Can Hybrid Poplar Plantations Reduce the Cost of Achieving Caribou Conservation Goals?

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Agricultural and Resource Economics

Department of Resource Economics and Environmental Sociology

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Abstract

This study investigates the role hybrid poplar may play in reducing the cost of achieving self-sustaining status in herds of boreal caribou, an ecotype of woodland caribou, *Rangifer tarandus caribou* found in northeast Alberta. Boreal caribou are currently listed as threatened both provincially in Alberta and federally in Canada. As hybrid poplar has a short-rotation and high yields, incorporating their use as a form of intensive forest management might reduce the pressure to harvest in the extensively managed forest which contains caribou habitat. A timber supply optimization model is developed which incorporates both timber values and the rate of change in caribou populations. As regulations exist which would restrict the use of hybrid poplar on public land, several alternative policy scenarios that relax these regulations are developed. The timber supply model is used to analyze the impact that each alternative policy will have on the net present value of a forestry firm, rates of caribou population change, and the cost of increasing the those rates to a sustained level. The results could contribute to policy discussion surrounding the use of hybrid poplar in Alberta.

Dedication

For my parents.

Acknowledgments

I would like to thank my supervisor Dr. Vic Adamowicz for his guidance throughout this process. I will always be grateful for all the time, effort and support you have provided me. To my co-supervisor Dr. Marty Luckert, thank you for the time taken to help me become a better writer and presenter. Special thanks to Dr. Jay Anderson, you have been such a valuable mentor to me. In addition, my thanks to Dr. Glen Armstrong for your patience through my many coding questions.

For funding this research, my thanks go to Genome Canada, Genome Alberta, Genome British Columbia and Alberta Innovates Bio Solutions.

To the staff of Resource Economics and Environmental Sociology, past and present, none of us could do this without you. Robin, some days you are a therapist, other days you are an actual superhero—thank you for always keeping things in perspective for me and always having your door open for all of us.

To my fellow graduate students, there are not enough words to show how grateful I am to you. All those long days and nights, I am so glad you are the group I got to do this with.

Finally, to my family and friends, you made this all possible for me. Joshua, you never let me doubt myself. Mom, Dad and Vikki, you supported me through any and every aspiration.

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Chapter 1. Introduction

A guiding principle in Canadian forestry is sustainable forest management which has been defined as finding a "balance between the demands placed on our forests for products and benefits, and the maintenance of forest health and diversity" (Canadian Council of Forest Ministers 2014). Sustainable forest management policies seek to maintain the forest in a manner which the many values can be produced sustainably for current and future generations.

The boreal forest is very important to Canada, contributing economic, ecological social, historical and cultural value. Forests help generate considerable regional economic activity in Canada, providing over 600,000 direct and indirect jobs with an estimated 200 communities reliant on the forestry industry (Natural Resources Canada 2014). Ecologically, the boreal forest provides habitat to a wide-ranging array of wildlife and supplies many ecosystem services. Traditionally, aboriginal communities, 80% of which are in the boreal forest, have been dependent on the forest for food, shelter, spirituality, and cultural traditions (Natural Resources Canada 2014).

In the boreal forest of Canada, sustainable forest management typically results in multiple use management. In multiple-use management, all hectares in the forest should be managed to provide acceptable benefits of the forest such as timber production, watershed protection, or recreation. In other words, to satisfy the many demands society many have from the forest, all the stands of the forest should be managed for all outputs. However, at the stand level, multiple-use may be inefficient as, management could favor the dominant use in each stand (Vincent and Binkley 1993), which often is timber production. If management favors one benefit of the forest, such as timber production, non-timber benefits may be inefficiently supplied. Instead of multiple-use in each stand, it has been argued that land use specialization could be used to reduce inefficiencies (Vincent and Binkley 1993, Anderson et al. 2012).

Land-use specialization would still result in the forest being managed for the multiple uses it provides. However, instead of managing all stands for all benefits, land use specialization or zoning would result in the land being split into stands which are defined by a specific objective. As an example, the objective of one zone could be for producing timber while another could specialize in conservation. By splitting the land into zones, each zone could prioritize and optimally manage for their specific objective and reduce the inefficiency caused by having to manage for more than one use.

However, land- use specialization will not always be the ideal solution. Land- use specialization might only be successful if the specialized land has heterogeneity leading to a comparative advantage (Zhang 2005). For example, zones of intense timber production should have qualities such as access to market and appropriate soil quality, whereas zones of conservation might be less accessible and further away from dense populations. Furthermore, land-use specialization expansion might only increase with evolving technological advancement coupled with a real or perceived scarcity of environmental resources (Zhang 2005).

