Carbon Sequestration: Trade-offs of Planting Trees on Agricultural Land

by

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ABSTRACT

For some time, climate change has been considered by many to be one of the world's greatest, and most critical, environmental concerns of our age. In 1997 these concerns led to the creation of the Kyoto Protocol, which was designed to limit greenhouse emissions in an attempt to mitigate climate change. Canada's commitment under this agreement is a reduction in emissions to 6% below its 1990 levels, and one of the options that is under consideration to enable Canada to partially meet its commitments is carbon sequestration by planting trees on marginal land. The sequestered carbon can then be counted as a credit in Canada's net emissions budget. Hybrid poplar (*Populus hybrids*) has been identified as the tree species for this purpose in the study region of this thesis, due to its high growth rates. Landowners, however, prefer a mix of trees.

In this thesis I explore some of policy implications involved in the undertaking of a large-scale tree planting program by developing a non-linear programming model that examines the trade-offs between carbon sequestration, tree species diversity and net profits in terms of net present value (NPV). In the context of the model developed, tree species diversity is used as a proxy for biodiversity and landscape diversity, and a landowner survey is used to determine the mix of tree species that landowners would prefer. Eight tree species are considered in the context of the model, using two different discount rates, and a series of tree planting scenarios are developed, which show the tradeoffs that result from planting varying amounts of each tree species in the Peace River regions of Alberta and British Columbia. Land availability in this region is estimated using a land supply function that is based on predicted crop yields from the landowner survey.

The full range of trade-offs are illustrated, in part, through a series of production possibility relationships, which plot the three main policy objectives against each other. The results indicate that NPV can range from -$18.4 million over the 120 year planning period to just over $10.4

million, depending on the species mix planted and the discount rate utilized. Similarly, carbon sequestered can range from some 233 thousand tonnes to around 2.4 million tonnes over the same period, and the trade-offs with diversity can be significant.

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1 INTRODUCTION

In this thesis I seek to establish a quantitative methodology for examining the trade-offs between various policy objectives under a program of tree planting on marginal agricultural land for the purpose of carbon sequestration. In particular, I will develop a methodology to examine the trade-offs between tree species diversity, carbon sequestration and profit levels on afforested land in the Peace River Regions of British Columbia and Alberta.

In this regard, I will build on a series of papers and studies on the subject of afforestation for the purpose of carbon sequestration (van Kooten and Krcmar, 2001; Suchánek *et al.*, 2001). The main purpose of the research to date has been to investigate tree planting on agricultural land as a means for Canada to reduce its net carbon emissions as part of a global effort to mitigate, or prevent, humanity's contribution to global warming.

In this current study, I seek to build on this work by integrating multiple policy objectives, including another global environmental concern, that of biodiversity loss, and its associated potential for species extinction, into the framework of afforestation. More specifically, I utilize stand diversity, in terms of tree species diversity, as a proxy for biodiversity and landscape diversity in the management of afforestation on marginal agricultural land.

The underlying assumption of this thesis is that, following the most recent round of discussions on the Kyoto agreement, the government of Canada will pursue the use of carbon sinks as credits for the purpose of partially meeting its carbon reduction targets. I do not enter into an economic evaluation of whether this policy makes sense; rather I assume that a policy of afforestation-reforestation will be undertaken, and that appropriate economic incentives will be provided to landowners. The evaluation of the overall costs of such a program is complex, and should be weighed against the costs of other carbon reduction initiatives.

It is my position in this thesis that any afforestation effort should not be pursued as a single-objective policy decision to reduce atmospheric carbon. Rather, such an undertaking provides an opportunity for the government to pursue concurrently multiple afforestation objectives, including the promotion of biodiversity and protection of habitat, the amelioration of disease and pest damage that may be related to forest monoculture regimes, and the avoidance of negative aesthetic effects sometimes associated with monoculture forestry practices.

In this context, I will run a series of scenarios that will illustrate the trade-offs between various policy choices available in the context of the afforestation of marginal agricultural land. These scenarios will be applied through a case study in the Peace River Region of Alberta and British Columbia. This framework could then, in theory, be utilized as a multi-objective forest management planning tool that could be adapted to other areas, both in Canada and abroad. The advantage of such an approach is that it examines multiple policy objectives simultaneously, including carbon sequestration, net financial benefits of commercial plantations, and landscape diversity in terms of species diversity.

The resulting model will rely on both scientific and policy-oriented inputs. Actual or estimated data for variables such as stand growth rates for various tree species, carbon uptake rates, and biomass estimates will be required. Current market prices for softwood and hardwood species, along with planting and harvesting estimates will be utilized, and two discount rates will be used for comparative purposes.

Results of an existing survey (Suchánek *et al.*, 2001) will also be used to illustrate farmers' preferences regarding afforestation. The results of this survey show, for example, that farmers have different preferences for which tree species they would prefer to plant on their land. Provincial and federal land and land-use surveys will also be utilized, to illustrate government's interest in promoting multiple afforestation options. The resulting model will then be used to produce a series of production possibility relationships, illustrating the trade-offs between tree species diversity, harvesting profits based on net present value, and carbon uptake levels.

Survey data will also be used to estimate the proportion of agricultural land that farmers claim to have in various marginal categories. The results of this work will then be used to construct a supply function, which will be used to estimate the amount of land that might be available for planting trees in the study region, and in the Canadian Prairies as a whole.

Species diversity is used as a proxy for biological diversity and landscape diversity, in order to respond to landowners' concerns regarding pests, disease, conservation and landscape aesthetics. In this regard, farmers' preferences, as stated in the survey of western Canadian landowners (Suchánek *et al.*, 2001), will be used to examine the trade-offs associated with implementing a planting program based on these preferences.

Some of the policy implications related to this study are discussed, particularly in the context of policy objective trade-offs. In this research, however, I will not enter into a qualitative valuation of these policy decisions. Policy decisions will, at some point, have to be made concerning the importance of species diversity versus the maximization of economic value and carbon uptake priorities.

The relevant terms and concepts upon which the model is built are first discussed, including some of the political and historical issues involved. In Chapter 2, I discuss Climate Change, its history, its likely causes, and the international agreements created to deal with it. Then, in Chapter 3, I describe Carbon Sequestration and the use of carbon sinks to offset carbon buildup in the atmosphere.

In Chapter 4, I discuss the survey work done by Suchánek et al., and will present the results of this survey that are pertinent to this thesis. In Chapter 5, I use data from the survey to create a supply function that shows the relationship between marginal rates of return of agricultural land and the amount of land available in each category. This supply function will then be used to estimate how much land is potentially available for afforestation.

In Chapter 6, I develop the non-linear programming model that is utilized in this thesis. In this context, I will first describe the approaches used to calculate carbon sequestration and to quantify diversity, and then lay out the Case Study used in the thesis, along with the various scenarios to be compared.

The findings are summarized and illustrated through the use of tables and graphs in Chapter 7, which also contains some conclusions of the results.

A final discussion on the results is found in Chapter 8, including recommendations for further study.

2 CLIMATE CHANGE

2.1 Introduction

For some time, climate change has been considered by many to be one of the world's largest, and most critical, environmental concerns of our age. Average global temperatures are predicted to increase by 1.0 to 3.5 degrees Celsius by 2100, and global mean sea levels are predicted to rise by 15-95cm (Watson *et al.*, 1997). The results of such temperature increases are difficult to predict, although it seems certain that rising ocean levels will cause drastic impacts on the world's population through the flooding of coastal zones, displacing perhaps millions of people who now live in these areas. Agricultural and recreational land along our shorelines will also be severely impacted, resulting in economic losses.

In addition, the desertification of large tracts of land is likely, as current "arid" zones suffer from increased temperatures. Many waterways in these areas are likely to dry up, affecting human activities through the loss of potable drinking water and the lack of water for irrigation purposes.

Many of our biogeoclimatic zones are certain to shift, impacting not just human land use and settlement, but also the natural world. Plants and animals conditioned to life in a certain temperature range will have to adapt, migrate or perish, while new habitats will developed in other areas, with the net result unknown. Those that are unable to adapt or migrate may perish, and a lack of migratory corridors due to the proliferation of human land use may exacerbate any loss of life.

Although the actual causes of climate change are still disputed by many, it is generally agreed that the emission of greenhouse gases by a variety of human activities is, at the very least, aggravating or accelerating this increase in global temperatures. In a recent declaration by the United Nations, climate scientists declared that "most of global warming is attributable to human activities" (IPCC, 2001*a*).

In 1988, the Intergovernmental Panel on Climate Change (IPCC) was established jointly by the UN Environment Program (UNEP) and the World Meteorological Organization (WMO) to "provide scientific, technical and socio- economic advice to the world community, and in particular to the 170-plus Parties to the United Nations Framework Convention on Climate Change (UNFCCC)".

The 2001 report of the IPCC (2001b) nearly doubled its prediction of likely warming in the coming century, saying it could be as much as 5.8 degrees Celsius. The report stated that global warming is already well under way. The report noted that since the 1960s snow cover has fallen by around 20%, the Arctic ice cap has thinned by approximately 40% and spring thaw on lakes is coming two weeks earlier.

It should be noted, however, that the IPCC report (2001*b*) claims concerning drastic increases in global temperatures have been recently refuted by McIntyre and McKitrick (2003), who show that there were errors in compilation of the data. This is an ongoing debate, so this matter is yet to be resolved. Figures 1 and 2 show data from sources other than the IPCC that seem to indicate temperatures may indeed be rising, both in Canada and globally.

In addition to the purported rise in temperatures, analyses performed on polar ice cores indicate that carbon dioxide (CO_2) concentrations in the atmosphere were relatively constant at around 280 ppm for the 1,000 years leading up to the early 1800s (IPCC, 2001*b*). Direct atmospheric measurements began in the middle of the 20th century, and recent estimates put 1999 levels at around 367ppm, an increase of 31% in the past 200 years. The IPCC attributes this drastic increase primarily to deforestation and fossil-fuel combustion, with the latter contributing to 70%-90% of the increase over the past 20 years. CO_2 is further considered to be the dominant human-created greenhouse gas, representing 60% of the changes in long-lived atmospheric greenhouse gases (IPCC, 2001*b*).

Methane (CH_4) levels have seen an even greater increase, rising to around 1,745ppb in 1998 from pre-industrial revolution levels of around 700ppb. In its scientific assessment of the impacts of climate change, the IPCC estimates that current atmospheric CH_4 levels have not been exceeded in the past 420,000 years (IPCC, 2001*b*).

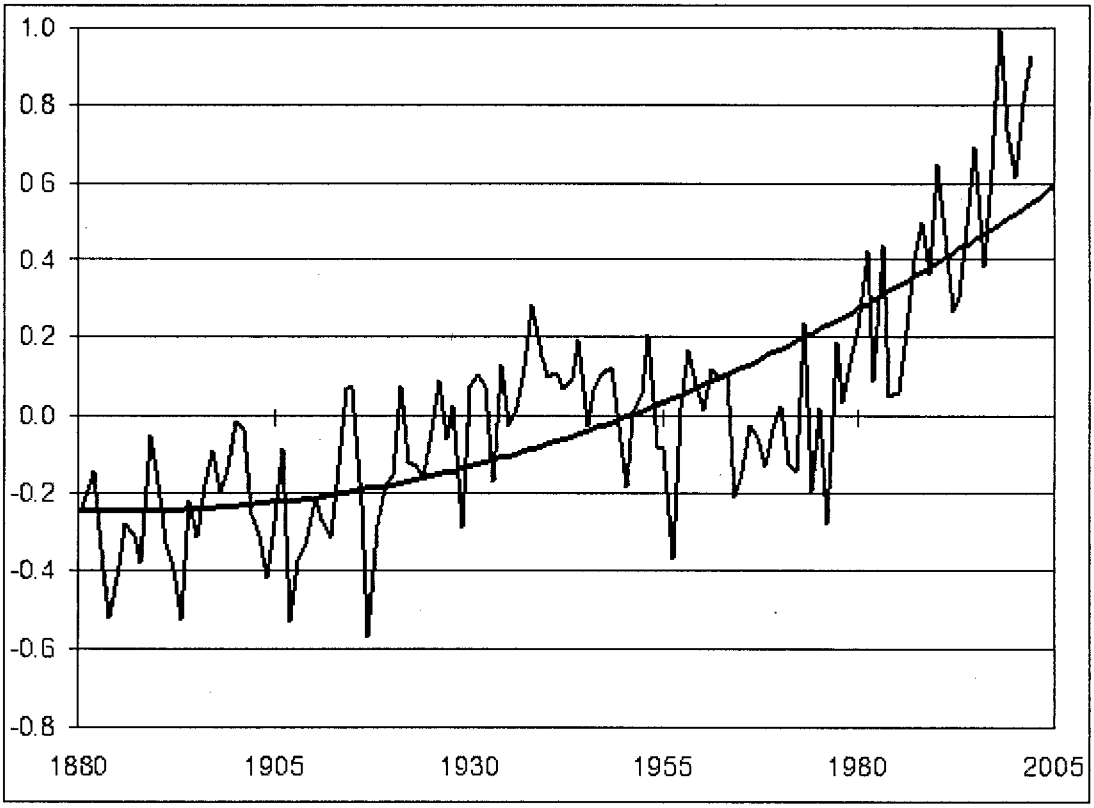

Figure 1. Global surface temperature anomalies in deg. C, 1880-2002
Source: National Oceanic & Atmospheric Administration (NOAA), U.S. Dept. of Commerce, 2003

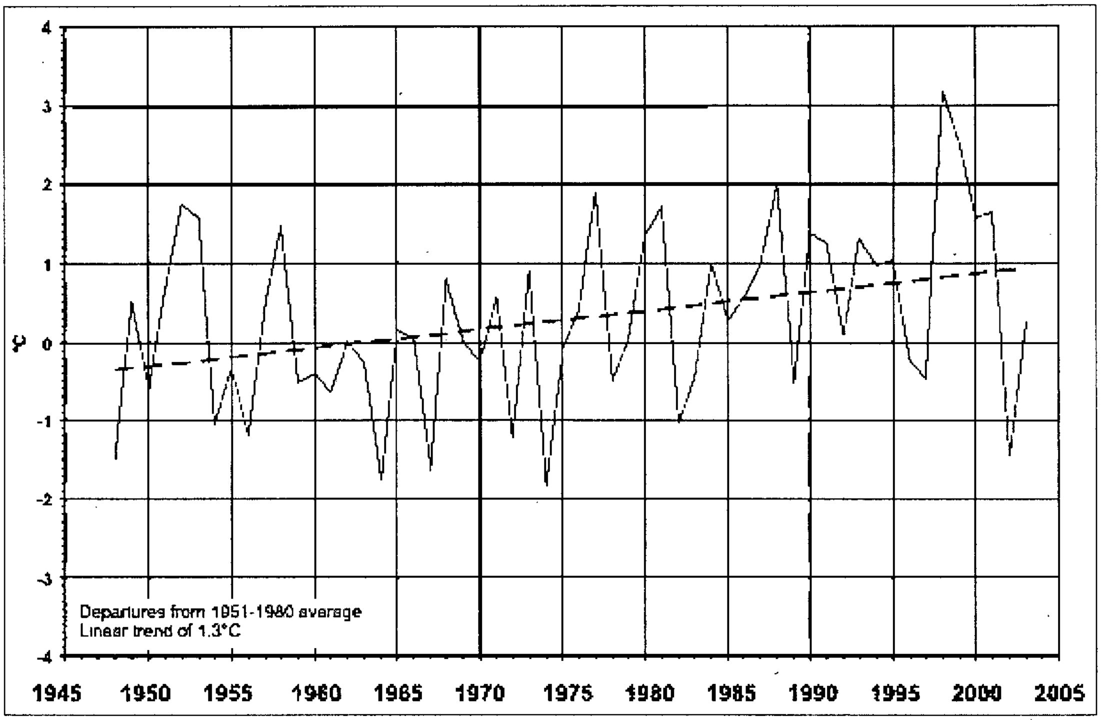

Figure 2. Spring national temperature trends in Canada (deg. C), 1948-2003
Source: Environment Canada, 2003

2.2 The Kyoto Protocol

Based in part on the IPCC's assessment, the December 1997 Kyoto Protocol calls for a reduction in the emission of six greenhouse gases (GHGs), including CO_2, by the first commitment period of 2008-2012. Some 160 countries that were the Parties to the 1992 UN Framework Convention on Climate Change signed the agreement. Under Article 3.1 of the Protocol these countries, including Canada, have agreed to reduce emissions of GHGs by the first commitment period.

In November 1998, a new round of international negotiations was launched, resulting in the 2001 Bonn Agreement, which signed off on some of the most controversial issues, including the use of forest and agricultural sinks as a Kyoto mechanism. Building on this agreement in 2001, all members of the Accord agreed to a final comprehensive legal and technical package of decisions known as the Marrakesh Accords.

While the ultimate fate of the Kyoto agreement is still in doubt, due in large part to the non-participation of the United States, it seems clear that most industrialized countries around the world, including Canada, are committed to reducing emissions in the long run.

2.3 The Kyoto Accord and Canada

In the context of the Kyoto agreement, Canada agreed to a 6% reduction in 1990 GHG emissions by 2012. Estimates show, however, that emissions in 1996 had already exceeded those of 1990 by 12%, illustrating a more urgent need for the government to take action. Environment Canada estimated that 1990 energy-related emissions of CO_2 were in the neighbourhood of 461 megatonnes (MT), and by 1999 were estimated to have risen to around 699 MT (Environment Canada, 2001).

