	-1.67	-2.49
4	-2.08	-3.32	-4.83
6	-3.02	-4.91	-7.05
8	-4.00	-6.44	-9.25
10	-4.88	-7.86	-11.38
12	-5.74	-9.34	-13.26
14	-6.48	-10.51	-15.37
16	-7.29	-11.91	-17.29
18	-8.09	-13.31	-19.21
20	-8.88	-14.69	-21.12
30	-12.67	-21.24	-27.83
40	-15.50	-23.12	-25.81
50	-17.63	-25.92	-25.64
60	-18.07	-21.09	-21.15
70	-15.08	-12.75	-10.66
80	-15.78	-11.45	-7.77
90	-16.95	-11.16	-1.50
100	-18.59	-11.13	0.29
150	-26.36	-15.02	3.66
200	-34.56	-19.45	4.90
300	-28.11	-0.13	7.53
400	-25.60	15.19	54.16
500	-30.41	28.80	68.61