One type of forest specialization that has been suggested is triad forest management (Seymour and Hunter 1992). Triad forest management splits the land into three zones, intensive, extensive and protected. The intensive zone would concentrate on the production of wood with the objective to increase or maintain current levels of timber supply. The extensive zone is designed for ecosystem management where ecological goals such as water quality could be prioritized. Minimal harvesting from native long-rotation species could also occur in the extensive zone.

Finally, a third protected zone would be designated for conservation where no harvest or activity would occur. The intensive zone would compensate for the loss of timber production in the extensive and protected zones. The presence of an intensive zone might also reduce the pressure on the extensive forest and the amount of land needed to supply mills with timber. A zonal approach such as triad might be a plausible way to incorporate the multiple functions of the boreal forest, while decreasing the inefficiencies of a multiple-use approach.

At the same time, the viability in forestry in Canada has been decreasing since the 1990's. The reasons for the decline stem from both domestic and global origins. Domestically, downward pressures on the forest industry include a decrease in the availability to find accessible and quality timber, rising energy costs, rising labour costs, and the costs to meet environmental requirements among others. Globally, the economic downturn, decreasing demand from Canada's largest trading partner the United States, and competition from emerging suppliers have contributed to the decline (Luckert et al. 2011). These emerging suppliers are predominately from tropical regions (Carle et al. 2001) and are shifting their timber harvested from natural forest to high yield, short rotation plantations. Plantations comprise 7% of the world's total forest cover (FAO 2010), and are forecasted to provide 50% of the future timber supply (Sedjo 2001). However, a majority of harvest in Canada still consists of older growth forests with long rotations. Implementing plantation forestry in Canada in a zonal management system then might also increase the economic viability of Canadian forestry.

Several studies have examined the potential of plantation forestry in Canada (Rodrigues 1998, Anderson and Luckert 2007, Joss et al. 2008). Using slower growth native boreal species in plantations has been shown to be not financially feasible in Canada (Rodrigues 1998, Adamowicz et al. 2003) and would not be appropriate in an intensive zone. However, hybrid poplar could be used in an intensive zone in Canada. Hybrid poplar is a short rotation, fast growth woody tree whose potential for plantation growth in Canada has been studied (Anderson and Luckert 2007, Anderson et al. 2012, Joss et al 2008, Fortier et al. 2012). Hybrid poplar could have the potential not only to contribute to timber supply but also to help in climate change mediation through carbon storage and its potential use as a bioenergy feedstock (Yemshanov and McKenney 2008, Joss et al. 2008). Furthermore, there is a large potential for in the use of biotechnologies in hybrid poplar which could increase the yields they produce. The potential of hybrid poplar in the intensive zone of a triad management system has been both simulated and attempted in Canada successfully (Montigny and Maclean 2006, Messier et al. 2009).

By utilizing a fast growth short rotation hybrid poplar in an intensive zone, the pressure on the extensive and often old growth forest to produce the needed timber supply might be reduced. The reduction in pressure could generate several other benefits. Economically, since a majority of the wood production will occur in an intensive zone likely located closer to mills, the costs associated in transportation and infrastructure required to haul timber long distances could be reduced (Anderson et al. 2012). Ecologically, the extensive zone could prioritize the ecological benefits such as specific habitats or water quality. Large tracts of land could also be set aside in the conservation zone. Having areas of conservation could increase the social value including recreational benefits of the land. At the same, conservation areas could be very important to the habitat of many species, such as boreal caribou.

Woodland Caribou *(Rangifer tarandus caribou)* or an ecotype found in Alberta, boreal caribou, prefer habitats of large continuous tracks of old growth forest. They are slow to reproduce and especially sensitive to habitat degradation. As such their success might be used as an indication of the integrity of the boreal forest and the extent of development. Boreal caribou are listed as threatened federally in Canada under the Species at Risk Act (Parks Canada 2013) and provincially in several provinces including under Alberta's Wildlife Act (2013). In 2012, as required by the federal Species at Risk Act, a recovery strategy for the boreal caribou in Canada (Environment Canada 2012) was released. The recovery plan identifies the habitat which is crucial to caribou survival and outlines general approaches to achieve population objectives.

In Alberta, traditional caribou ranges often overlap with prime lands for industry such as oil, gas, and forestry. In fact, the Alberta-Pacific Forest Management Area, one of largest tenure agreements in Alberta overlaps with the range of 6 caribou herds (Alberta-Pacific 2012). As industrial activities and caribou share similar landscapes, there is a cost to achieving the goals outlined by the recovery plan for caribou under the Species at Risk Act. In particular, Schneider et al. (2010) estimates a land value of the caribou ranges of north eastern Alberta in excess of $100 billion. Restricting industrial activity on this high value land in order to ensure the survival of caribou could result in high opportunity costs.