More recently, Environment Canada has estimated that Canadians now directly add over 700 megatonnes of CO_2 equivalent of GHGs to the atmosphere each year (Environment Canada, 2002). With only one-half of a percent of the world's population, Canada is therefore responsible for around two percent of the world's greenhouse gas emissions.

In order for the government to meet its original reduction commitments, therefore, Canada will now have to reduce its emissions by around 65 MT per year during the 2008-2012 commitment period (Environment Canada, 2001) in order to achieve one-third of Canada's Kyoto target. To meet its commitment, the government intends to use terrestrial carbon sinks to achieve some 25% of emissions reductions. A further 35% reduction in emissions is to be brought about by subsidies, voluntary actions are projected to reduce emissions by a further 20%, and other actions are expected to bring about the remaining 20% (van Kooten, 2003). Therefore, although it is unlikely that Canada could use afforestation to meet completely its Kyoto commitments, by signing the Accord Canada has shown that it is committed to reducing anthropogenic GHG emissions in the long run.

According to the Kyoto Protocol, Canada can claim up to 44 MtC that is above and beyond so-called "normal" forestry activities as credit towards its total commitments. Moreover, and as a result of the Marrakesh negotiations, Canada can claim up to 12 MtC per year from business-as-usual forest management, which includes replanting and fire suppression activities. For this reason, the longer-term use of carbon sinks for net CO2 reductions is being looked at as, at the very least, a stopgap measure until alternative technologies allow for the reduction of GHG emissions.

Provincial governments are playing a role too. For example, after Kyoto the government of Alberta (the province where much of the case study in this thesis is located) set a 14% emission reduction target, and claims that the province "has already reduced emissions by 10%" (DMI, 2000).

2.4 Definitions

The principal aspects of the Kyoto Accord relating to forests and forest management are found in Articles 3.3 and 3.4 of the original Kyoto Protocol, and fall under the provisions relating to Land Use, Land Use Change and Forestry (LULUCF). Article 3.3 pertains to the establishment of new forests on lands that were not forested prior to 1990, and to the permanent removal of forests. Article 3.4 allows the eligibility of other carbon sequestration activities in forests, provided that they are human-induced and that they have occurred since 1990. Due to the uncertainties involved in the interpretation of these articles, many of the items in the Accord, including the definitions of important terms, were not agreed on in Kyoto, and were thus left for future resolution.

In the June 2001 negotiations at the 6th Conference of the Parties in Bonn, Germany (Cop6), draft decisions, including definitions, were agreed upon. The 7th Conference of the Parties (CoP7) was concluded November 2001 in Marrakech, Morocco, where the Parties conference adopted all the draft decisions agreed upon in Bonn, including detailed technical rules for accounting, reporting and review. These decisions are referred to as the 'Marrakesh Accords', and include definitions concerning forests.

For the purposes of this thesis the following United Nations Framework Convention on Climate-Change (UNFCCC) definitions, as outlined in Marrakesh and adopted for the article 3.3 of the Kyoto Protocol as they are stated in the annex to decision 11/CP.7 (FCCC/CP/2001/13/Add.1), will apply:

> " '**Forest**' is a minimum area of land of 0.05-1.0 hectares with tree crown cover of more than 10-30 per cent with trees with the potential to reach a minimum height of 2-5 meters at maturity in situ. A forest may consist either of closed forest formations, where trees of various storeys and undergrowth cover a high proportion of the ground or open forest. Young natural stands and all plantations which have yet to reach a crown density of 10-30 per cent or tree height of 2-5 metres are included under forest, as are areas normally forming part of the forest area which are temporarily unstocked as a result of human intervention such as harvesting or natural causes but which are expected to revert to forest. "

> " '**Afforestation**' is the direct human-induced conversion of land that has not been forested for a period of at least 50 years to forested land through planting, seeding and/or the human-induced promotion of natural seed sources."

> " '**Reforestation**' is the direct human-induced conversion of non-forested land to forested land through planting, seeding or human-induced promotion of natural seed sources, on land that was forested but that has been converted to non-forested land. For the first commitment period (2008-2012), reforestation activities will be limited to reforestation occurring on those lands that did not contain forest on 31 December 1989."

> " '**Deforestation**' is the direct human-induced conversion of forested land to nonforested land."

> " '**Revegetation**' is a direct human-induced activity to increase carbon stocks on sites through the establishment of vegetation that covers a minimum area of 0.05 hectares."

3 CARBON SEQUESTRATION

3.1 Introduction

Carbon dioxide (CO_2) is the most common greenhouse gas released by human activities. Fortunately, the more potent greenhouse gases such as Methane (CH_4), Nitrous Oxide (N_2O) and Halocarbons are released in much smaller amounts. CO_2 is produced from decaying materials, respiration of plant and animal life, and the combustion of organic materials and fossil fuels such as natural gas, oil and coal. CO_2 stays in the atmosphere until it is removed through photosynthesis and ocean absorption.

Trees and other vegetation sequester atmospheric carbon through the conversion of CO_2 to carbon by way of photosynthesis (Birdsey, 1992). Essentially, plants use the sun's energy to "weld" the CO_2 molecules to water molecules, in order to form the carbohydrates that plants need for growth. Through respiration, combustion and decomposition, the absorbed CO_2 is eventually returned to the atmosphere, unless it is stored longer-term in plant-based products such as furniture made from wood. Human activities have accelerated this process, with land being cleared away for forestry, pasture land, human settlement and agricultural land.

Forestland sequesters more carbon than other land uses such as agriculture (Plantinga *et al*, 1999), with younger trees absorbing carbon at a faster rate than older trees. As can be seen in Table 1, only wetlands store more carbon than forests, on a per hectare basis. Forests currently contain nearly half of global carbon stocks.

In a forest environment, carbon sequestration occurs in at least four different areas: understory vegetation, forest floor and soil, with tree carbon containing some 80% of ecosystem carbon (Birdsey, 1992). The IPCC (2001*a*) estimates that newly planted forests continue to uptake carbon for 20 to 50 years or more after being planted, depending on species and site conditions.

Table 1. Global carbon stocks in vegetation and soil carbon pools down to a depth of 1m[a]

BIOME	Area (10^9 ha)	Global Carbon Stocks (Gt C)			
		Vegetation	Soil	Total	Gt / 10^9 ha
Tropical Forests	1.76	212	216	428	243.2
Temperate Forests	1.04	59	100	159	152.9
Boreal Forests	1.37	88	471	559	408.0
Tropical Savannas	2.25	66	264	330	146.7
Temperate Grasslands	1.25	9	295	304	243.2
Deserts and Semideserts	4.55	8	191	199	43.7
Tundra	0.95	6	121	127	133.7
Wetlands	0.35	15	225	240	685.7
Croplands	1.60	3	128	131	81.9
	15.12	466	2,011	2,477	163.8

[a] Note: There is considerable uncertainty in the numbers given, because of ambiguity of definitions of biomes, but the table still provides an overview of the magnitude of carbon stocks in terrestrial systems

Source: IPCC (2001*a*)

The potential for increasing carbon stocks in the terrestrial biosphere might be limited compared to total greenhouse gas emissions, but their impact could be considerable in relation to the reductions necessary for compliance in the first commitment period (2008-2012). Land-use change and forestry projects, then, are considered a low-cost option for addressing climate change mitigation (van Kooten *et al.*, 2002). In Canada, afforestation is being considered to sequester enough carbon to meet at least 20% of its international obligations, and at a lower cost than emissions reduction (van Kooten *et al.*, 2002).

3.2 Carbon and the Kyoto Protocol

According to the Intergovernmental Panel on Climate Change (2001*e*), "Forests, agricultural lands, and other terrestrial ecosystems offer significant carbon mitigation potential". For this reason, the Kyoto Protocol allows for another option for the reduction in total CO_2 emissions: that of carbon sequestration. This is considered to be fundamental for Canada achieving its Kyoto target.

Under the agreement, countries are able to claim credit for carbon sequestered through afforestation or reforestation, while carbon lost through deforestation is counted as a debit. Namely, Article 3.3 of the Kyoto Protocol provides that:

> "The net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990, measures as verifiable changes in carbon stocks in each commitment period, shall be used to meet the commitments under this Article of each Party included in Annex 1. The greenhouse gas emissions by sources and removals by sinks associated with those activities shall be reported in a transparent and verifiable manner and reviewed in accordance with Articles 7 and 8."

The use of carbon sinks as credits to complement emission reduction commitments was one of the most contentious issues at Kyoto, in part because of uncertainties in measuring the removal of atmospheric carbon dioxide by sinks. For this reason, it was decided in subsequent negotiations held in Bonn that the uncertainties were sufficient to warrant a special report by the IPCC. These uncertainties included:

- The amount of land that is available and suitable for tree planting projects
- The long-term security of forests as carbon sinks
- The viability of various forestry activities in certain regions, due to the effects of climate change.

As noted in Chapter 2 of this thesis, these uncertainties were largely resolved through the 2001 Bonn Agreement and subsequent Marrakesh Accords, which signed off on the most controversial issues, and recognized carbon sinks as a Kyoto mechanism. All Parties agreed to a final comprehensive legal and technical package of decisions concerning the use of sinks and the definitions surrounding their establishment.

Under the Clean Development Mechanism (CDM), however, only reforestation and afforestation projects will be considered eligible under the first commitment period, and these will be subject to a cap of 6 Mt CO_2/year for Canada.

4 SURVEY OF WESTERN CANADA LANDOWNERS

4.1 Survey Background

As part of a series of research papers on afforestation for the purpose of carbon sequestration, a survey of farmers in the study region (Suchánek *et al.*, 2001, van Kooten *et al.*, 2002) was conducted in July 2000. This survey was designed to determine prairie farmers' willingness to participate in a government afforestation program designed to help mitigate climate change.

The survey questionnaire was mailed in July 2000, to 2,000 randomly selected farmers with farms over 160 acres. Questionnaire recipients were located in the grain belt region of the Canadian Prairies, and included landowners in Manitoba, Saskatchewan, Alberta and northeastern British Columbia. Dairy farmers were not included in the survey.

Addresses used in the survey were purchased from Watts Brokerage Listing. Of the 2,000 surveys mailed out by Pavel Suchánek, some 379 surveys were returned as undelivered, largely due to outdated addresses. Reminder cards were sent out three weeks after the original survey mail-out, and after correcting for the returned surveys the effective response rate was around 13%, and a total of 182 of these surveys were usable. Although respondent bias is possible, respondents were from a variety of ages, income levels and farm sizes according to the survey responses.

Although the survey's main purpose was to determine farmers' willingness to accept (WTA) compensation for tree planting, the survey also gathered data on farmers' agricultural operations, as well as their knowledge of climate change and carbon credits. For example, the survey asked farmers to respond to questions concerning their age, income level, size of farm, crops or animals raised and amount and use of marginal fields (Suchánek *et al.*, 2001). The survey was also designed to familiarize farmers with the climate change process.

An analysis of the survey found that transaction costs might prove to be a significant barrier to farmers' participation in any afforestation program launched by the federal government (Suchánek *et al.*, 2001). Full survey results can be obtained from Suchánek (2001). Suchánek found that even if they are fully compensated for lost agricultural revenues and tree-planting costs, more than one-quarter of the 208 survey respondents would not be willing to enter voluntarily into such a program.

For those that would enter into a program, the average annual amount that farmers would need to be compensated to plant trees on marginal agricultural land was estimated by Suchánek to be about $40 per acre, or nearly $100 per ha. As van Kooten and Krcmar (2001) note, this is over and above the actual afforestation and associated costs and is about six times the opportunity cost of the land.

This does not mean, however, that there is no room for domestic afforestation projects, as much of the analysis was based on average and not marginal considerations. It is likely that, at the margin, there are afforestation strategies that make economic sense for both landowners and the government.

Several questions were posed in the survey that are of particular relevance to this thesis. These include questions about land use, asking what aspects of an afforestation program respondents would be interested in, and what species of trees they would be interested in planting. These sections of the survey are in the appendix to this thesis.

4.2 Survey Results

Survey responses were entered into a single worksheet in Excel, with each column representing an individual question or, for multiple-choice questions, each choice. This allowed the use of Excel's Pivot Table function, which I used to produce much of the following section.

In one section of the survey, farmers were asked what kind of planting program they would be interested in participating in, and gave their preferences for which tree species that they would be interested in planting. The following section represents the results of this section of the survey.

Willingness to plant trees

Participants in the survey were asked if they would be interested in participating in planting trees to mitigate climate change, given certain criteria. One question in this section of the survey asked if they would voluntarily plant trees if it did NOT have a negative effect on their eligibility for government agricultural programs or any tax benefits. If they answered yes they were then asked why they would plant trees, and were given six choices to choose from, as well as a blank space to put their own answer (Table 2).

They were then asked to suppose that they were to enter a contract that permits someone to plant trees on some proportion of their land. They were told that all direct costs of tree planting would be covered, and that they would be provided with annual compensation, although compensation levels were not specified in the questionnaire. They would not, however, have any right to harvest the trees before the contract expires. When the contract expires, however, the trees would become their property. Those that would consider involvement in a tree planting program under this scenario were then asked what type of program they would participate in, and were given five options as well as a blank space to put a different answer if it applied (Figure 4).

As can be seen in Table 2 and Figure 3, of the farmers that were willing to plant trees, the majority were most concerned with environmental conditions on their land (33%), but they were also interested in making use of unused land. Interestingly, a relatively small number of farmers (20%) were interested in being involved in block forest planting. Although the reasons for this are not clear, one could speculate that it might be due, in part, to so-called "cultural biases" against being involved in forestry. Many farmers are not familiar with silvicultural techniques, and are therefore hesitant to start growing trees for commercial reasons.

Table 2. Respondents' reasons to voluntarily plant trees

Reasons to plant trees, given for those respondents who would voluntarily plant trees	**Peace Region (BC & AB)**	**Prairies Total**
Prevent Soil Erosion	45.5%	33.2%
Provide Shade	27.3%	22.3%
Provide Fuelwood	9.1%	5.0%
Grow Commercial Timber	0.0%	4.1%
Diversify Production	9.1%	7.7%
Make use of Idle Land	0.0%	15.0%
Affinity	0.0%	0.9%
Wildlife Habitat	0.0%	3.6%
Conserve Moisture	0.0%	1.4%
Trap Snow	0.0%	3.6%
Improve Air Quality	0.0%	0.5%
Wind Break	9.1%	2.7%
Total	100.0%	100.0%

Source: Landowners survey

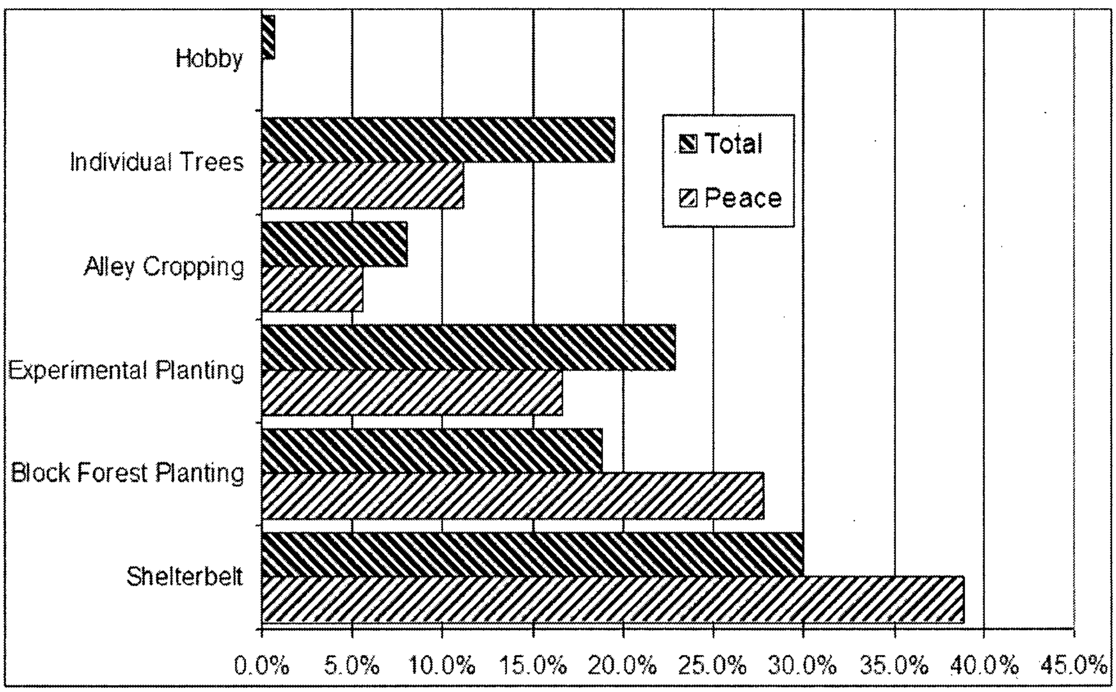

Figure 3. Farmer's response when asked if they would consider a tree-planting program, if they were adequately compensated for land and production losses (% responding yes)

This unwillingness to be involved in the establishment of productive woodlots may also be evident when farmers who were not interested in being involved in any tree-planting program are examined. As can be seen in Figure 4, the majority of these farmers are either content with the status quo (43%) or felt that afforestation was a waste of productive farmland (19%), and thus were not very receptive to doing anything but traditional farming.