As there is potential for zoning management using hybrid poplar plantations to reduce the pressure on the extensive forest and potentially create zones of conservation, such a method might also reduce the cost to forest companies to achieve self-sustaining boreal caribou populations, a goal of the federal recovery plan.

Unfortunately, the use of hybrid poplar has not been widely adopted across Canada for several reasons. The largest barrier to the use of hybrid poplar is that exotic trees are permitted only on private land in most provinces in Canada. Private land has many competing land uses such as agriculture which might decrease the feasibility of using the land for plantation forestry. The use of exotic trees on crown land in Canada is generally not permitted. Plantation forestry and the use of exotic trees have also been found to have a negative public perception (Neuman et al 2007, Harshaw et al 2012). The negative perception likely supports the restrictions of hybrid poplar in Canada.

Although the use of hybrid poplar plantations is in most of Canada limited to private land, Anderson et al. (2012) showed that on public land their use could be feasible if certain constraints preventing their use are relaxed under various policy scenarios. Anderson et al. (2012) identified the potential for an increase not only in net present value but also the in the amount of land that is conserved as a result of the use of hybrid poplar in zonal management such as triad. However, the benefit provided by the increase in conserved land is not accounted for the study done by Anderson et al. (2012).

This thesis extends of the work by Anderson et al. (2012) by providing an example of a benefit of using hybrid poplar in a zoning management system, the reduction in cost to a forestry firm to achieve caribou conservation goals.

1.1 Research Objectives

The research aims to understand whether a type of zoning forest management using high yield short rotation hybrid poplar in plantations might reduce the need for the extensive forest to provide timber supply and reduce the cost of meeting the goal of self-sustaining boreal caribou populations in Alberta. While there are several regulations which prevent the implementation of such a zoning system, several policy alternatives are examined which relax these regulatory constraints. This is done to investigate the potential benefits of changing the regulatory structure. Using a timber supply model, the effects of alternative policy scenarios on the behavior of a forestry firm and the resulting cost to achieve self-sustaining caribou populations will be analyzed.

The work in this thesis builds on the work of Anderson et al. (2012) but differs in several ways. First, Anderson et al. (2012) presents a stylized model which is representative of the boreal forest but is not for a particular location. Our study loosely models the Alberta-Pacific forest management area which overlaps with several caribou ranges and is also an area with an active industrial sector development in Alberta. Similar to Anderson et al. (2012), this model focuses on the behaviour of a forestry firm. Second, simplifying the Anderson et al. (2012) model, our model does not include haul zones or consider as many management intensities. Finally, our model considers the effect of including a benefit of conserved land, the reduced cost to achieve the goal of self-sustaining caribou populations.

The results of this study could be of use to both government and industry with respect to the potential of implementing a zoning system and/or hybrid poplar plantations. Insight into the preservation of boreal caribou using these techniques is also provided. The specific objectives of this study are:

1. Develop a linear programming framework which allows for the implementation of a zoning system using hybrid poplar which incorporates harvesting, regeneration of multiple types of trees and the examination of the cost-effectiveness of achieving self-sustaining caribou populations.

2. Understand how establishing hybrid poplar, short rotation high yield trees, might affect the behaviour and net present value of a forestry firm. Under what conditions would profit maximizing firms implement plantations of hybrid poplar and reduce the pressure on the extensive forest, leaving zones of old growth forest which may aid in caribou conservation?

3. What are the consequences of alternative policies for hybrid poplar use to the costs of boreal caribou conservation and to the profitability of forestry?

4. There is currently a federal recovery plan which might lead to an increased rate of caribou survival in Canada. If action is taken to increase the survival of caribou, could allowing hybrid poplar plantations on the landscape reduce the need to harvest old growth forest, the caribou's preferred habitat, and therefore reduce the cost of achieving self-sustaining boreal caribou populations?

5. Examine the sensitivity of the behaviour of a forestry firm to key parameters such as hybrid poplar yield, discount rate, and timber price.

1.2 Thesis Structure

The thesis is organized in the following manner. Chapter 2 provides a background of forestry management in Canada, triad forest management, hybrid poplar, and caribou. Included in this chapter is also a review of the methods used to incorporate ecological values into forest optimization. Chapter 3 presents the policy scenarios which will be analyzed. The modelling framework will be explained in Chapter 4. Chapter 5 describes the experimental design and data used in the model. The results and sensitivity analysis is given in Chapter 6. Finally, the last chapters discuss possible policy implications, limitations and conclusions of the study.

Chapter 2. Background

2.1 Canadian Forestry

Forested land makes up 39% of the land base in Canada and 30% of the world's boreal forest (Natural Resources Canada 2014). Most of the forest in Canada, 93% is publicly owned by both the federal and provincial governments. A majority of the public forest is owned and managed by the provincial and territorial governments. The federal government and Aboriginal peoples own and manage 2% of the public forest each. The remaining forested land is privately owned. (Natural Resources Canada 2014).

With such a large amount of forest in public ownership, policy is important in managing these forests. Both the federal and provincial government play a role in the management of forests. However, a majority of the jurisdiction falls provincially. Transferring the ownership of timber harvest rights in public ownership to private firms for development is done through the use of some form of tenure (Luckert et al. 2011). The tenures are distributed for use in exchange for payments to the provincial government in form of royalties, stumpage fees or other levies. Certain practices must often be maintained in order to keep the tenure.

For many years the main objective of forestry was industrial development through sustained yield. Of the many ways to describe sustained yield, one is the continuation of the forest harvest and of forest growth (see: Luckert and Williamson 2005). In other words the harvest of the forest cannot in the long run exceed the growth of the forest. In the past couple decades; with increasing public involvement and environmental awareness of the health and future of the forest in Canada, a multi-stake approach was taken including a wide range of actors such as Aboriginal

Peoples and environmental groups (Canadian Council of Forest Ministers 2014). As a result, "Sustainable Forest Management" (SFM) was adopted.

The overarching goal of SFM in Canada is to "achieve a balance between the demands placed on our forests for products and benefits, and the maintenance of forest health and diversity" (Canadian Council of Forest Ministers 2014). SFM is meant to balance the importance of the economic, ecological, and social benefits of the forest.

Although SFM has been adopted in Canada, the objectives have not been easy to achieve as forest tenures have become increasingly complex. Even though provinces have responded with a movement towards an ecological focus in addition to economic goals, under such complexity, the multifaceted goals of SFM are difficult to define and achieve. As innovative ways to integrate environmental concerns into tenures have not been designed, regulations and constraints on existing tenures have been put in place instead (Luckert et al. 2011).

Tenure holders are then left with many demands to maintain their agreements, which have serious implications for economic efficiency and international competitiveness within the market (Luckert et al. 2011). Even with the shift to SFM, most provinces including Alberta still follow the practices of sustained yield (Schneider and Walsh 2005). As a result, most of the provinces still practice low intensity silviculture, managed for multiple use. With these complex tenure agreements, and a tendency towards the old paradigm of sustained yield, it might be difficult to meet environmental, social and economic objectives. One suggestion to meet the objectives of SFM in Alberta is through the triad forest management (Schneider and Walsh 2005).

2.2 Triad Forest Management

Triad forest management is a form of zoning management first described by Seymour and Hunter (1992). A goal of triad forest management is to maintain or increase the amount of timber production while simultaneously creating zones of preservation. Increasing timber production will help to ensure the economically and socially important forestry industry stays globally competitive. At the same time, preservation which is increasingly of growing social and ecological concern can be maintained or increased. Maintaining these two seemingly opposing objectives in forestry is not easily achieved in traditional multiple use forest management. Triad forest management provides a potential solution.

Triad forest management, as the name implies consists of three zones, intensive, extensive and protected. Each zone is managed for very different and specific objectives. The intensive zone is managed for timber production, often consisting of carefully managed species which are high yield and can be harvested often (Messier et al. 2003, Fortier et al 2012). The extensive zone is managed less for wood production and more to emulate natural conditions of native species. The extensive zone might additionally have a component with a specific ecological component and be managed for aspects such as non-timber values including habitat and water quality (Hunter and Seymour 1999, Montigny and Maclean 2006). Tree in this zone will often have long rotations similar to their natural conditions resulting in low timber production. In the protected zone, no timber is harvested allowing the natural ecological processes of the forest to occur. The lowered timber productions in both the extensive and protected zones are meant to be compensated by the intensive zone (Seymour and Hunter 1992, Hunter and Calhoun 1996, Binkley 1997, Messier et al. 2003, Messier et al. 2009).

There are several potential advantages to a zoning type of forest management. The method is supported partially by economic theory. Managing every hectare of land for the multiple values it provides might be economically inefficient (Vincent and Binkley 1993, Anderson et al. 2012). Vincent and Binkley (1993) found that land use specialization or unevenly distributing the management in forest stands could lead to more efficient production of the values compared to multiple-use management or even distribution of effort. When management effort is evenly distributed, the dominant use of the stand might be favored which could lead to an inefficient use of inputs to produce the timber and non-timber benefits of the stand. Specialization of management into different zones might be a solution to these inefficiencies. In essence, the triad form of forest management acknowledges that managing the land for all types of uses may not result in the most optimal use of inputs and outputs of the forest. By allowing zoning, separate objectives can be prioritized, potentially reducing inefficiencies.