Although only 4% claimed that their decision was due to their being unsure of the benefits (see Figure 4), it may be that those who claim other reasons for non-involvement might yet be convinced of the benefits of planting trees. They may not realize, for example, that the planting of shelterbelts or riparian buffers may actually improve crop production. As shown in Table 2, those who are willing to enter into such a program are largely motivated by soil erosion prevention, the provision of shade or the use of windbreaks.

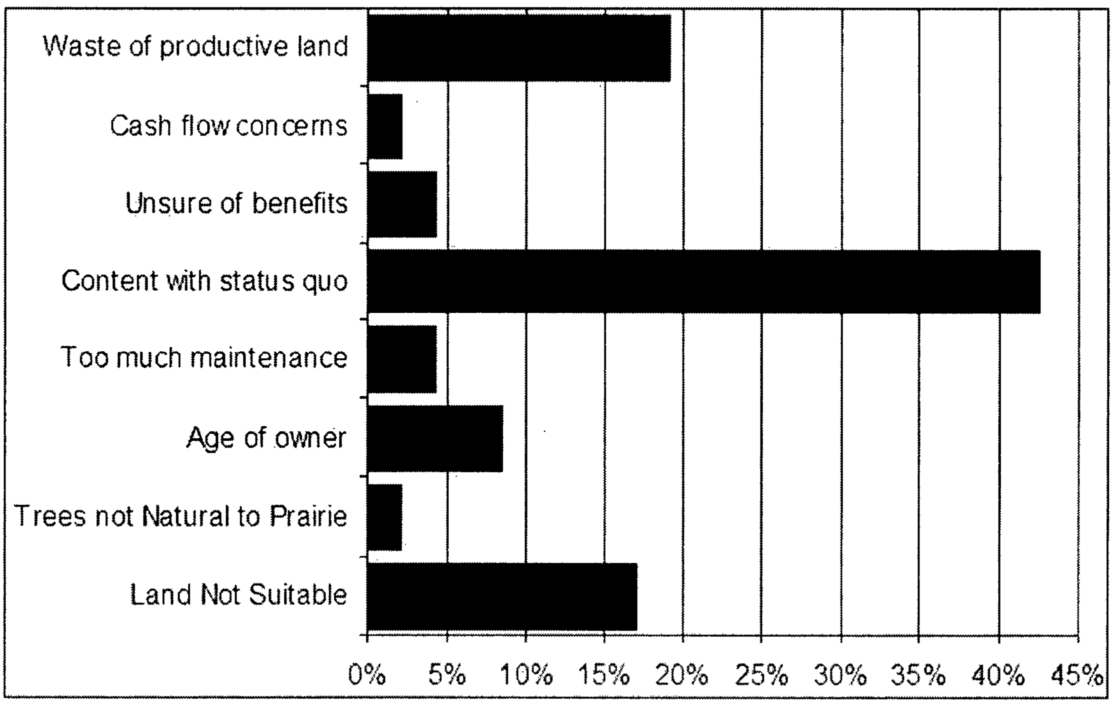

Figure 4. Prairies' Respondents' main reasons for not considering planting trees on their land (% indicating the stated reason)

In addition, although high enough subsidization may ultimately entice uninterested landowners into participating, a well-designed promotional program, informational campaigns showing the gains to be made, or support for local woodlot programs, may be much more effective incentive mechanisms, particularly in procuring involvement in the establishment of woodlots for commercial purposes (Gilsenan, 2003). Moreover, partnerships with commercial forestry companies may also provide the extension services needed for such involvement, as well as providing a guaranteed market for timber for those willing to plant commercial woodlots.

Even so, I will use the above results to determine what the potential ramifications of such preferences are in terms of policy goals for carbon sequestration and stand diversity maximization.

Tree Species Preferences

Farmers who considered themselves interested in participating in a planting program were asked what species they would prefer for planting. In this context, they were given a choice of three different species (poplar, pine and spruce), mixed, or other. They were also given the choice to specify what other species they might be interested in.

In response to this, the survey finds that farmers indicate a preference for a variety of tree species. As can be seen in Figure 5 and Table 3, of the farmers who expressed preferences, farmers surveyed were divided in their preferences for softwood and hardwood species, with respondents in all provinces preferring a mix of species over any one single species. Interestingly, some 10% of respondents chose fruit trees, even though this was not given as one of the choices. The totals in Figure 5 and Table 3 add up to more than 100% because most respondents chose more than one answer.

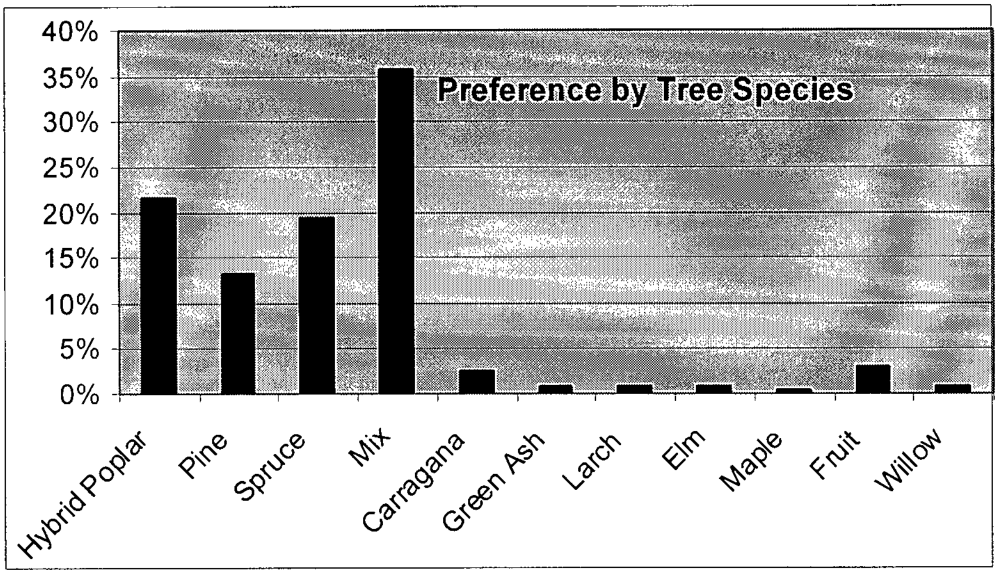

Figure 5. Tree species preferences of Prairies' respondents that would participate in a tree planting program if adequately compensated (% choosing each category)

Table 3. Tree species preferences of prairies respondents that would participate in a tree planting program if adequately compensated, by region (% choosing each category)

Species	Manitoba	Sask.	Alberta	British Columbia	Peace (BC & AB)	Prairies Total
Hybrid Poplar	47.1%	40.8%	25.6%	50.0%	40.0%	39.8%
Pine	11.8%	26.8%	18.6%	50.0%	20.0%	24.1%
Spruce	35.3%	31.0%	37.2%	0.0%	40.0%	36.1%
Mix	70.6%	60.6%	58.1%	50.0%	50.0%	64.7%
Carragana	0.0%	5.6%	4.7%	0.0%	0.0%	4.5%
Green Ash	0.0%	2.8%	0.0%	0.0%	0.0%	1.5%
Larch	0.0%	2.8%	0.0%	0.0%	0.0%	1.5%
Elm	0.0%	1.4%	2.3%	0.0%	0.0%	1.5%
Maple	0.0%	1.4%	0.0%	0.0%	0.0%	0.8%
Fruit	0.0%	5.6%	7.0%	0.0%	10.0%	6.0%
Willow	0.0%	1.4%	2.3%	0.0%	0.0%	1.5%

Source: Landowners survey

In terms of farmers' willingness to plant trees, of the 25% of respondents who were not interested in entering into a tree-planting program if adequately compensated, most indicated that it boiled down to farm operations preferences (Table 4). Many cited environmental concerns as also being an important factor, and only 26% considered a loss of visual appeal to the landscape to be a somewhat or very important consideration.

Table 4. Relative importance of factors in not wanting to be involved in a planting program (% responding yes to each category)

Prairies Total	Loss of Visual Appeal of Landscape	Environmental Concerns	Farm Operation Preferences	Insufficient Knowledge
Not at all	64%	33%	7%	55%
Somewhat important	17%	44%	21%	26%
Very important	19%	22%	71%	19%
Total	100%	100%	100%	100%

Source: Landowners survey

In order to refine stated tree preferences further, Table 5 illustrates what species or categories of trees correspond with what kind of planting program. In this table, the vertical headings refer to the Prairies totals found in Table 2 (i.e. what type of tree planting program would farmers be interested in if they were adequately compensated), and the horizontal headings refer to the Prairies totals found in Figure 5 (i.e. what species would these farmers prefer planting).

The percentages in Table 5 represent the ratio of tree preferences to the number of farmers who would choose a given type of program if adequately compensated. The first cell, for example, tells us that of the farmers who would plant shelterbelts (if adequately compensated), almost 42% would choose to plant hybrid poplar. Note that since many respondents chose more than one type of tree (or mix), the columns do not add up to 100%.

The table shows us that there is a clear preference for planting a mix of trees, regardless of what the trees are planted for. Strangely, the farmers who chose the option of block forest planting were the least interested in planting hybrid poplar, which is the fastest growing commercial species. This would seem to indicate that most of them are not interested in the potentially higher harvest volume related to growing hybrid poplar.

Table 5. Respondents' stated tree species preferences according to different tree-planting options (% of respondents who would choose a species given their tree-planting preference)

	Shelterbelt	Block Forest Planting	Experimental Planting	Alley Cropping	Individual Trees
Hybrid Poplar	41.6%	35.7%	38.2%	37.5%	44.8%
Pine	27.0%	30.4%	22.1%	25.0%	27.6%
Spruce	31.5%	32.1%	30.9%	29.2%	27.6%
Mix	64.0%	60.7%	70.6%	75.0%	65.5%
Carragana	5.6%	5.4%	4.4%	8.3%	6.9%
Green Ash	1.1%	3.6%	1.5%	4.2%	1.7%
Larch	2.2%	3.6%	1.5%	4.2%	1.7%
Elm	2.2%	1.8%	1.5%	4.2%	0.0%
Maple	1.1%	1.8%	1.5%	4.2%	1.7%
Fruit	6.7%	5.4%	7.4%	8.3%	8.6%
Willow	2.2%	0.0%	0.0%	0.0%	3.4%

Source: Landowners survey

4.3 Conclusions

The survey concludes that farmers in the Canadian Prairies are largely unwilling to participate in an afforestation program. For those that are willing to be involved in a program, the motivations for involvement are varied, but there does not seem to be much interest in growing trees for commercial purposes. Of course, this bias against the establishment of woodlots may be at least partially overcome by a carefully designed incentives program that illustrates the value of trees for erosion and windbreak purposes, as well as describing the benefits of establishing woodlots for commercial purposes.

Overall, respondents show a preference for planting a mix of tree species, which would likely not be optimal for planting for the purposes of carbon sequestration. This, again, may be due to a lack of knowledge concerning forests and forestry practices. These results, however, should be taken into account when assessing the viability of a major afforestation program, or in the design of an incentives program targeted at farmers in the Prairies.

In this thesis I assume that a federal afforestation program will provide sufficient incentives to involve landowners in the process. The scenarios, however, will take these farmers' preferences into account when calculating the amount of carbon sequestered.

5 LAND AVAILABILITY

5.1 Introduction

The total landmass in Canada is 998 million hectares, of which 417.6 million hectares are currently forested, and 68 million hectares are in agricultural use (Statistics Canada, 2003). Guy and Benowicz (1998), in a study prepared for the Canadian Pulp and Paper Association, estimated that there were more than seven million hectares of land in Canada that would be available for either reforestation or afforestation plantations. The majority of this land is in the grassland to forest transition zone of the northern prairies. They further estimated that if all this land could be converted to forested land, up to 2,040 MT of CO2 could be sequestered by the year 2020. Although this figure should be treated with caution, due to optimistic estimates of soil carbon and non-inclusion of carbon depletion through the use of forested timber, it is clear that the afforestation of plantable land could contribute to a reduction in net carbon emissions.

Subsequent studies undertaken by the Sinks table of the National Climate Change Process (Environment Canada, 1999) estimated that between 1.1 - 1.4 million hectares of unforested land would be readily available, accessible and productive for the first commitment period.

5.2 Land availability in the Canadian Prairies

For the purposes of this thesis, I utilize the Farmer's Survey introduced in Chapter 4, in order to estimate the amount of marginal agricultural land throughout the Canadian Prairies that is potentially available for afforestation. In the survey, farmers were asked to identify up to four of their least productive fields to be used in 2000, according to crops planted, size of field, and expected approximate yield. If the landowner had less than four fields, they were asked to indicate all of their fields.

Of the 208 survey respondents, 127 farmers, representing 88,096 ha of farmland, gave full responses for at least one field in this section, providing information on some 22,052 ha of their productive fields. Expected yields given were mostly in terms of bushels per acre, which were converted using provincial conversion factors (Government of Alberta, 2003) so that all yields could be expressed in tonnes/ha.

Based on the address of each respondent, fields were then classified according to soil zone. Crop revenues per hectare for each identified field were then calculated by multiplying provincial crop prices per tonne for 2000 (AAFRD, 2003) by projected yields in tonnes per hectare according to the survey. This can be represented by the following function:

(5.1) $$Rev = P \times Y$$

where, Rev represents predicted revenues/tonne/ha
P represents price/tonne, and
Y represents farmers' expected yield/ha in tonnes

Since the survey data did not contain information on landowner expenditures, provincial estimates on expenditures per hectare by crop and soil zone (Breitkreuz, 2003) were then subtracted from the per hectare revenues to arrive at net revenues per hectare, for each identified field in the survey area. Expenditure estimates include the cost of seed, fertilizer, herbicides, fungicides, crop insurance, fuel, machinery repairs, building repairs, labour, irrigation, operating expenses and rent. Provincial estimates on expenditures used in this thesis are found in Table5.1, and net revenues are represented in Formula 5.2.

(5.2) $$NR = Rev - Cost$$

where, NR represents estimated net revenues/tonne/ha
Rev represents predicted revenues/tonne/ha
Cost represents average costs/tonne/ha

The main discrepancy in this approach is that Farmers' predicted yields in the survey varied greatly, such that average costs are likely a poor estimate of many farmers' actual costs, particularly those with very high or very low yield predictions. However, while it is noted that subtracting average costs per hectare from predicted revenues per hectare may not yield a very accurate profile of net revenues on an individual level, the results of this work will nevertheless be used to create a "supply function" to approximate prices for land identified in the survey.

For fields devoted to pasture/grazing, rent estimates were based on the value of Animal Unit Months (AUM) of forage according to soil zones in Alberta, in order to calculate the value of each field on a per hectare basis (van Kooten et al, 1999*b*). Rents in Alberta are based on a standard AUM, which represents the amount of forage consumed per month by a 450kg cow. Using data on stocking rates in AUMs per hectare and the private market value of an AUM of pasture use, van Kooten et al (1999*b*) were able to estimate the opportunity cost of lost pasture use. Net returns for pastureland and costs for various crops by soil zone are found in Table 6.

Table 6. Per hectare net revenues and costs for various soil zones in the Canadian Prairies

Soil Zone	Pasture (net return based on AUM)	Hay (Cost)	Wheat (Cost)	Canola (Cost)	Oats (Cost)	Flax (Cost)
Brown	$50.84	$105.02	$276.75	$317.52	$258.02	$293.98
Dark Brown	$74.94	$144.77	$318.00	$365.60	$283.82	$327.05
Black	$115.96	$213.32	$358.98	$399.88	$328.80	$362.15
Gray	$143.34	$194.29	$360.09	$413.27	$321.28	$395.81
Dark Gray	$85.12	$181.47	$380.85	$397.55	$314.78	$374.82

Sources: AAFRD, 2003, Breitkreuz, 2003, and van Kooten et al, 1999b

Hectares of farmland in the survey, based on the number of hectares in each identified field, were then grouped according to the projected net returns in Table 6, in order to estimate how much land farmers might have available at each net revenue level. These were then sorted into net revenue groupings according to $50 increments. The results of this work can be seen in Table 7 and Figures 6 and 7.

In Figure 6 the area in gray represents the distribution of the 88 kha of land, distributed according to the estimated net return of that land.

In Table 7, the amount of land within each marginal net revenue grouping can be seen, as well as a running total that represents the amount of land identified that is below a given net revenue threshold. This running total could then be used to estimate the supply of land potentially available for afforestation at a given price level.