Decreasing the inefficiencies may lead to other advantages. Globally, there is a trend towards plantation forestry where trees grow to a higher yield with a faster rotation. Plantation forestry accounts for 7% of the world's forest but produces and estimated 27-35% of global round wood with an expected increase to 64% by 2050 (FAO 2001). These plantations are expected to grow by on average 5 million hectares per year (FAO 2012). The dominant practice in forest management in Canada is low intensity silviculture, harvesting old growth or naturally regenerated forest and regenerating it to provincial standards with very little plantations. In fact Canada ranked 59 out of 61 by size of plantations forest on a survey completed by the FAO of the countries with the most significant forest (FAO 2006). An intensive zone of plantations might allow forestry to remain economically viable and globally competitive. The use of zoning could also create an area specifically for other types of increasingly valuable non-timber uses, such as wildlife habitat and recreation without decreasing the production value of timber. Creating preservation zones is important in protecting the ecological integrity of the boreal forest. Furthermore, as the competition for land amongst multiple users increases, having zonal management might create less conflict by creating zones for each type of use.

There are several studies which have attempted to apply triad forest management. A triad project had been attempted in Maine in the 1990's (Redelsheimer, 1996). Although the project was able to conserve some land, it was later abandoned. Another project in Kelowna, British Columbia had plans to implement triad to a tree farm license, but was the land was bought out before the implementation (D'Eon 2004). Most recently in Quebec, the Maurice TRIAD project was implemented in 2008 (Messier et al. 2009). The Maurice project covers a forest management unit of 0.86 million hectares. Initially, in 2003, the forest management unit had 5% of land in wood production, 93% in an extensive type zone with only 2% preserved. Although many regulatory considerations would need to be made for greater adoption, the project could have the potential to protect 11% of land, leaving 20% for wood production and 68% in an extensive zone. The project has found the triad method to be economically viable, ecologically preferable, and socially acceptable by many stake holders and a good fit for public forests in Canada (Messier et al. 2009).

As there have been few real world examples, many studies have simulated triad management. Anderson et al. (2012) found that by allowing hybrid poplar on public land in an intensive zone, some forests could be preserved as they would no longer be required to feed the mill. Cote et al. (2010) provided a simulation on the Maurice project presented above and found that triad had the ability to minimize negative effects while maintaining timber supply over the long term. In New Brunswick, a simulation showed reserves, where natural ecological processes unaffected timber production occur, could increase from 5% to 15% through the use of intensive management which would also increase timber supply (Montigny and MacLean 2006). All of these simulation studies seem to conclude that triad management would increase the conserved forest area while increasing or maintaining timber supply.

A potential issue with implementing triad forest management is that growing native trees intensively might not work well in practice (Rodrigues 1998, Adamowicz et al. 2003). However, there might be potential for the use of non-native species in plantations. Intensive management of hybrid poplar in the boreal region has been shown to be potentially financially feasible at the stand and forest level (Anderson and Luckert 2007, Anderson et al. 2012).

2.3 Hybrid Poplar Plantations

Poplar trees belong to the genus *Populus* of which there are many species and subspecies. They occur naturally in the northern hemisphere, where they are the fastest growing trees (van Oosten 2006). Poplars easily propagate through vegetative means. An infinite amount of identical poplars can be planted with ease through stem cuttings. (van Oosten 2006).

Poplars can be improved by creating a hybrid poplar which may have more desirable traits. Hybrid poplars are created when two parents who have different genetic make-up are crossed. Hybridization of poplars can occur naturally, or through traditional assisted breeding. Parent trees in traditional breeding are chosen for their observed desirable traits. The resulting improved hybrid poplar should exhibit superior qualities to their parents such as disease resistance and increased growth rate.

There are many potential benefits to using hybrid poplar in Canada. Hybrid poplar has potential to be used in plantations in Canada (Joss et al. 2008, Anderson and Luckert 2007, Fortier et al.

2012). As plantation forestry has been predicted to supply much of the world's future timber demand (Sedjo 2001), to maintain globally competitive, hybrid poplar could be beneficial to the future viability of Canadian forestry. Hybrid poplar could also play a role in climate change policy in Canada as it has potential for carbon storage. At the same time, the use of short rotation high yield trees such as hybrid poplar also has potential as a feedstock in the growing bioenergy sector in Canada. Using hybrid poplar as a feedstock might help meet provincial and federal renewable fuel standards (see: Environment Canada 2014) and the growing interest in clean energy in Canada.