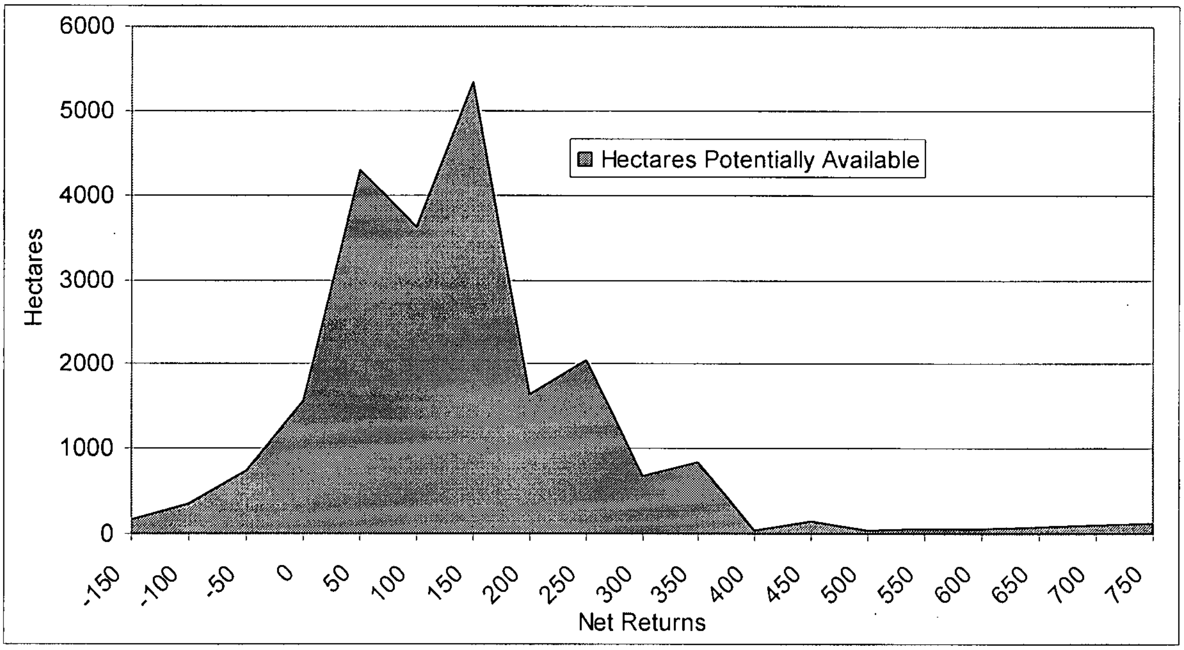

Figure 6. Estimated net returns and land availability of agricultural land in the Canadian Prairies

Table 7. Hectares of agricultural land available in the Prairies according to net returns

Net Return ($/ha)	Hectares Available	Running Total	Percentage of Total Available	Running Total
-150 to -199	170	170	0.2%	0.2%
-100 to -149	357	527	0.4%	0.6%
-50 to -99	740	1268	0.8%	1.4%
0 to -49	1,566	2834	1.8%	3.2%
50 to 1	4,293	7127	4.9%	8.1%
100 to 51	3,619	10746	4.1%	12.2%
150 to 101	5,344	16090	6.1%	18.3%
200 to 151	1,638	17728	1.9%	20.1%
250 to 201	2,044	19772	2.3%	22.4%
300 to 251	678	20450	0.8%	23.2%
350 to 301	838	21288	1.0%	24.2%
400 to 351	40	21329	0.0%	24.2%
450 to 401	140	21469	0.2%	24.4%
500 to 451	32	21501	0.0%	24.4%
550 to 501	59	21560	0.1%	24.5%
600 to 551	69	21628	0.1%	24.6%
650 to 601	85	21713	0.1%	24.6%
700 to 651	108	21821	0.1%	24.8%
750 to 701	121	21943	0.1%	24.9%
800 to 751	0	21943	0.0%	24.9%
850 to 801	28	21971	0.0%	24.9%
900 to 851	0	21971	0.0%	24.9%
950 to 901	0	21971	0.0%	24.9%
1000 to 951	0	21971	0.0%	24.9%
1050 to 1001	0	21971	0.0%	24.9%
1100 to 1051	81	22052	0.1%	25.0%

Figure 7 represents potential land availability in the Peace River Regions of Alberta and BC. The curve illustrates the range of net revenue levels found using the above calculations.

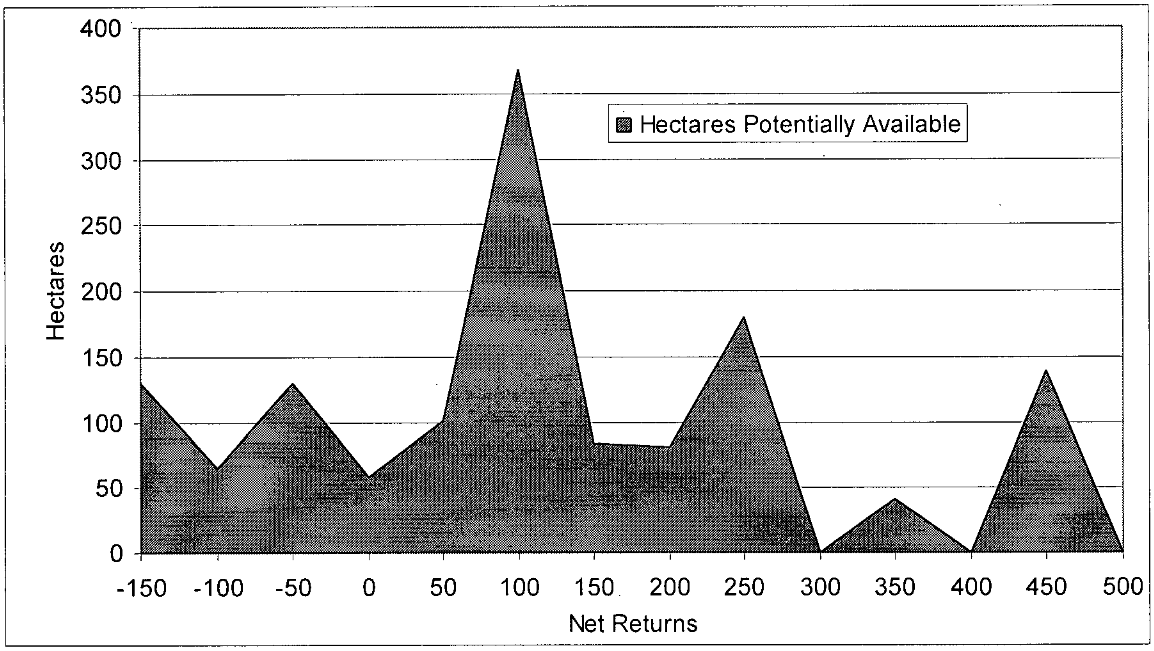

Figure 7. Estimated net returns and land availability of agricultural land in the Peace Region

Survey respondents were also asked to identify how much of their land was not being used, and of this land how much was currently covered with trees. Although it is not clear why this land is unused, it is assumed for the purposes of this thesis that this land has a net revenue that is either zero or idle (due to taxes and maintenance), and as such may be available for tree planting. For those respondents who had also given details on their least productive fields, then, this response was used to determine how much unused land might be available that is not already covered with trees. It was found that this unused, unforested land amounts to 2,370 ha, or 2.7% of the 88,096 ha of the total land identified by survey respondents who gave detailed information on their land use.

Land availability in the Prairies as a whole can now be estimated by taking the amount of land available below a given marginal revenue as a percentage of total land available by those same respondents, and then extrapolating this percentage to the Prairies as a whole. A cutoff point of $15/ha has been chosen, as this is the average return to White Spruce, a softwood species commonly grown in the Prairies, as calculated later in this thesis. The actual cutoff point of any afforestation program is unknown at this point.

In Table 8, the percentage of land with a net marginal return less than $15/ha (i.e. 1.8%) is added to the amount of unused land that is not forested (i.e. 2.7%), and the total percentage (i.e. 4.5%) is then applied to the amount of farmland available in each province according to the 2001 Agricultural Census, to arrive at 1.34 million ha of land potentially available for afforestation in the Canadian Prairies as a whole. Similar calculations for the Peace Region show there to be some 12,482 ha available in that region.

Table 8. Land available with a net marginal revenue less than $30/ha

	Total Provincial land area	Land in crops	Land available
Manitoba	7,601,779	4,714,830	210,640.5
Saskatchewan	26,265,645	15,375,929	686,937.4
Alberta	21,067,486	9,728,181	434,617.7
BC-Peace	868,599	279,396	12,482.3
Total	55,803,509	30,098,336	1,344,677.9

Source: 2001 Agricultural Census

It should be noted at this point that the estimates of land available found in Table 8 are subject to a number of possible errors. As pointed out earlier, there may be several errors arising from the fact that the supply function has been constructed by subtracted average costs across the Prairies from revenues based on predicted yields. There may also be sampling errors brought about by the nature of survey respondents. Landowners who took the time to fill in the responses may not be representative of all farmers across the Prairies or in the Peace region. Respondents may, for example, be more likely to have unused land, or land with poor returns than non-respondents.

The level of net returns to be considered, and thus the amount of land potentially available, will ultimately depend on the type of incentive offered to landowners. However, an approach similar to the one used here could prove to be a valuable tool for setting any level of financial compensation to landowners. For the purposes of this thesis, the totals found in Table 8 will be utilized to examine the policy trade-offs of an afforestation program in the Prairies.

6 THE MODEL

6.1 Introduction

The study area for the purpose of this thesis will focus on the Peace River Regions of Alberta and British Columbia. Using the land availability established in Chapter 5, I will find the number of plantable hectares of a mix of tree species, given certain optimization criteria. The mix of tree species used in the model is based on a review of papers on afforestation in the Prairies. The amount of land to be afforested and reforested will not vary, in order to explore the trade-offs between planting different species, or combinations of species.

The model utilizes a non-linear program (NLP) to optimize net present value, the total amount of carbon sequestered, and stand diversity, given certain constraints. Excel is used to calculate the model, and to find many of the choice variable inputs for the NLP, as described in this chapter. Two discount rates are utilized for comparative purposes, and Excel's Solver is used to find the optimal values. A variety of constraints are introduced into the model, including constraints based on farmers' preferences, in order to further examine the trade-offs involved.

6.2 Tree Species

A number of different approaches have been used to model afforestation scenarios on the Canadian Prairies, typically with different studies using a different mix of tree species. Nagle (1990), for example, utilizes nine different species common to the Canadian Prairies. Peterson *et al.* (1999) list the top ten species, as distributed to landowners in Manitoba, Saskatchewan, and Alberta from the PFRA Shelterbelt Centre in 1997, but only use white spruce, green ash (using Aspen growth volumes), and hybrid poplar, as they consider that these species are most likely to dominate a large-scale afforestation program. Another approach was taken by van Kooten et al. (1999*a*), who combined the single species of hybrid poplar with two other categories comprising of a mix of other hardwoods and a mix of softwoods, with the assumption that hybrid poplar will be used for carbon sequestration.

In order to reflect the preferred mix of species indicated by landowners responding to the landowner survey, an approach utilizing a relatively large number of different tree species is indicated, as survey respondents indicated preferences for ten distinct species, as well as a mix of species. Indeed, it may be possible that some landowners will only participate in a tree-planting program if it involves a species other than poplar. Although Peterson et al. (1999) have argued that providing for this kind of variety may not be realistic in terms of a large-scale afforestation program, there may still exist cost effective ways to provide landowners with the species of trees that they are interested in planting.

With this in mind, the mix of species used by Nagle (1990) will also be used in this study, minus white fir (*Abies concolor*), for reasons described later in this chapter. The eight species to be used in this thesis, then, consist of five species of softwood, white spruce (*Picea glauca*), black spruce (*Picea mariana*), jack pine (*Pinus banksiana*), larch (*Larix occidentalis*), and lodgepole pine (*Pinus contorta var. latifolia*), and three hardwood species, aspen (*Populus tremuloides*), white birch (*Betula papyrifera Marsh.*), and hybrid poplar (*Populus hybrids*).

6.3 Estimating Tree Growth

In order to calculate the amount of carbon stored in tree biomass over time, tree growth volumes (m^3/hectare) for the tree species under consideration needed to be found and verified. The growth volumes for eight of the species listed by Nagle in the *Trees for Canada Program* (1990) paper, however, were questionable, so a literature search was undertaken for another source for growth volumes for these species. White Fir, the ninth species, was not used, as difficulties were encountered in finding reliable growth rates for this foreign tree species.

When no other single source that contained all eight species was found from a literature search, the Canadian Forest Service (Silviculture Operations, Northern Forestry Centre) in Edmonton, Alberta was contacted in June 2003, in order to request growth volumes for these species, based on seedlings currently used in the Peace River Region of Alberta. The growth volumes provided were based on historic afforestation trials of 24-31 year old trees, and were considered to be average for managed stands in the Peace River and Boreal region of Alberta. The growth rate for each individual species was then compared with growth rates from various other sources (Alberta Forest Service 1985; B.C. Ministry of Forests 2002; Burns and Honkala 1990; Nagle 1990) that contained at least one of the species under consideration, and were seen to be slightly higher than average growth rates on medium quality sites, and significantly higher than growth rates on low quality sites.

Since it is being assumed in this thesis that the afforestation and reforestation will be largely undertaken on marginal land, a more extensive comparison was made with tree growth rates on lower quality sites, utilizing the above sources. It was found, on average, that the growth rates from the CFS were higher than growth rates from the other sources listed above for by a factor of 2.2 for softwoods, for hybrid poplar by a factor of 1.2, and for other hardwoods by a factor of 2.0. On this basis, a third set of growth volumes (i.e. in addition to the Nagle and CFS growth volumes) was developed by dividing the CFS volumes by these factors.

The three sets of growth volumes were then sent to Dr. Barb Thomas (University of Alberta and Poplar Research Specialist at Genstat Consulting) for review, and to ask if she had access to a better set of growth volumes for these species. Of the three sets of growth volumes, Dr. Thomas felt that the modified CFS growth volumes best reflect growth volumes in the Peace River region. The adjusted CFS growth volumes are utilized in place of the Nagle growth volumes. Table 9, then, contains tree bole (i.e. the commercial component of the tree) growth volumes (m^3/hectare) based on the adjusted CFS growth volumes.

In Table 9, the time series for both Aspen and Hybrid Poplar are left blank after reaching full maturity, as beyond these points the tree volumes start to decrease due to death and decomposition. In the model these species will be harvested prior to this point.

Table 9. Volume over time for eight Peace River Region tree species (m^3/ha)

Age (Years)	White Spruce	Black Spruce	Jack Pine	Larch	Lodgepole Pine	Aspen	White Birch	Hybrid Poplar
0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	1
10	0	0	2	1	1	0	0	42
15	0	0	6	7	5	1	2	149
20	1	0	13	17	13	10	8	238
25	6	2	23	31	26	36	21	286
30	17	8	35	47	43	75	38	308
35	36	20	48	63	63	117	58	317
40	61	39	61	78	85	153	78	321
45	90	62	73	91	107	182	96	323
50	121	86	85	101	128	202	111	
55	152	110	95	110	149	216	123	
60	180	132	104	116	167	225	132	
65	204	150	112	122	184	231	140	
70	226	165	119	126	200	235	145	
75	243	177	125	129	213	237	150	
80	258	187	130	131	225	238	153	
85	270	194	135	133	235	239	155	
90	279	199	138	134	244	240	157	
95	286	204	141	135	251	240	158	
100	292	207	144	136	257	241	159	
105	297	209	146	136	263		160	
110	300	211	148	137	267		160	
115	303	212	149	137	271		160	
120	305	213	150	137	274		161	

Source: CFS, adjusted for low quality sites

In order to utilize these growth numbers in the model, the time series in Table 9 for each species were then fit to the following Chapman-Richards growth function:

(7.1) $$V(t) = A(1-e^{-kt})^m,$$

where A is the maximum stem wood volume, t is time in years, and k and m are parameters

Values for A, k and m were then estimated using a non-linear regression in SPSS, the results of which are found in Table 10, with graphical representation found in Figure 8.

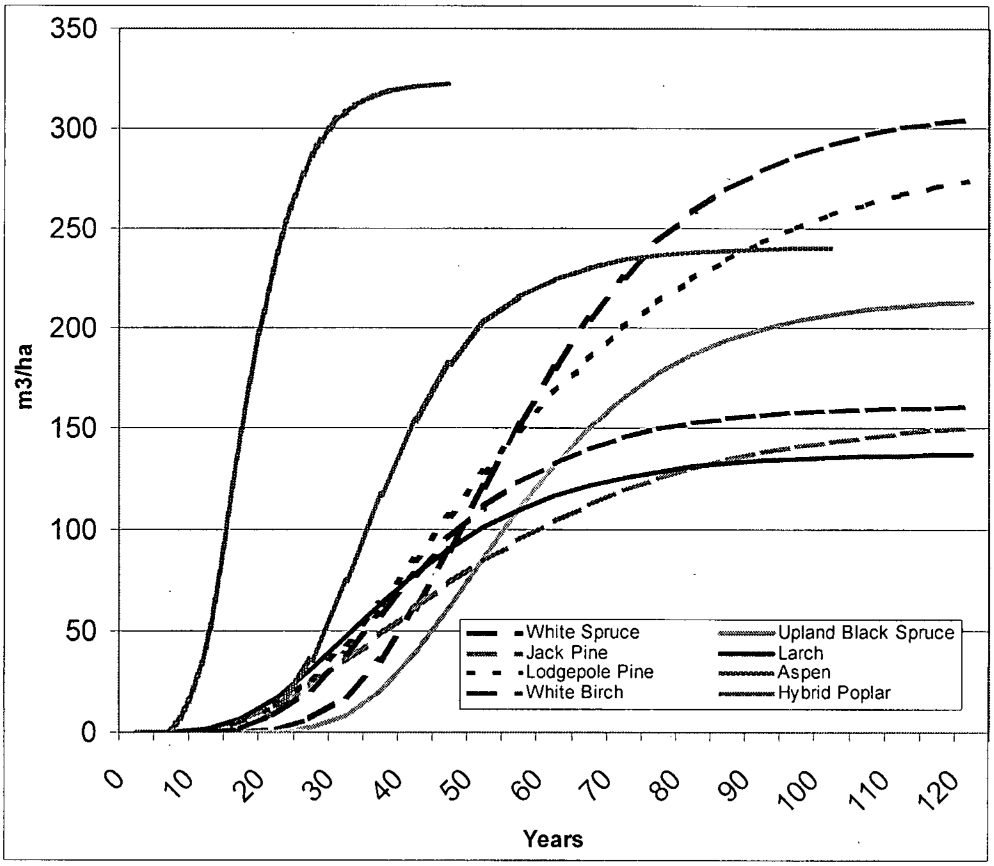

Figure 8. Growth curves of eight tree species compared

Table 10. SPSS estimates for A, k and m for the Chapman-Richards growth function

Species	A	k	m
Softwood			
White Spruce	312.8	0.05196	12.26048
Black Spruce	216.0	0.06059	18.47850
Jack Pine	155.7	0.03950	4.08133
Larch	137.8	0.05898	5.72517
Lodgepole Pine	290.5	0.03674	4.71749
Hardwood			
Aspen	240.9	0.09361	18.85844
White Birch	161.3	0.06395	9.04902
Hybrid Poplar	323.7	0.18152	11.45542

Source: SPSS Version 10

6.4 Carbon Uptake

Total carbon uptake is then calculated by first multiplying the tree volume given by the Chapman-Richards growth function (7.1) by an expansion factor of 1.57 (van Kooten *et al.*, 1999a), to obtain total above-ground biomass (G). Root biomass (R) is related to above-ground biomass for softwoods and hardwoods as follows:

$$\text{Softwoods: } R_S = 0.2317G$$

$$\text{Hardwoods: } R_H = 1.4319G^{0.639}.$$

Total carbon content of the timber, in tonnes, is then calculated by multiplying tree volume by 0.207 for softwoods and 0.187 for hardwoods (van Kooten *et al.*, 1999a).

In the case of trees harvested, however, only about 40% of softwood logs go into the production of wood products, such as furniture, that continue to hold on to their carbon (Row and Phelps, 1995). The remaining 60% can be considered waste, some of which is used as fuel, and as such the carbon cannot be kept in the carbon stock. For deciduous species, the vast majority of logs go into the production of pulp products (B.C. Ministry of Forests, 2003). Due to recent innovations in pulping processes, the amount of carbon retained in pulp products may actually be upwards of 70% (Bill White and David Price, CFS, personal communication, 2003), however much of this carbon is subsequently lost when these products are discarded or burned. The amount that recycling offsets this loss is unclear (Jaakko Pöyry Consulting, 1999), so the retention rate of 40% will also be used for the carbon retention rate of pulp products (Bill White, personal communication, 2003). For the purposes of this thesis, then, 60% of the carbon sequestered is subtracted from the amount of overall carbon sequestered at the point of harvest.

6.5 Rotation Age, Volume and Net Present Value

In order to compare net present value, carbon uptake and biodiversity trade-offs between different planting scenarios, a common end-of-period harvest for all species needed to be established. With a common time horizon, all simulations can be run so that tree species with different growth rates and different optimal harvest periods can be compared.

To choose a time period that was divisible by harvest rotations for each tree species, I first calculated optimal harvest rotations in terms of Net Present Value for each species, utilizing tree volume based on the Chapman-Richards growth functions found earlier. Since Net Present Value (NPV) will also be an output of the main NLP model, NPV was used to determine optimal rotation periods, which were then rounded to rotation ages that are divisible into a common time frame. NPV is calculated as follows:

Net present value

NPV is equal to the difference between the discounted value of revenues (PVR) and the discounted value of costs (PVC) over a given rotation, and can be represented by the following function:

(7.2) $$NPV = PVR - PVC$$

Revenues, in terms of PVR, from the sales of timber over one rotation is found by calculating the discounted end of period revenue, and can be represented by the following function:

(7.3) $$PVR = (P_S * V_S)/(1+r)^t$$

where S represents the species of tree,
t represents time in years,
P_S represents the price/m^3 of species S,
V_S represents the volume/ha of species S in m^3, and
r represents the discount rate

Costs, in terms of PVC, over a single rotation is calculated by taking the planting costs at the beginning of the period and the discounted harvesting cost at the end of the period. PVC can be represented by the following function:

(7.4) $$PVC = B_S + (C_S * V_S)/(1+r)^t$$

where S represents the species of tree,
t represents time in years,
B_S represents the base planting cost per hectare of species S,
C_S represents the harvesting costs/m^3 of species S,
V_S represents the volume in m^3 of species S, and
r represents the discount rate

Average prices per cubic meter for each species are based on B.C. interior log market prices (B.C. Ministry of Forests, 2003), and are found in Table 11. These prices were applied to the amount of timber harvested at the end of one rotation period, and a discount rate of 4% (Krcmar *et al.*, 2003) was applied to the end of period revenue, in order to calculate future income in current terms at the end of one harvest rotation period. A discount rate of 6% was also used for sensitivity analysis. Planting costs by hectare and species were estimated by the Canadian Forest Service (personal communication, 2003), and are given in Table 11.

Harvesting Costs of $12.86 per m^3 (Kuhnke *et al.*, 2002) were applied to harvests at the end of one rotation period for each species, and discount rates of 4% and 6% were applied to this cost at the end of each period, so that NPV can be calculated for each species. Land conversion costs are ignored.

Table 11. Planting costs for eight tree species

Species	Average price per cubic meter	Base Planting Cost
White Spruce	$54.67	$1,100.00
Black Spruce	$54.67	$1,100.00
Jack Pine	$54.67	$950.00
Larch	$77.39	$1,050.00
Lodgepole Pine	$54.67	$980.00
Aspen	$35.03	$1,500.00
White Birch	$35.03	$1,500.00
Hybrid Poplar	$35.03	$1,900.00

Source: CFS (2003)

Data for each species was entered into an Excel spreadsheet, and Solver was used to find the optimal time period (t), in years, that maximized NPV for each species. These rotation ages were then rounded into the nearest number that was divisible into a common time frame, determined to be 120 years after the results were considered, in order to have the model calculate the end of period carbon uptake, net present value and biodiversity.

The results of this work for the eight tree species is found in Table 12, with the first column under each discount rate representing the NPV optimized rotation period, in years, and the second column representing the rounded out rotation ages that will be used in the main optimization model. As can be seen in the table, a higher discount rate results in a shorter rotation period because it is less tolerant of the slower growth of each species as they near maturity.

Table 12. Optimal rotation ages determined by Solver and rounded rotation ages to be used in the model for eight prairie species

	4% discount rate		6% discount rate	
	Optimal Rotation Age	Rotation Age for model	Optimal Rotation Age	Rotation Age for model
White Spruce	54.8	60	47.7	40
Black Spruce	55.9	60	49.6	40
Jack Pine	41.3	40	33.6	30
Larch	38.4	40	32.5	30
Lodgepole Pine	46.0	40	37.6	40
Aspen	40.9	40	36.8	40
White Birch	43.1	40	37.4	40
Hybrid Poplar	22.0	24	19.8	20

Forgone Income

Foregone income for agricultural production or other land-use purposes is not taken into account in this model. As seen in the results of the Suchánek survey, most farmers willing to participate in a planting program do so because they see other benefits that will be brought about by planting trees on their property. The amount of savings brought about by the establishment of windbreaks or other trees planted for erosion control, for example, offset to some degree any costs associated with being involved in such a program, and are difficult to quantify. In addition, any financial incentives provided by the government for involvement in a tree planting program imply that the net costs to landowners may be either zero or positive. Moreover, it is assumed that some farmers will convert idle land that is serving little, or no, productive value, such that for them the issue of forgone income is likely not relevant.

Therefore, since it is assumed that the decision to change land-use has already taken place on the basis of unknown economic variables, the value of foregone income from other uses is simply considered here to be zero.

6.6 Per Hectare Calculations

In order to convert the problem into a NLP, I first calculate the volume in cubic metres (m^3) of one hectare of each species over the model's 120-year period, given the rotation ages identified in the previous section. This is done by using the Chapman-Richards growth to calculate tree volume per hectare after one rotation, and then multiplying this result by the number of rotations in the 120-year period. With this information I am then able to calculate the net present value of revenues (NPV) and carbon accumulation (C) per hectare for each species over the 120-year period, based on a their respective rotations.

Net present value

NPV over the 120-year period (NPV_{120}) is equal to the difference between the discounted value of revenues (PVR_{120}) and the discounted value of costs (PVC_{120}) over the 120-year period, and can be represented by the following function:

(7.5) $$NPV_{120} = PVR_{120} - PVC_{120}$$

Revenues, in terms of PVR_{120}, from the sales of timber over the planning horizon is found by adding together the discounted end of period revenues over 120 years, and can be represented by the following function:

(7.6) $$PVR_{120} = \sum_S \sum_t (P_S * V_S)/(1+r)^{tS}$$

where S represents the species of tree,
t represents time in years,
tS represents time, in years, at the end of each rotation by species,
P_S represents the price/m^3 of species S,
V_S represents the volume/ha of species S in m^3, and
r represents the discount rate

Costs, in terms of PVC_{120}, over the planning period is represented by adding together planting costs at the beginning of the first period, discounted planting costs at the beginning of each remaining period and discounted harvesting costs at the end of each period over 120 years, and can be represented by the following function:

(7.7) $$PVC_{120} = \sum_S \sum_t ((B_S/(1+r)^{tS-RS}) + (C_S*V_S)/(1+r)^{tS})$$

where S represents the species of tree,
t represents time in years,
tS represents time, in years, at the end of each rotation by species,
RS represents the length of one rotation by species,
B_S represents the base planting cost per hectare of species S,
C_S represents the harvesting costs/m^3 of species S,
V_S represents the volume in m^3 of species S, and
r represents the discount rate

Tonnes of carbon accumulated (C) at the end of the 120-year period is found by multiplying 40% (to represent carbon that stays sequestered) by the total amount of carbon in the study area. Total carbon (C) is found by adding together the total amount of carbon sequestered in all softwood (C_S) and hardwood (C_H) trees. Calculations for carbon are described previously, and can be represented by the following functions:

(7.8) $$C_S = 40\% * \sum_S(0.207*BM_{SS}*N_S) \text{ for softwoods}$$

and

(7.9) $$C_H = 40\% * \sum_S(0.187*BM_{HS}*N_S) \text{ for hardwoods}$$

where S represents the species of tree,
N_S represents the number of rotations in 120 years, by species
BM_{SS} represents biomass/ha by softwood species, and
BM_{HS} represents biomass/ha by hardwood species

Biomass (BM) for each species per rotation period is calculated separately for softwoods and hardwoods, as described earlier, and can be represented by:

(7.10) $$BM_{SS} = \sum_S (V_S*1.57)*(1+0.2317) \text{ for softwoods}$$

and

(7.11) $$BM_{HS} = \sum_S ((V_S*1.57)+1.4319*(V_S*1.57)^{0.639}) \text{ for hardwoods}$$

where S represents the species of tree,
V_S represents the one rotation volume/ha of species S in m^3,

Using the results for costs, revenue and carbon accumulation calculated on a per hectare basis, the non-linear tree growth function is not needed in the NLP itself. Rather, the static results of the tree growth per hectare calculation, in terms of net revenue and carbon accumulation per hectare, for each species over the time period, is used as inputs in the NLP model. This approach avoids the problem of trying to solve for the non-linearities of tree growth.

The results of the above calculations for the eight tree species under consideration, based on the rotation ages in the second columns of Table 12 for each discount rate are found in Table 13.

Table 13. Per hectare calculations for each tree species

Species	m3/ha harvest at optimal rotation	Value per ha	Cost per ha	Net Benefits per ha	Biomass (root & above-ground) per ha	Carbon (tonnes per ha)
4% discount rate						
White Spruce	180	$1,021.80	$1,444.92	-$423.12	347.20	57.50
Black Spruce	132	$749.96	$1,380.98	-$631.02	254.83	42.20
Jack Pine	61	$865.86	$1,392.77	-$526.91	117.47	29.18
Larch	78	$1,574.75	$1,575.94	-$1.18	150.93	37.49
Lodgepole Pine	85	$1,206.33	$1,510.41	-$304.07	163.67	40.66
Aspen	153	$1,400.90	$2,391.80	-$990.90	288.45	64.73
White Birch	78	$710.49	$2,138.34	-$1,427.85	153.00	34.33
Hybrid Poplar	279	$6,200.19	$5,363.40	$836.79	508.21	190.07
6% discount rate						
White Spruce	61	$357.19	$1,301.36	-$944.17	117.43	29.17
Black Spruce	39	$228.71	$1,271.14	-$1,042.43	75.19	18.68
Jack Pine	35	$404.39	$1,244.34	-$839.95	67.91	22.49
Larch	47	$770.53	$1,398.23	-$627.70	91.41	30.28
Lodgepole Pine	85	$497.85	$1,201.65	-$703.80	163.67	40.66
Aspen	153	$578.14	$1,872.26	-$1,294.11	288.45	64.73
White Birch	78	$293.21	$1,767.65	-$1,474.44	153.00	34.33
Hybrid Poplar	238	$3,773.36	$4,143.56	-$370.20	436.66	195.97

6.7 Diversity

In the context of this thesis, stand diversity will be defined as tree species diversity within a forest stand or a region. There are a number of reasons to increase or maximize stand diversity within a forest stand or region, including:

1) Creating a more biodiversified forest environment,
2) Reducing the risks of forest destruction brought about by species-specific disease or pests,
3) Creating a more aesthetically pleasing landscape.

Ambuel and Temple (1983) have argued that biodiversity is closely related to structural (tree size and species distribution) diversity within a forest environment. Although it may be considered a simplification, Onal (1997) considers that structural diversity of forested land can be used as a proxy for biodiversity. As Steventon (1994) notes, "we cannot manage for every species individually." Therefore, the best way to maintain a full range of biological diversity throughout a forest environment is by ensuring a diverse range of forest environments (Greenough and Kurz, 1996).

Moreover, forest management regimes designed for maximizing volume tend to involve single-species stands with relatively short rotation cycles. These short rotation cycles tend to be prone to a variety of species-specific insect pests and diseases (Hopkin and Cheliak, 1995), although these rarely lead to widespread plantation mortality, and resistance tends to depend on clones used (Hubbes and Lin, 1995). Still, an argument can be made for a more varied forestry application in order to avoid such problems.

Although there is a wide divergence of views as to what constitutes an aesthetically "pleasing" landscape, there does seem to be general consensus that a diversely forested landscape is more pleasing than a homogeneous one (Hunziker, 1995). Moreover, studies have shown that a slightly forested landscape is preferred over either a cleared landscape or a completely forested landscape (Hunziker and Kienast, 1999). In addition, landscape aesthetics also affect tourism potential and external perception of a region's ecological management (Hunziker, 1995).

Stand diversity, then, has great value, both in economic terms and with respect to the environment. Large amounts of money have been spent on its enhancement and protection by governments. The majority of farmers responding to the landowners survey (Suchánek et al., 2001) were interested in planting a mix of species on their land, and the Kyoto Protocol may provide them with a way to accomplish this through the use of Carbon Credits and government sponsored afforestation programs.

In this thesis, then, tree species diversity, as a proxy for biodiversity and landscape diversity, will be an output of the model that will be calculated for each scenario. Using this output, the trade-offs of the various scenarios in terms of species diversity can also be seen.

Quantifying diversity

Species diversity models can be grouped into three broad categories (Magurran, 1988). The first of these contains species richness indices, which are usually based on the number of individual species in a defined area. The second category consists of species abundance or evenness models, which calculate the distribution of abundance or dominance among different species. While high evenness is often equated with diversity, an even distribution of species (or forest structure) is not always an appropriate measure of biodiversity (van Kooten and Krcmar, 2001). The third species diversity category consists of indices based on the proportional abundance of species within a defined area or region.

Shannon Diversity Index

The Shannon Index, also known as the Shannon-Weiner Index and the Shannon-Weaver Index, fits into the third category of indices. It assumes that individuals are randomly sampled from an effectively infinite population (Pielou, 1975). It assumes that all species are represented in the sample. The Shannon Index takes the following form:

$$S=-\sum p_S \log p_S, \tag{7.12}$$

where p_S is the proportion of all individual organisms accounted for by species S, log refers to Base 10, and n_S is the total number of species in the ecosystem

The maximum diversity found using the Shannon Index occurs when all species were equally abundant, so can easily be calculated for comparative purposes. As pointed out by Pielou (1969), after finding the maximum value of the Shannon Index, the ratio of observed diversity to maximum diversity could then be used as an indicator of evenness. The Shannon Index also meets three desirable properties as described by Pielou (1977):

"1) Given a number of species, the index reaches its greatest value when the community is completely even (i.e., the proportion of individuals of each species is 1/s where s represents the number of species).

2) Given two completely even communities, the one with the greatest number of species should have the larger index value.

3) Given a community that can be classified in several ways, the sum of the index values at each level of classification should equal the value using all levels of classification."

The Shannon index also meets a fourth criteria, as described by Patil and Taillie (1982), that diversity indices should increase with transfers of abundance from one species to another less abundant species within the same community. Moreover, as Holland et al. (1994) point out, The Shannon Index is open-ended, with maximum possible values increasing with the number of categories being considered.

The Shannon Index was originally to be used as the only index in this thesis, due to its wide acceptance and its applicability to the data gathered. However, when used as either an objective or as a constraint of the model, the Shannon Index frequently caused Excel's Solver program to fail, except when the choice variables were very near to the optimal solution. Therefore, while the Shannon Index will still be used as an output of the model, another index was needed for use in the model's objective function.