There is potential in the future for poplar breeding assisted by the use of genetic markers which could further increase their yield and growth attributes. By using genetic markers, the position of the genes which control specific attributes of interest can be targeted and identified within parent trees (Hadley et al. 2001). Parent trees can then be chosen for breeding based on whether they possess the desirable attributes. Using genetic markers differs from traditional breeding as the parent trees with the most desirable traits can be selected before the traits become observable. As a result, parent trees can be chosen at an age much younger than traditional breeding (Bucher et al. 2007). By choosing parent trees at a younger age, multiple generations of trees could be bred in a shorter amount of time (Bucher et al. 2007). However, realizing the potential of hybrid poplar created through traditional or genetic marker assisted breeding may be limited as there are several regulations pertaining to their deployment.

Most provinces in Canada preclude the use of hybrid poplar on public land with two exceptions. Under some conditions, British Columbia and Quebec both allow the use of hybrid poplar on public land. The Ministry of Natural Resources and Wildlife of Québec has been breeding hybrid poplar since 1969 and strictly controls their deployment on public and private land (Derbowka et al. 2012). In British Columbia, hybrid poplar can be planted on public lands so long as it is registered and meets height and geographic requirements (Derbowka et al. 2012). In Alberta, tree improvement and deployment is detailed in the “Standard for Tree Improvement in Alberta” (Alberta Sustainable Resource Development 2005). There are strict regulations on hybrid trees in Alberta. In limited cases, where the parents are from within the same seed zone as deployment, hybrid poplar is permitted on public land. However, in general most hybrid poplars in Alberta are considered non-local, non-native or exotics. Exotics are only permitted on private land in Alberta. (Alberta Forest Genetics Research Council 2005).

2.4 Public Perceptions

A potential challenge in the use of exotics such as hybrid poplar in plantations is how they are perceived by the public. There are two potential issues that may arise, plantation forestry and the use of exotics in forestry.

Plantation forestry whether using native or exotic trees often has a negative perception. Studies have shown that there are cultural issues associated with plantation forestry such as non-traditional trees as opposed to food crops and the potential impact to local employment (Neumann et al. 2007). Another study showed that the replacing native trees with plantations were not favorable among the public (Harshaw 2012). However, a study has also shown that plantations were acceptable under some conditions including being owned and operated by a private landowner as opposed to a large firm (Williams 2014).

Although there have been studies on the public perception of the use of genetic engineering, few studies to our knowledge discuss the perception of using non-native or exotic trees including those bred using genetic marker assistance. Genetic engineering involves selectively inserting desirable DNA from an artificial or existing organism into another. Many environmental NGO's strongly oppose the use of genetic engineering in forestry such as Greenpeace which calls the practice "genetic pollution" (Greenpeace 2008). Genetic pollution refers to the potential loss of genetic diversity due to the spreading of non-native species in the natural ecosystem. As a result of negative image of genetic engineering, although breeding methods are very different, they could be misconstrued as the same technologies with the same negative consequences. Knowledge of genetic biotechnologies by the public such as genetic engineering and genetic markers has been found to be limited (Hallman et al. 2003). The perception of the public of the use of exotic or non-native trees such as those which might be bred using traditional or genetic marker assistance might also preclude their use on public land.

2.5 Boreal Caribou

Boreal caribou are often viewed as indicators of the ecological integrity of forest lands in Alberta. They are currently listed as threatened under Canada's Species at Risk Act (Parks Canada 2012) and Alberta's Species at Risk Program (Alberta Environment Sustainable Resource Development 2014a). Recovery strategies have been developed both federally (Environment Canada 2010) and provincially (Alberta Sustainable Resource Development and Alberta Conservation Association. 2010). Boreal caribou prefer habitats of continuous undisturbed old growth coniferous forest abundant in lichen, their primary source of food (Environment Canada 2012). In recent years several factors have been threatening the habitat of the caribou including increased habitat alteration (including loss, degradation, and fragmentation), changing predator prey dynamics, and human disturbance (Environment Canada 2012). In Alberta, factors threatening the boreal caribou populations result from the direct effects of human disturbances such as mining, logging, energy, and recreation industries as well as indirect ones such as climate change and increased predator access (Environment Canada 2012). Human disturbances may also cause indirect threats to boreal caribou including climate change and the increase in both predator access and numbers. Aside from their preference for old growth coniferous forest, boreal caribou are also slow to reproduce and have low densities over large areas. As such, they are especially sensitive to habitat degradation and their success can be an indicator of the extent of the impact of development on the boreal forest.