Simpson's Diversity Index

Simpson's Index also fits into the third category of diversity indices. As Magurran (1988) notes, this index is weighted towards the most abundant species, and less sensitive to species richness. Moreover, as May (1975) has shown, when the number of species in a sample exceeds ten, the value of Simpson's Index is highly dependent on species abundance. For the purpose of this model, Simpson's Index can be represented by:

(7.13) $$D = [\sum X_S(X_S-1)]/[M(M-1)]$$

where D_t is diversity,
X_S is the number of hectares of species S, and
M is the total number of hectares of all species

Since there are only eight species under consideration in this thesis, Simpson's diversity index will not be overly dependent on species abundance in this model. In fact, using 29 separate scenarios of the model, the comparative results of Simpson's Index very closely approximated the comparative results of the Shannon Index, the only difference being amplitude. A comparison of the two runs can be seen in Figure7.2, where stand diversity is simply defined as tree species diversity within the study region.

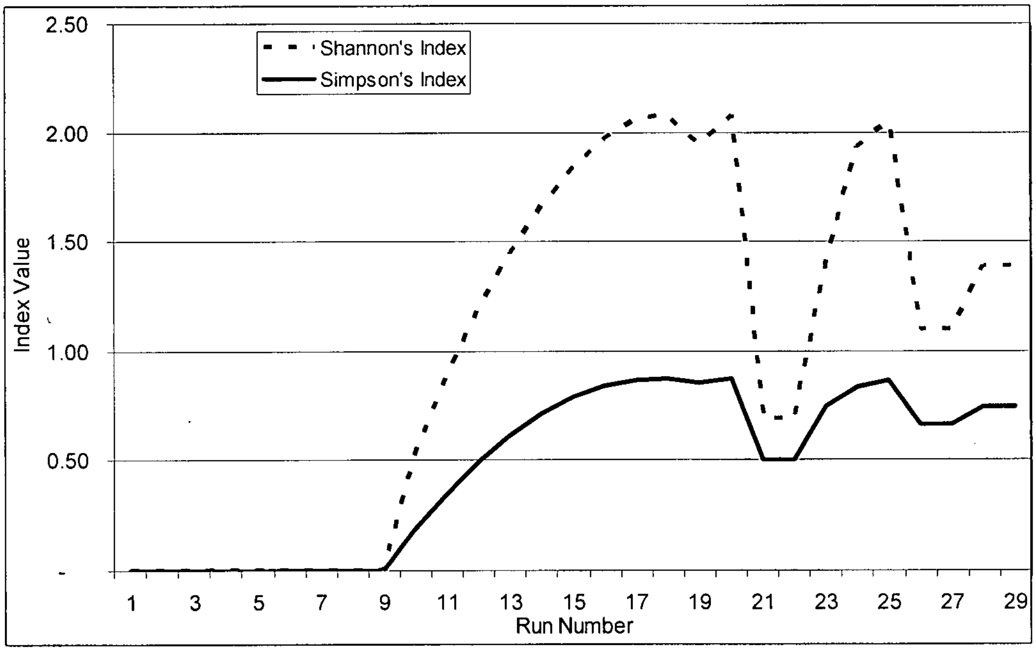

Figure 7.2: Comparison of the Shannon and Simpson's Indices using 29 model scenarios

6.8 The non-Linear Programming Model

Land used in this case study consists of marginal agricultural land in the Peace River Region, as previously defined in Chapter 5. It is assumed that there are few, or no, trees of any significance on this land. This land is therefore considered to be suitable for afforestation, and as such can be made available for planting for the purpose of carbon sequestration. In the study I estimate that there are some 12,482.34 hectares of plantable land in the study region.

The primary objective of the model is to maximize one of three policy objectives, diversity, NPV_{120} or carbon (C) sequestered in the Peace River Region, by determining the number of hectares planted of each tree species, subject to a variety of constraints in a number of different scenarios. Since Simpson's diversity index will be one of the constraints of the model, Solver will be run in non-linear mode.

The model will also be used to calculate a series of planting configuration scenarios, based on fixed percentages of each species, or mix of species, planted, in order to further examine the trade-offs involved.

The results of these scenarios will be compared, in order to examine more closely the policy trade-offs involved. The three objective functions of the model, then, will maximize either net present value (NPV_{120}) as defined in function (7.5), total carbon sequestered (C) as defined in functions (7.8) and (7.9), or stand diversity as defined in function (7.13), and can be represented by the following functional forms:

Maximize: $NPV_{120}(X_S) = PVR_{120}(X_S) - PVC_{120}(X_S)$

Maximize: $D(X_S) = [\sum X_S(X_S-1)]/[M(M-1)]$

And

Maximize: $C(X_S) = C_S(X_S) + C_H(X_S)$

where (X_S) represents the number of hectares planted of species S,
NPV represents net present value,
D represents diversity, and
C represents carbon sequestered

Constraints

The model will be constrained to ensure that the number of hectares planted be fixed at the number of potentially available hectares determined in Section 5 (i.e. 12,482.34 hectares). This constraint can be represented by:

$$\sum X_S = 12{,}482.34$$

where (X_S) represents the number of hectares planted of species S

Non-zero constraints will be utilized in place of non-negativity constraints, as the functional form for the diversity index does not allow for zero hectares of a particular species. Due to an absence of greater-than zero or less-than zero constraints in Solver, this non-zero constraint will take the form of:

$$X_S \geq 0.0000000001, \text{ for all } X_S$$

where (X_S) represents the number of hectares planted of species S

Although this constraint will inevitably result in very small amounts of every species being planted, the NPV and carbon amounts will be insignificant, and the effect on the diversity index will be negligible.

After the model is run to maximize and minimize NPV, diversity and carbon uptake with no constraints on the objective functions, these base cases will serve as upper and lower bounds over the time horizon. This will be done by using the three equations as constraints, with the level of the constraint varying from the lower to upper bound. These constraints can be represented as follows:

$$NPV \geq Min\ (NPV)$$
$$NPV \leq Max\ (NPV)$$

$$C \geq Min\ (C)$$
$$C \leq Max\ (C)$$

$$D \geq Min\ (D)$$
$$D \leq Max\ (D)$$

Where NPV represents net present value,
C represents carbon sequestered, and
D represents diversity

Once the range of the diversity index is determined, a number of scenarios will be run to determine the effect of lowering or raising the maximum or minimum diversity constraints, respectively, and then solving for each of the three objective functions. The results of this will effectively give the shadow value of diversity, in terms of carbon and NPV.

The remainder of the constraints in this model will vary according to the scenario run. Each scenario will vary either the minimum percentage of each of the species under consideration, or minimum percentage of softwoods and hardwoods planted. These constraints can be represented by the following functional forms and are described in detail in the next section:

$$\%X_S \geq \%Y, \text{ for all } X_S$$

$$\%X_{SS} \geq \%Y, \text{ for all } X_S$$

$$\%X_{HS} \geq \%Y, \text{ for all } X_S$$

Where $\%X_S$ represents the % of hectares planted of species S
$\%X_{SS}$ represents the % of hectares planted of softwoods
$\%X_{HS}$ represents the % of hectares planted of hardwoods, and
$\%Y$ represents the constraint in percentage terms

6.9 Afforestation Scenarios

The model will first be run with no constraints, in order to find out the planting configurations required for maximizing and minimizing NPV, diversity and carbon on the land available. The results of other scenarios will then be compared with these baseline results with no constraints to see the trade-offs involved.

As indicated in Chapter 4, farmers (those that are willing to enter into a tree planting program) in this region, indeed in the Prairies in general, generally show a preference for a mix of species to be planted over that of any single species. By developing and running a variety of tree-planting scenarios, I am able to examine the trade-offs, in comparison with the baseline case, brought about by each scenario. Among the scenarios considered under this study, then, will be a scenario that reflects both farmers' preferences based on the landowner survey.

Lacking any further refinement in the definitions of planting "mixed forests" or "for conservation purposes" chosen by respondents in the landowner survey, I assume for the purposes of this thesis that those who expressed such preferences will plant an equal number of each of the trees considered here. Although this is likely not realistic on an individual level, in the aggregate it may represent a close approximation.

Scenarios considered are as follows:

- The two most productive species in terms of NPV
- The two most productive species in terms of carbon sequestered
- Survey respondent's preferences based on Table 3
- 50% hardwood and 50% softwood, with an even distribution within each class
- Equal mix of the top 3 carbon sequestering species
- Equal mix of the top 3 revenue producing species
- Equal mix of the top 4 carbon sequestering species
- Equal mix of the top 4 revenue producing species

In addition to the scenarios above, a Visual Basic program was written to run a series of scenarios that would increase the percentage of each species grown in ten percent intervals, such that all possible combinations (in 10% increments) of the eight species could be plotted in scatter plots. This was achieved by using a series of nested For-Next loops that decreased the percentage of each species from 100% to 0% planted, outputting results that were equal to 100%.

The output of this program was used to create two scatter plots for each discount rate, which show the trade-offs between the three main output variables in the model (i.e. NPV, carbon sequestered and biodiversity). These production possibility relationships (PPRs) show the relationships between i) the sequestration of carbon vs. stand diversity and ii) net present value vs. stand diversity. A line traced through the outermost bounds on the scatter plots then represents the production possibility frontiers (PPFs) for planting the eight species. These scatter plots could be used to make policy decisions by examining the full range of trade-offs possible.

7 RESULTS

The following scenarios assumed that all planted trees would be harvested at least twice during the simulation period, with some species undergoing more harvests due to shorter rotation ages. It is assumed that all timber will be harvested at the end of the 120-year period, in order that net revenues and carbon sequestered could be calculated for the full period.

The model was constructed in Microsoft Excel, and Excel's Solver was used to calculate the results. The land base used in all scenarios totalled 12,482 ha, as identified in Chapter 5 of this document. The results are presented in this section.

The results are illustrated through a series of comparative tables showing different NPV levels, carbon uptake levels, and tree species diversity levels as calculated by the Simpson's and Shannon Indices. The results of the Visual Basic program were then used to create Production Possibility Relationships (PPRs) plotted as scatter graphs, which illustrate the policy trade-offs between the various scenarios for each discount rate.

7.1 The maximum NPV and carbon scenarios

As expected, the maximization of NPV and carbon both resulted in 100% of available land planted with hybrid poplar for both discount rates in the unconstrained case.

The model calculated that planting the total 12,482 ha of land with this one species would result in an NPV of just over $10 million over the 120 years using a discount rate of 4%, and -$4.6 million using a discount rate of 6%. This equates to an average NPV of $87,042 per year using a discount rate of 4% and -$38,508 using a rate of 6%. In both cases, some 2.4 million tonnes of carbon would be sequestered, or an average 20,385 tonnes of carbon per year over the 120-year period, as shown in Table 14. Biodiversity, as calculated by the both indices, is equal to zero when NPV and carbon are maximized.

7.2 The minimum NPV and carbon scenarios

The unconstrained minimization of NPV resulted in 100% of available landed planted with white birch for both discount rates, with an NPV of -$17.8 million with associated with a 4% discount rate, and an NPV of -$18.4 million for the 6% case. This represents an NPV of $28.3 million less than maximum NPV for the 4% discount rate case, and $13.8 million less in the 6% case.

The unconstrained minimization of carbon resulted in 100% of available landed planted with jack pine with some 364,244 tonnes of carbon sequestered using a 4% discount rate, and 100% of black spruce planted, resulting in 233,132 tonnes of carbon sequestered for the 6% case. This represents just 14.9% of maximum carbon in the 4% scenario, and 9.5% of maximum carbon for the 6% scenario. Biodiversity, as calculated by both indices, is equal to zero.

The reason for different species being planted for minimum carbon levels under the two different discount rates is due to the different optimal rotation ages that result from optimizing NPV under the two discount rates, as illustrated in Table 12.

7.3 The maximum species diversity scenario

In contrast, if the model were forced to plant all species in equal amounts by maximizing diversity, NPV amounts to some -$5.4 million using a 4% discount rate, or $15.9 million less than maximum NPV, and -$11.4 million using the 6% rate, or $6.8 million less than maximum NPV. Total carbon sequestered would be 774 thousand tonnes using a 4% discount rate, or 31.6% of maximum carbon, and 681 thousand tonnes in the 6% rate case, or 27.8% of maximum carbon. Biodiversity in this scenario is equal to 2.08 for the Shannon Index, and 0.875 for the Simpson's Index.

A large variance between results was found in these first three scenarios, illustrating the utility of using this approach. The results of these three scenarios represent a baseline with the maximum and minimum results for each of the three output variables of the model. These results are summarized in Table 14.

Table 14. Maximum and minimum values for NPV, carbon and diversity

	NPV	Carbon Sequestered	Shannon Index	Simpson's Index
4% discount rate				
Maximum NPV and Carbon	$10,445,096	2,446,190	0.00	0.00
Min NPV and Carbon	-$17,822,924	364,244	0.00	0.00
Max Diversity (both indices)	-$5,411,500	774,152	2.08	0.25
6% discount rate				
Maximum NPV and Carbon	-$4,620,978	2,446,190	0.00	0.00
Min NPV and Carbon	-$18,404,462	233,132	0.00	0.00
Max Diversity (both indices)	-$11,385,156	680,763	2.08	0.88

Source: Excel Solver calculations

7.4 Imposing diversity constraints

In the previous section it was determined that the Simpson's Index ranged from 0.0 to 0.875. In order to see the effects of imposing the diversity constraint, NPV and carbon were maximized while imposing minimum constraints of 0.25, 0.50, and 0.75 on the Simpson's Index. The results of these trials represent, in part, the shadow prices of diversity, and are contained in Tables 15 through 18.

Table 15. Maximizing carbon while constraining minimum diversity: percentage species mix

Simpson's Index Constraint	White Spruce	Black Spruce	Jack Pine	Larch	Lodgepole Pine	Aspen	White Birch	Hybrid Poplar
4% discount rate								
0.25	4.8%	0.0%	0.0%	0.0%	0.0%	9.2%	0.0%	86.0%
0.50	10.2%	3.5%	0.0%	1.4%	2.8%	13.4%	0.1%	68.5%
0.75	7.1%	7.1%	7.1%	12.0%	7.1%	7.1%	7.1%	45.3%
6% discount rate								
0.25	0.0%	0.0%	0.0%	0.0%	0.7%	13.8%	0.0%	85.5%
0.50	2.1%	0.0%	0.0%	2.6%	6.7%	16.2%	4.2%	68.3%
0.75	7.2%	7.2%	7.2%	11.7%	7.2%	7.2%	7.2%	45.3%

Source: Excel Solver calculations

Table 16. Maximizing carbon while constraining minimum diversity: other outputs

Simpson's Index Constraint	Softwoods	Hardwoods	NPV ($1,000s)	Carbon (1,000 tonnes)	Shannon Index	Simpson's Index	% Max carbon
4% discount rate							
0.25	4.8%	95.2%	$7,586	2,149	0.50	0.25	87.8%
0.50	18.0%	82.0%	$4,562	1,847	1.05	0.50	75.5%
0.75	40.5%	59.5%	$907	1,370	1.74	0.75	56.0%
6% discount rate							
0.25	0.7%	99.3%	-$6,244	2,206	0.44	0.25	90.2%
0.50	11.3%	88.7%	-$7,574	1,871	1.04	0.50	76.5%
0.75	40.3%	59.7%	-$8,642	1,341	1.74	0.75	54.8%

Source: Excel Solver calculations

Table 17. Maximizing NPV, while constraining minimum diversity: percentage species mix

Simpson's Index Constraint	White Spruce	Black Spruce	Jack Pine	Larch	Lodgepole Pine	Aspen	White Birch	Hybrid Poplar
4% discount rate								
0.25	0.0%	0.0%	0.0%	14.6%	0.0%	0.0%	0.0%	85.4%
0.50	2.1%	0.0%	0.0%	23.6%	8.2%	0.0%	0.0%	66.1%
0.75	10.7%	5.8%	8.3%	20.8%	13.6%	0.0%	0.0%	40.8%
6% discount rate								
0.25	0.0%	0.0%	0.0%	14.6%	0.0%	0.0%	0.0%	85.4%
0.50	0.0%	0.0%	0.0%	23.3%	10.8%	0.0%	0.0%	65.9%
0.75	6.5%	1.3%	12.1%	23.4%	19.4%	0.0%	0.0%	37.2%

Source: Excel Solver calculations

Table 18. Maximizing NPV, while constraining minimum diversity: other outputs

Simpson's Index Constraint	Softwoods	Hardwoods	NPV ($1,000s)	Carbon (1,000 tonnes)	Shannon Index	Simpson's Index	% Max carbon
4% discount rate							
0.25	14.6%	85.4%	$8,913	2,094	0.42	0.25	85.6%
0.50	33.9%	66.1%	$6,482	1,736	0.90	0.50	71.0%
0.75	59.2%	40.8%	$2,178	1,272	1.57	0.75	52.0%
6% discount rate							
0.25	14.6%	85.4%	-$5,092	2,143	0.42	0.25	87.6%
0.50	34.1%	65.9%	-$5,820	1,754	0.85	0.50	71.7%
0.75	62.8%	37.2%	-$7,471	1,158	1.52	0.75	47.3%

Source: Excel Solver calculations

We can see from Tables 16 and 18 that the imposition of different levels of diversity constraints helps to illustrate that the maximization of carbon and NPV do not necessarily result in the same mix of species planted, particularly once the diversity constraint is large enough. These differences may be even more significant elsewhere in Canada, particularly if other species (such as fruit trees) are brought into the equation.

Also, as can be seen from the tables, the cost of diversity is quite a bit higher for higher levels of the diversity constraint. When using a discount rate of 4%, for example, the shadow value of an increase in diversity from 0.5 to 0.75 is $4.3 million, whereas an increase from 0.25 to 0.5 is $2.4 million. Using a discount rate of 6%, these same shadow prices are $1.7 million and $0.7, respectively.

Interestingly, when using a 4% discount rate NPV remains positive, even with a level of diversity that is around 86% of maximum diversity. Using a 6% discount rate maximum NPV was already below $0, so imposing diversity constraints only increased the loss in terms of NPV.

Maximizing Diversity

It was found that once the model was run to maximize the Simpson's Index, Solver could then easily be used to maximize the model for the Shannon Index since the model was already very close to the maximum value of the Shannon Index. Therefore, if the Shannon Index is considered to be more reliable (as described in Section 7.7), the model can now be utilized to maximize the Shannon Index by first maximizing the Simpson's Index and using the results as a starting point.

In order to compare the results from the two diversity indices, each of the two indices were maximized while imposing maximum constraints of 0.25, 0.50, and 0.75 on the Simpson's Index. The results of these trials are contained in Tables 19 through 22.

Table 19. Maximizing Simpson's Index, while constraining maximum diversity: percentage species mix

Simpson's Index Constraint	White Spruce	Black Spruce	Jack Pine	Larch	Lodgepole Pine	Aspen	White Birch	Hybrid Poplar
4% discount rate								
0.25	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	86.5%
0.50	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	69.8%
0.75	28.1%	9.7%	1.4%	1.4%	1.4%	28.3%	1.4%	28.4%
6% discount rate								
0.25	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	86.5%
0.50	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	69.8%
0.75	7.8%	2.6%	2.9%	2.9%	26.5%	16.4%	2.9%	37.9%

Source: Excel Solver calculations

Table 20. Maximizing Simpson's Index, while constraining maximum diversity: other outputs

Simpson's Index Constraint	Softwoods	Hardwoods	NPV ($1,000s)	Carbon (1,000 tonnes)	Shannon Index	Simpson's Index	% Max carbon
4% discount rate							
0.25	9.7%	90.3%	$7,990	2,125	0.66	0.25	86.9%
0.50	21.6%	78.4%	$4,970	1,821	1.20	0.50	74.4%
0.75	41.9%	58.1%	-$3,164	1,180	1.53	0.75	48.2%
6% discount rate							
0.25	9.7%	90.3%	-$5,668	2,173	0.66	0.25	88.8%
0.50	21.6%	78.4%	-$6,957	1,837	1.20	0.50	75.1%
0.75	42.8%	57.2%	-$9,065	1,260	1.62	0.75	51.5%

Source: Excel Solver calculations

Table 21. Maximizing the Shannon Index, while constraining maximum diversity: percentage species mix

Simpson's Index Constraint	White Spruce	Black Spruce	Jack Pine	Larch	Lodgepole Pine	Aspen	White Birch	Hybrid Poplar
4% discount rate								
0.25	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	86.5%
0.50	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	69.8%
0.75	7.8%	7.8%	7.8%	7.8%	7.8%	7.8%	7.8%	45.6%
6% discount rate								
0.25	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	86.5%
0.50	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	69.8%
0.75	7.8%	7.8%	7.8%	7.8%	7.8%	7.8%	7.8%	45.6%

Source: Excel Solver calculations

Table 22. Maximizing the Shannon Index, while constraining maximum diversity: other outputs

Simpson's Index Constraint	Softwoods	Hardwoods	NPV ($1,000s)	Carbon (1,000 tonnes)	Shannon Index	Simpson's Index	% Max carbon
4% discount rate							
0.25	9.7%	90.3%	$7,990	2,125	0.66	0.25	86.9%
0.50	21.6%	78.4%	$4,970	1,821	1.20	0.50	74.4%
0.75	38.9%	61.1%	$583	1,378	1.75	0.75	56.4%
6% discount rate							
0.25	9.7%	90.3%	-$5,668	2,173	0.66	0.25	88.8%
0.50	21.6%	78.4%	-$6,957	1,837	1.20	0.50	75.1%
0.75	38.9%	61.1%	-$8,828	1,348	1.75	0.75	55.1%

Source: Excel Solver calculations

As can be seen from Tables 20 and 22, maximizing the Shannon Index while constraining the Simpson's Index results in slightly higher values for the Shannon Index in at least one case. While this may imply that the Shannon Index is more precise, this is not clear from the tests run.

Also of note is the fact that the shadow prices of diversity, in terms of NPV, are different when diversity is being maximized, as opposed to when NPV is being maximized.

7.5 Other Scenarios

Tables 23 and 25 show eight scenarios in terms of the percentage of each of the species planted for each discount rate under consideration. These scenarios were run using hard constraints in Solver, in order to examine trade-offs between species. Scenarios are as described in Chapter 7 and listed in the column on the left.

The results of these scenarios, in terms of the percentages of softwoods and hardwoods, NPV generated, carbon sequestered and diversity levels achieved, are found in Tables 24 and 26.

Table 23. Percentage of each species planted in 8 scenarios (4% discount rate)

Scenario	White Spruce	Black Spruce	Jack Pine	Larch	Lodge-pole Pine	Aspen	White Birch	Hybrid Poplar
Two top species (NPV max)	0.0%	0.0%	0.0%	50.0%	0.0%	0.0%	0.0%	50.0%
Two top species (carbon max)	0.0%	0.0%	0.0%	0.0%	0.0%	50.0%	0.0%	50.0%
Respondents' preferences	15.3%	15.3%	12.3%	5.8%	12.3%	5.8%	5.8%	27.8%
50% hard-50% soft	10.0%	10.0%	10.0%	10.0%	10.0%	16.7%	16.7%	16.7%
Top 3 carbon	33.3%	0.0%	0.0%	0.0%	0.0%	33.3%	0.0%	33.4%
Top 3 NPV	0.0%	0.0%	0.0%	33.3%	33.3%	0.0%	0.0%	33.4%
Top 4 carbon	25.0%	25.0%	0.0%	0.0%	0.0%	25.0%	0.0%	25.0%
Top 4 NPV	25.0%	0.0%	0.0%	25.0%	25.0%	0.0%	0.0%	25.0%

Table 24. Results of 8 scenarios (4% discount rate)

	% Softwood	% Hardwood	NPV (millions)	Carbon (millions of tonnes)	Shan. Index	Simp. Index
Two top species (NPV max)	50.0%	50.0%	$5.22	1.42	0.69	0.50
Two top species (carbon max)	0.0%	100.0%	-$0.96	1.59	0.69	0.50
Respondents' preferences	61.0%	39.4%	-$2.14	1.06	1.94	0.84
50% hard-50% soft	50.0%	50.1%	-$5.65	0.86	2.05	0.87
Top 3 carbon	33.3%	66.7%	-$2.39	1.30	1.10	0.67
Top 3 NPV	66.6%	33.4%	$2.22	1.12	1.10	0.67
Top 4 carbon	50.0%	50.0%	-$3.77	1.11	1.39	0.75
Top 4 NPV	75.0%	25.0%	$0.34	1.02	1.39	0.75

Table 25. Percentage of each species planted in 8 scenarios (6% discount rate)

Scenario	White Spruce	Black Spruce	Jack Pine	Larch	Lodge-pole Pine	Aspen	White Birch	Hybrid Poplar
Two top species (NPV max)	0.0%	0.0%	0.0%	0.0%	50.0%	0.0%	0.0%	50.0%
Two top species (carbon max)	0.0%	0.0%	0.0%	0.0%	0.0%	50.0%	0.0%	50.0%
Respondents' preferences	15.3%	15.3%	12.3%	5.8%	12.3%	5.8%	5.8%	27.8%
50% hard-50% soft	10.0%	10.0%	10.0%	10.0%	10.0%	16.7%	16.7%	16.7%
Top 3 carbon	0.0%	0.0%	0.0%	0.0%	33.3%	33.3%	0.1%	33.3%
Top 3 NPV	0.0%	0.0%	0.0%	33.3%	33.3%	0.0%	0.1%	33.3%
Top 4 carbon	0.0%	0.0%	0.0%	0.0%	25.0%	25.0%	25.0%	25.0%
Top 4 NPV	0.0%	0.0%	25.0%	25.0%	25.0%	0.0%	0.0%	25.0%

Table 26. Results of 8 scenarios (6% discount rate)

	% Softwood	% Hardwood	NPV (millions)	Carbon (millions of tonnes)	Shan. Index	Simp. Index
Two top species (NPV max)	50.0%	50.0%	-$6.70	1.48	0.69	0.50
Two top species (carbon max)	0.0%	100.0%	-$10.39	1.63	0.69	0.50
Respondents' preferences	61.0%	39.4%	-$9.91	0.96	1.94	0.84
50% hard-50% soft	50.0%	50.1%	-$11.73	0.79	2.05	0.87
Top 3 carbon	33.3%	66.7%	-$9.86	1.25	1.11	0.67
Top 3 NPV	66.6%	33.4%	-$7.09	1.11	1.11	0.67
Top 4 carbon	25.0%	75.0%	-$11.99	1.05	1.39	0.75
Top 4 NPV	75.0%	25.0%	-$7.93	0.90	1.39	0.75

While not necessarily realistic in terms of planting configurations, from Table 24 we can begin to examine some of the trade-offs involved in these scenarios. It is obvious, for example, that there can be a high price to pay, in terms of NPV, for carbon sequestered. We can also see that landowners' preferences, as defined in the landowner survey, are closer to the maximum diversity levels than to NPV or carbon.

To further aid in visualizing the potential trade-offs involved, Figures 9, 10 and 11 provide direct relationships between the three primary outputs of this model. These figures represent Production Possibility Relationships (PPRs), illustrating the range of trade-offs possible.

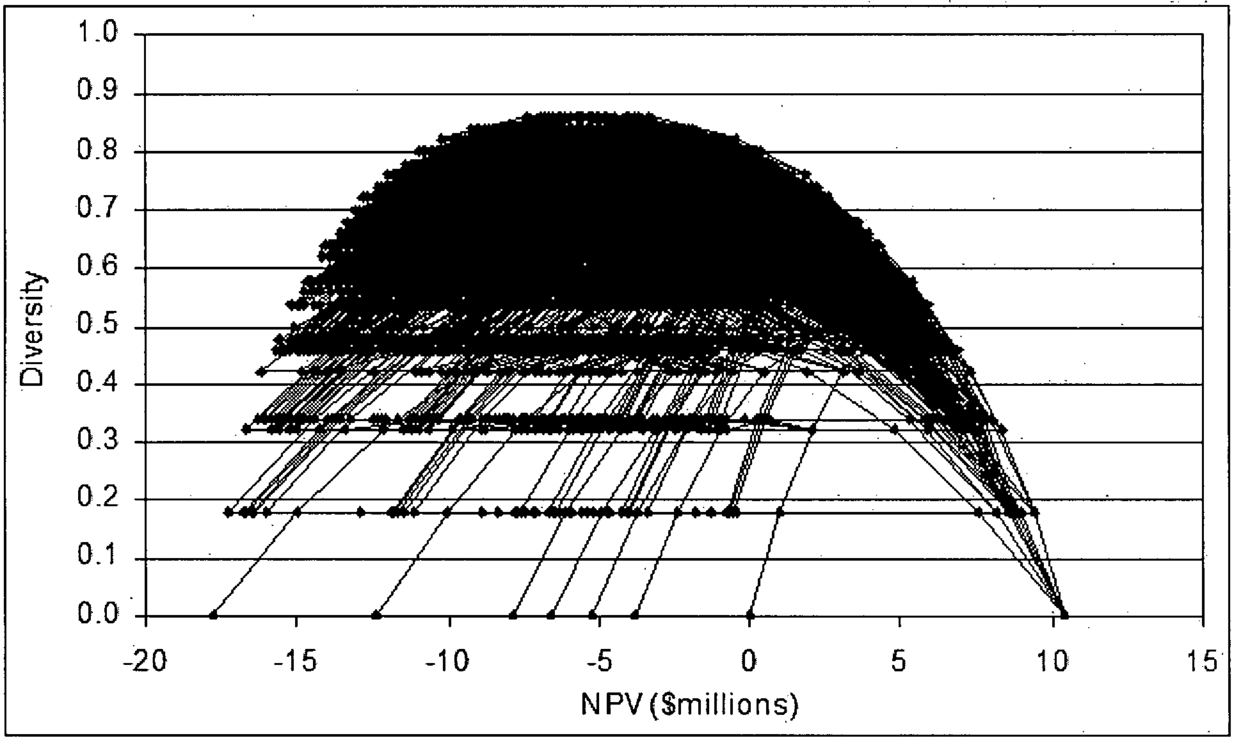

Figure 10. PPR between NPV and diversity, as measured by the Simpson's Index (4% discount rate)

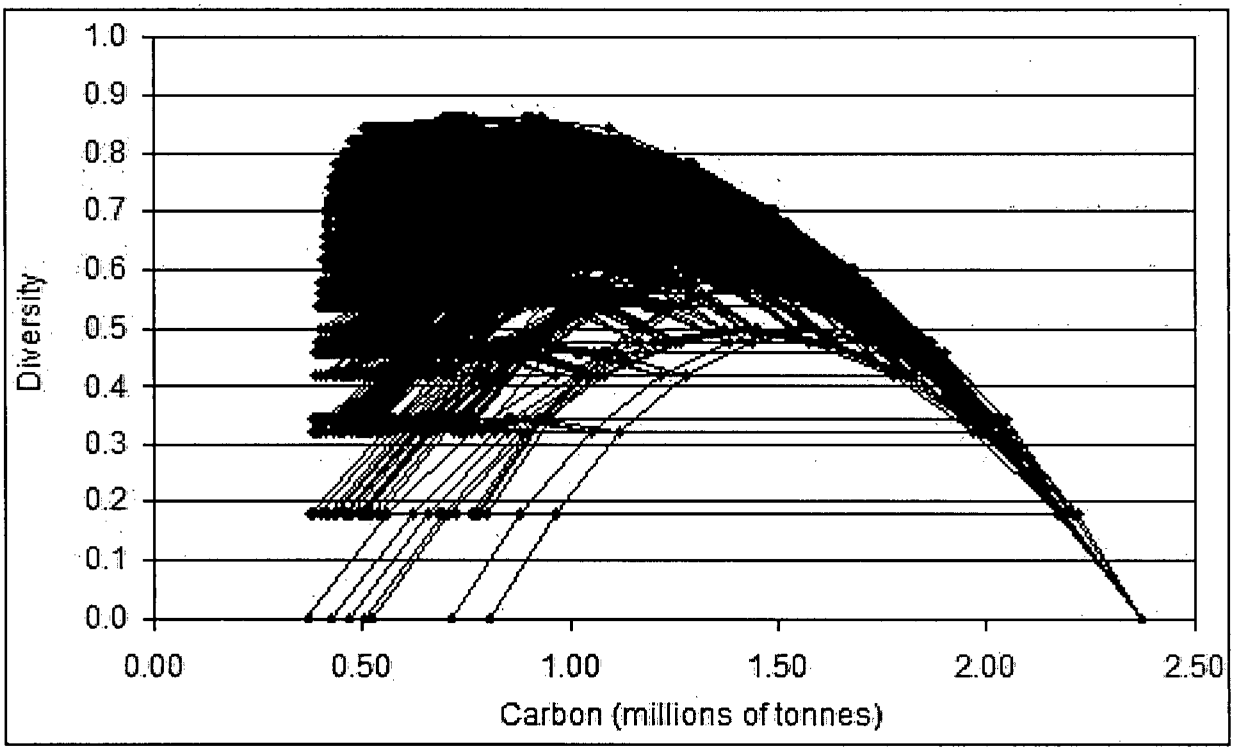

Figure 11. PPR between carbon sequestered and diversity, as measured by the Simpson's Index (4% discount rate)

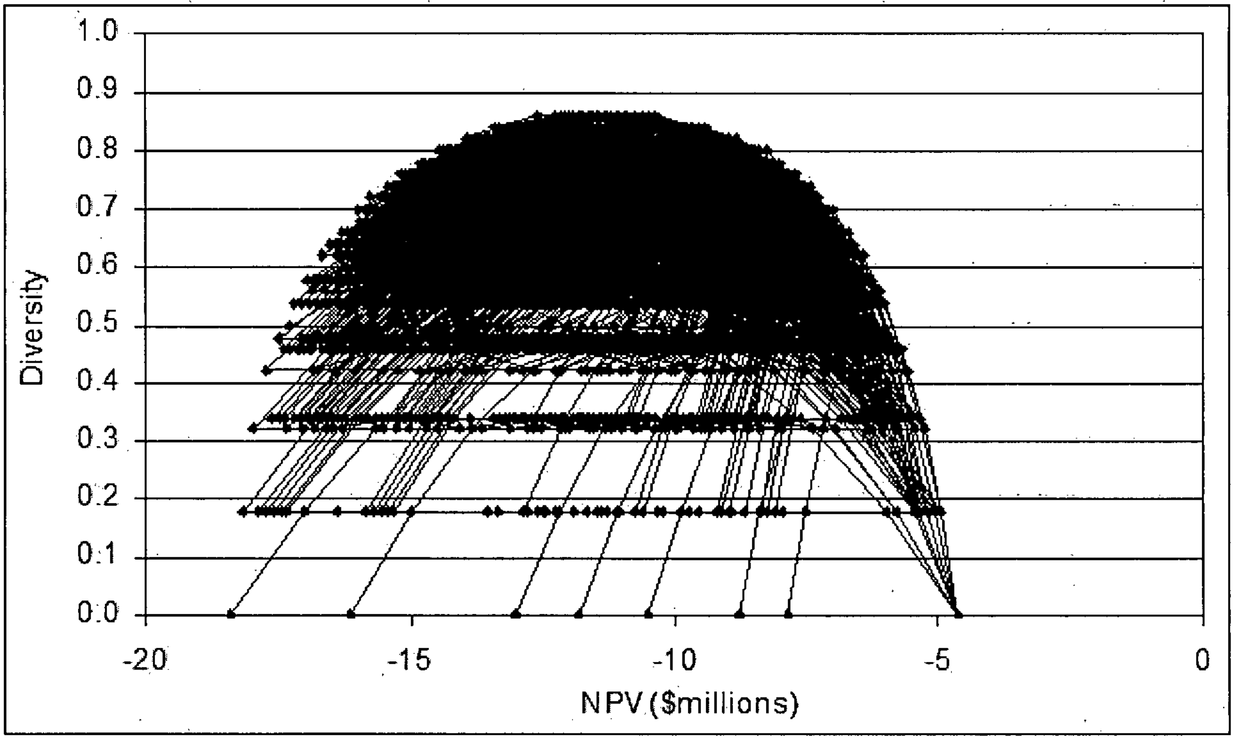

Figure 10. PPR between NPV and diversity, as measured by the Simpson's Index (6% discount rate)