Self-sustaining

Self-sustaining is a term often used in the recovery strategies for caribou in Canada. Self-sustaining status of caribou was defined by Sorenson et al. (2008) and Schneider et al. (2010) and defined the rate of population change of greater or equal to one as sustainable. Sorenson et al.'s (2008) study examined the relationship between functional habitat loss and the rate of population change (λ) of 6 herds in Alberta. Assuming a stable age structure of existing caribou in the herd, the rate of population change is defined by the amount that must be multiplied in one time unit which would give the population size in the next time unit. As an example, a λ of 1.2 would mean the population would grow by 20%. The study hypothesized that the habitat loss of caribou was a result of 1. The proximity of herds to anthropogenic disturbances such as oil and gas, logging, mining, and pipelines and 2. The amount of habitat disturbed by wildfire. The results of their empirical analysis indicated that both these factors were significant in the loss of caribou habitat. Schneider et al. (2010) used a similar regression technique updating the λ for 9 caribou herds in Alberta. The study altered the equation slightly separating the 2 major causes of habitat loss to be: 1. Proximity to linear density features such as roads, pipelines and seismic lines and 2. The percentage of young forest. Where young forest was defined by harvested cut blocks and areas disturbed by fire in the past 30 years. The resulting equation will be discussed further in chapter 4.

Economic Valuation

People's preference or value for boreal caribou is an example of an existence, non-use or passive use value. They are solitary animals preferring old growth forest undisturbed by human development. Caribou traditionally sought protection from predators by choosing habitat away from other prey such as deer, moose and elk (Environment Canada 2012). As a result, they are often not hunted or even seen by most humans meaning the economic value of boreal caribou would be difficult to measure through actual behavior such as hunting or wildlife photography. Instead people value the existence of boreal caribou or they have values for the improvement of caribou populations. The value of boreal caribou can be estimated using non-market valuation techniques, where individuals' willingness to pay for caribou conservation can be elicited. A study was conducted on Alberta residents using contingent valuation and attribute based choice techniques to elicit the willingness to pay for caribou conservation in Alberta (Harper 2012). This study utilized the criteria of self-sustaining herds to measure conservation. Respondents stated their willingness to pay for an increase in the number of herds which are self –sustaining. Self-sustaining herds are those which are able to maintain or increase their populations over a period of 50 years. The definition of self-sustaining will be discussed further below. The study found that Albertan's were willing to pay $184.02 and $330.36 respectively per household per year to move from the current management strategy of 2 self-sustaining herds to 3 and 13 herds of caribou achieve self-sustaining status.

Federal Recovery Plan

The current federal recovery plan (Environment Canada 2012) identifies 65% undisturbed habitat which gives a 60% chance for a local populations to be self-sustaining. Undisturbed habitat is defined as land without any: i) anthropogenic disturbances with a 500m buffer and ii) no fire disturbance in the last 50 years. Self-sustaining in this context is described as the likelihood of observing a λ (over 20 years) which is stable or increasing and population above the quasi-extinction threshold of 10 reproductively active females.

2.6 Incorporating Biodiversity Value into an Optimization Framework

As can be seen in sustainable forest management, incorporating multiple objectives into a land management plan is important and increasingly necessary. Often forest planners want to integrate the timber harvests with non-market goods. Forest ecosystems have the potential to have value not only from timber but also from other market and non-market values including water systems, carbon, recreation, and habitats.

Although many forest optimization models use an objective function that maximizes the economic benefits of harvesting without considering the potential ecological benefits, many studies have attempted to integrate and balance the trade-offs between the two.

There are several ways in which ecological benefits has been incorporated into forest optimization models. One way, often referred to as a coarse filter approach is to ensure a specific amount of ecologically representative attributes to the land which may be beneficial to many species (The Nature Conservancy 1982, Armstrong et al. 2003, Yousefpour 2009). The advantage of this approach is there are many species that could benefit, however, these models might not take into account the needs of a specific species. The other method which is often referred to as a fine-filter approach is to manage for a specific species, or small set of species (Nalle 2004, Spring and Kennedy 2005, Nghiem 2014). Fine-filter objectives focus on one species or set of species which are often highly studied and representative of a specific area. Although it may be limiting in the number of species considered, this method can be advantageous because it simplifies the problem while giving an understanding of the benefits of a specific area of habitat. Some models integrate both approaches using the fine filter as a check on the coarse filter approach (Hauer et al. 2010). Models using both methods are often used in the biodiversity management portion of forest management plans in Alberta (Hannon and Macallum 2003). Course and fine filter objectives could be used in an optimization model in two ways: via the objective function and using constraints.

Integrating the ecological measures into the objective function requires knowledge of the value of fine or course filter objectives. As many fine and course filter objectives may not have an easily attained market value, their values could be elicited through complex valuation studies. However, even if these valuation studies are complete, aligning the units of biodiversity in the objective function could still be difficult. In the objective function, the elicited value may only be realized if certain conditions are met. The units of these conditions may not align with those of the elicited values. Depending on the units of the elicited value on the conditions necessary for their realization, modelling could become very complex. For example, non-market valuation studies seldom provide measures of the marginal value of the resource in question, while marginal values are typically required for incorporation into optimization models. One study incorporates the use of an existence value of possums in a multi stage dynamic optimization problem. The existence value is incorporated at the end of each stage based on the probability of survival (Spring and Kennedy 2004). However, few other studies of this type exist.