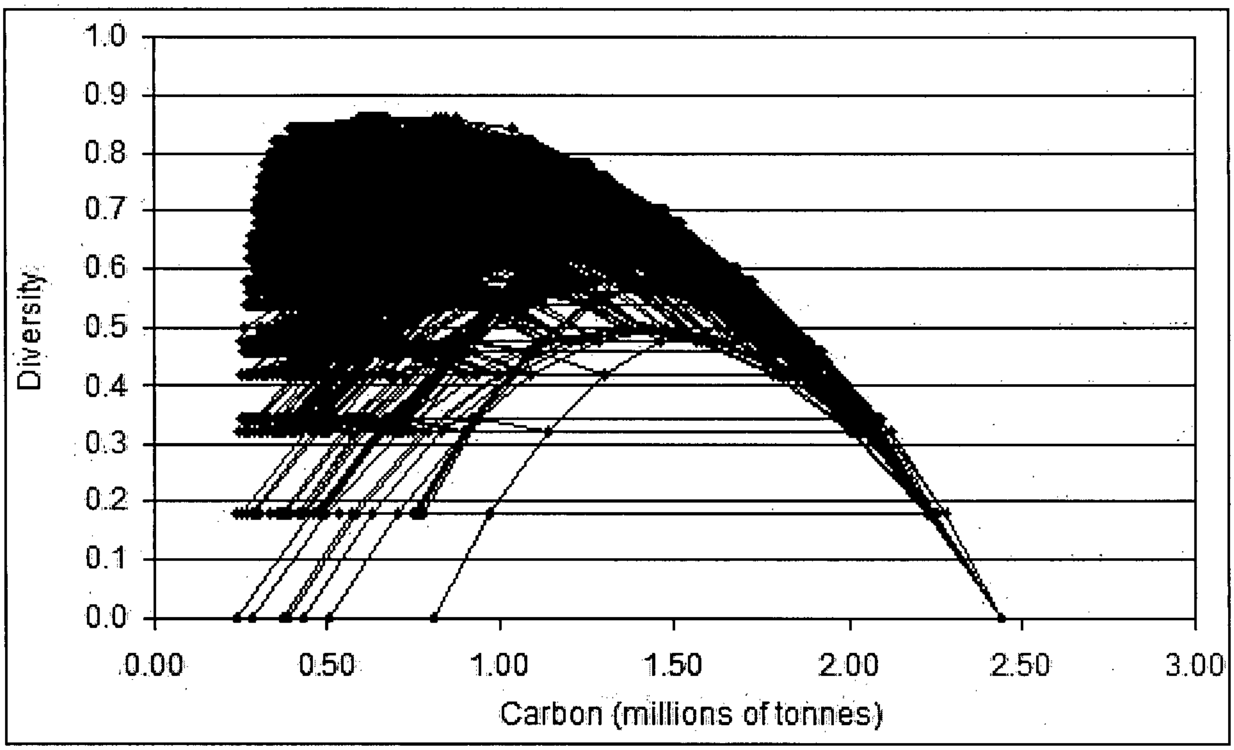

Figure 11. PPR between carbon sequestered and diversity, as measured by the Simpson's Index (6% discount rate)

These scatter plots can now be used to quickly estimate the trade-offs of imposing policy criteria in terms of the three policy variables of carbon sequestered, NPV and diversity. For example, using the scatter plots we can see that if the policy priority is to have the diversity index equal to at least 0.4, then the maximum amount of carbon that could be sequestered would be in the range of 2 million tonnes, or around 84% of the amount of maximum carbon that could be sequestered, for either discount rate.

Of note is the fact that the scatter plots also illustrate that there will often be a range of "optimal" solutions for a given constraint on, say, diversity in the model. Indeed, on subsequent runs of the model that imposed the diversity constraints introduced in section 8.4, different maximum solutions for carbon and NPV were found using different starting points for the choice variables. This is due to the non-linear nature of the diversity function, which gives different solutions, given different starting points.

7.6 Conclusions

The results of the mathematical program presented here indicate that there is a wide variance in the set of possible levels of NPV and carbon sequestered that could be achieved under a program of afforestation of marginal agricultural land for the purpose of carbon sequestration. Given the possibility of planting any combination of eight different tree species, the minimum amounts of NPV and carbon sequestered are considerably different from the maximum levels.

When minimum constraints are put on diversity it becomes clear that there is a high price, in terms of NPV and carbon sequestered, for diversity as measured by the Shannon and Simpson's indices, and this trade-off becomes disproportionately larger as the diversity constraint is increased.

When landowners' preferences are taken into account, the amount of carbon sequestered only amounts to 43% of the carbon sequestered under the maximum amount possible when the discount rate is set at 4%, and 39% when the discount rate is 6%. While these preferences may change given the right incentives, landowners' preferences could seriously impact any potential afforestation program for the purpose of carbon sequestration by driving up the cost of carbon sequestered.

Increasing the discount rate from 4% to 6% has a substantial impact on NPV, driving it from a positive value in many scenarios to a negative one in all scenarios. The change in discount rate also affects the amount of carbon sequestered, due to its effect on the optimal rotation ages of certain species. Errors in estimating the actual discount rate, then, could be quite costly in terms of NPV, and may also result in a species mix that is not optimal.

8 DISCUSSION

8.1 Introduction

The main goal of this thesis was to try to quantify the potential trade-offs involved in a policy of afforestation for the purpose of carbon sequestration. Three potential policy goals were considered, those of carbon sequestration, value of trees planted in terms of NPV, and diversity, utilizing tree species diversity as a proxy for biodiversity and landscape diversity. A non-linear programming approach was used to calculate these trade-offs over a 120-year planning period.

While many studies have shown that a program pursuing afforestation for the purpose of carbon sequestration in the Peace River Region may only make sense if hybrid poplar is the only species planted, landowners' preferences, as reported in the landowner survey, indicate a strong preference for a mix of species. Such preferences may need to be taken into account, as any potential planting program is likely to rely on planting trees on private land. It may be that the cost of providing incentives will be lower at the margin if landowners plant trees that they're interested in planting, such that the cost per tonne of sequestering carbon using hybrid poplar may be similar to the cost of carbon using, say, white spruce, at least for some landowners.

Moreover, if landowners see other benefits from planting certain species of trees, such as erosion control or fruit tree production, then any subsidies might be very small indeed. In fact, a small percentage of landowners expressed an interest in growing fruit trees, although they were not listed as a choice on the landowner survey. It should be noted, however, that planting trees for purposes such as erosion control and for fruit production might not have a very large impact in terms of carbon sequestered.

Although this study did not directly look at the costs of a tree planting program, it did confirm that hybrid poplar would likely be the species of choice for carbon sequestration in the

Peace Region, both in terms of carbon sequestered and in the value of net benefits from harvesting trees, when preferences and incentives are not taken into account. There would, of course, also be higher transaction costs involved in the creation of a more complex program that responds to individual landowners' preferences (van Kooten *et al.*, 2002).

There is also reason to believe that there are complementary policy goals that should be taken into consideration in the design of any afforestion program, particularly where different branches of the government may be pursuing different policy objectives, using similar means. For example, government policies designed to protect the forestry industry itself, namely those that seek to avoid the problems involved with monoculture tree planting, should also be considered when designing an afforestation program. In this case, the promotion of a more diverse forest environment may have other values that can offset the costs of implementing such a program.

Similarly, efforts to increase shelterbelts in Prairie regions and to improve erosion control in other ways may also be the fruits of a well-designed afforestation program, with benefits accruing to both landowners and the government due to increases in productivity.

Preferences of the general public should also be considered, particularly in terms of the policy goals that voters express to decision makers. Government policies to protect the environment and natural areas show, at least in part, the value that people place on the preservation of biodiversity. Protests on the part of individuals and conservation organizations also reflect the importance that some members of society place on the preservation and expansion of forested areas. It may make sense, then, for any policy of afforestation to include elements that create more diverse forest environments, and some of the costs for doing so may be offset, at least in part, by funds currently allocated for other purposes.

Even so, results of the model show that there is likely a very high price to be paid for diversity, both in terms of NPV and carbon sequestered, at least on agricultural land. Ultimately, decisions will have to be made on the basis policy priorities, which often favour budgetary concerns over others.

8.2 The programming approach

The non-linear program utilized in this thesis proved very useful for examining the policy trade-offs involved in planting trees. Although a tree-planting campaign that only plants a very slow-growing species is extremely unlikely, by modeling different planting configurations over 120 years, the implications of different policy choices is quite drastic. Moreover, by modeling landowners' stated preferences, policy makers are able to easily see the implications of such preferences, and thus be in a position to consider whether the associated tradeoffs are worthwhile.

The scatter plots illustrating the production possibility relationships proved to be perhaps the most useful output of the model, by providing a very quick way to view the effects of a given policy constraint on the two other policy targets under consideration.

8.3 Land Availability

The second objective of this thesis was to develop a methodology to estimate land availability based on data from the landowner survey. While this methodology may not been very accurate due to a lack of detailed data on landowners' projected expenditures, the process used to create the supply function presents a viable method for estimating land availability and its associated cost, given more detailed input data.

Moreover, if landowners' estimates are to be believed, it is clear from the survey data that there may be a large quantity of land in the Prairies that has very low production levels. This type of information may not be apparent when using data that just takes into consideration land use according to crops produced, but doesn't look at projected yields. Such data would likely overestimate land rental values for some farmers, and underestimate it for others.

In addition, along with land that is relatively unproductive, the survey also identified that there may be a large amount of land that is also sitting idle, and may therefore have negative returns. The land in these two categories totalled some 4.5% of all reported land, showing that, at the margin, there may be land available for a much lower cost than previously believed.

8.4 Recommendations for Further Study

The model in this thesis was used in a somewhat static fashion, in that it was used to quantify policy trade-offs on a pre-determined parcel of land. This "ceteris paribus" approach was used in order to directly compare the results of planting different species of trees, particularly in terms of landowner preferences, but did not fully integrate land rent values. Given more accurate data on expenditures, the model in this thesis could be extended to include land in crops as choice variables, with a given species of trees only being planted on land that is less productive than the net present value of the harvested timber. While this approach may not accurately take landowners' preferences into account, it would give a more accurate estimate of how much carbon could potentially be sequestered by taking land values at the margin into account.

In addition, the study area used in this thesis only represents a relatively small portion of the Canadian Prairies, and thus only a small proportion of the land that could potentially be considered for planting trees if a national afforestation program is undertaken. The methodology used could be extended to include a much larger area, given regional data on landowners' preferences, land-use data and tree growth. More detailed data on farm expenditures also could be combined with data on land use to give a much more accurate estimate of net returns on agriculture, and thus on land rental values.

By expanding the model to include the whole country, the amount of carbon sequestered by the end of the first commitment period (i.e. 2008-2012) could be easily calculated, and using an expanded dataset, the model could easily be used to estimate how much of Canada's total Kyoto commitment could be achieved under different planting scenarios.

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APPENDIX

Section 2: Describing Your Farm Enterprise

Instructions: Please fill in the blanks.

	# of acres
1. How large is your farm's land base? (include rented/leased area)	_______
2. How much land do you rent or lease from others?	_______
3. How much of your land is not used (not even for grazing cattle or as summerfallow)?	_______
3a. Of this unused land, approximately how much is currently covered by trees?	_______
4. Approximately what proportion of the remainder of your farm (i.e., other than the unused land) is covered by trees?	_______
5. Approximately what proportion of the remainder of your farm (i.e., other than the unused land) is in intensive crop production (excluding summerfallow and forage crops)?	_______

6. How much total subsidy do you expect to receive from government(s) during 2000? $_______________

7. Ignoring any of the unused land identified in question 3, how are your LEAST (up to 4) productive fields (to be) used in 2000? If you have less than 4 fields, indicate all of your fields. **Please ✓ the appropriate category** (one for each field).

	Field Identifier			
	#1	#2	#3	#4
Pasture/grazing	❒	❒	❒	❒
Hay/alfalfa	❒	❒	❒	❒
Wheat	❒	❒	❒	❒
Canola	❒	❒	❒	❒
Rye or oats	❒	❒	❒	❒
Flax	❒	❒	❒	❒
Other grain	❒	❒	❒	❒
Other crop (e.g. peas, lentils)	❒	❒	❒	❒
Summerfallow	❒	❒	❒	❒

Please provide the following information for the above fields. **Please fill in the table.**

	Field Identifier			
	#1	#2	#3	#4
Size of field (acres)				
Expected approximate yield				
Please identify units of yield (bu/acre, t/ha, etc.)				

4. Suppose you were to enter a contract that permits someone to plant trees on (some proportion of) your land. All direct costs of tree planting (e.g. establishment, monitoring, management, maintenance costs) are covered, AND you are provided annual compensation. You DO NOT have any right to harvest the trees before the contract expires. However, when the contract ends, trees become your property.

Would you consider a tree-planting program if you were adequately compensated? (**Please ✓**)

❐ YES →

5. What type of tree planting program would you participate in today if you were adequately compensated for land and production losses? (**Please ✓ ; more than one can apply**)

❐ shelterbelt

❐ block forest planting

❐ experimental planting

❐ alley cropping

❐ individual trees (including small clumps of trees)

❐ other (please specify) ____________________

6. What species would you prefer for planting? (**Please ✓**)

❐ hybrid poplar

❐ pine

❐ spruce

❐ mix

❐ other (please specify)

____

PLEASE CONTINUE ON THE NEXT PAGE

❐ NO ↓

Instructions: Only if you answered NO to question 4, please answer the following:

7. We are interested in how important some of these considerations are in your decision NOT to consider planting trees on your land. (**Please ✓ the appropriate categories**).

	not at all	somewhat important	very important
a) loss of visual appeal of landscape	❐	❐	❐
b) environmental concerns (e.g., trees take too much moisture)	❐	❐	❐
c) preference for the way I currently run the farm operation	❐	❐	❐
d) insufficient knowledge of issues involved	❐	❐	❐
e) other (please specify): ____________________	❐	❐	❐

8. What would you say was your main reason(s) for not considering planting trees on your land? (**Please identify**):

____

____

PLEASE GO TO SECTION 6

Section 4: Planting Trees to Mitigate Climate Change

Something about tree planting:
This information is useful for answering the following questions and determining the suitability of your land for growing various tree species. Hybrid poplar grows quickly with trees reaching maturity in 10-15 years. To achieve such growth, hybrid poplar requires more water than slower-growing species, such as spruce or pine, that generally require more than 40 years to reach maturity. Similar to hybrid poplar, spruce grows best on moist, well-drained, rich-in-nutrients soils. In contrast to hybrid poplar and spruce, pine tolerates low-nutrient conditions and does well in relatively dry environments.

1. Have you previously participated in a tree-planting project? (**Please ✓**)

❒ YES→

❒ NO

a) If YES, what type of planting project(s) were you involved in? (**Please ✓**)		b) Were you paid any remuneration? (**Please ✓**) NO	YES	If YES, how much PER YEAR?
shelterbelt	❒	❒	❒	$_____per acre over______years
block forest planting	❒	❒	❒	$_____per acre over______years
experimental planting	❒	❒	❒	$_____per acre over______years
alley cropping	❒	❒	❒	$_____per acre over______years
individual trees	❒	❒	❒	$_____per acre over______years
other (please specify)________	❒	❒	❒	$_____per acre over______years

2. Would you <u>voluntarily</u> plant trees on your land if it did NOT have a negative effect on your eligibility for government agricultural programs or any tax benefits? (**Please ✓**)

❒ YES→

❒ NO

a) If YES, why would you plant trees? (**Please ✓**)	b) What type of planting would you engage in? (**Please ✓ and provide area**)
❒ to prevent soil erosion	❒ shelterbelt #_____acres
❒ to provide shade	❒ block forest planting #_____acres
❒ to provide fuelwood	❒ experimental planting #_____acres
❒ to grow commercial timber	❒ alley cropping #_____acres
❒ to diversify production	❒ individual trees #_____acres (including small clumps of trees)
❒ to make use of idle land	
❒ other (please specify)__________ __________________	❒ other (please specify) #_____acres ____________

3. Do you have past experience harvesting and selling trees from your land, even if you relied on a contractor? (**Please ✓**)

❒ YES

❒ NO