Another way to incorporate ecological objectives into an optimization problem is through the constraint. This is a more indirect although less complicated and more commonly used method. The constraints can be in terms of the population (Nalle et al. 2004, Spring and Kennedy 2005, Nghiem 2014) of the species such as a minimum absolute amount or density. Another option for integrating species objectives into an optimization model is through their habitat such as amount of the most desirable habitat (Hauer et al. 2010, Ohman et al. 2011) or habitat quality (Armstrong 2003). Other studies use constraints defined on indices such as the Shannon index which is a widely accepted method to measure biodiversity (Yousefpour 2009, 2010).

The concepts and description of issues surrounding the use of hybrid poplar and the status of boreal caribou in Alberta was discussed in this chapter. Using this information the following chapters will describe alternate policy scenarios and develop a framework to analyze the impact of hybrid poplar plantations on the net present value of a forestry firm and the conservation of caribou.

Chapter 3. Policy Scenarios

Given the restrictions of forestry policies on the use of hybrid poplar in Alberta, we examine several potential policy scenarios that will relax the policy restrictions on flow and exotics in Alberta to examine their effect on the net present value of the forestry firm as well as the cost of maintaining self-sustaining caribou populations. These policy scenarios are adapted from Anderson et al. (2012).

Each policy is defined in detail below and will be identified with a three letter code: The first letter identifies the maximization criteria; total volume (V) or total net present value (D). The second letter distinguishes whether hybrid poplar plantations are not permitted (N), permitted on private land (P) or permitted on both private and public land (B). The third letter indicates the harvest volume flow constraint on the scenario; even-flow (F), even-flow harvest volume at maximum sustained yield (B), even-flow with a 25% increase from the Maximum Sustained Yield harvest volume (A), or unconstrained flow (U). The scenarios are summarized in Table 1.

Table 1. Summary of policy scenario descriptions [a]

	Maximize volume	Maximize net present value	No exotics permitted	Exotics permitted on private land	Exotics permitted on public land	Even flow	Initial harvest at MSY
VNF	*		*			*	*
DNB		*	*			*	*
DPB		*		*		*	*
DBB		*		*	*	*	*
DPF		*		*		*	
DBF		*		*	*	*	
DBA		*		*	*	*	
DBU		*		*	*		

a Adapted from Anderson et al. (2012)

3.1. Maximum Sustained Yield- Volume (VNF)

The current harvest policy in Alberta requires a perpetual sustained yield of timber from native tree species (Forests Act 1996). We represent this through a maximum sustained yield policy which does not include any zoning. Instead, public land forests are managed to maximize the timber produced from native deciduous and coniferous species. VNF will maximize volume harvested from native species on public land while maintaining an even-flow of harvest.

The MSY harvest volume will serve as the annual allowable cut (AAC) and baseline volume for several of the following policy scenarios. The annual allowable cut is defined as the amount that can be harvested on an annual basis.

Throughout the study the term MSY will be used to describe the maximum sustained yield of only native species. With the addition of fast growing non-native species in several of the policies described below, sustainable volumes of native and non-native trees may be higher than the MSY described in this way.

3.2. Maximum Sustained Yield- Net Present Value (DNB)

As there are several different harvest patterns which could achieve the MSY volume, in policy DNB, the model will choose the most profitable harvest to achieve MSY. This policy is identical to VNF, although it maximizes net present value rather than total volume. DNB will also serve as a base comparison scenario as it represents the MSY harvest volume while maximizing net present value.

3.3. Maximum Sustained Yield- Private Land (DPB)

Policy scenario DPB also maximizes net present value but relaxes the constraint on the use of hybrid poplar plantations on private land. DPB must maintain a maximum sustained yield of harvest however, it allows the combination of private and public land to produce the harvest level. Hybrid poplar plantations are permitted on private land while public land must use native species. DPB allows the model to meet the constraint on MSY using a combination of hybrid poplar on private land and native species on public land. Permitting a combination of private and public land to satisfy MSY has no impact on the amount of timber production. At the same time, now that MSY can be partially met using private land, public land that might otherwise be harvested could be preserved. The land that is preserved could reduce the cost to sustain caribou populations. Policy DPB differs from DNB by allowing hybrid poplar on private land. The policy will continue to maximize net present value while maintaining an even- flow of harvest at MSY levels.

3.4. Maximum Sustained Yield – Public land (DBB)

Policy scenario DBB maximizes net present value and further relaxes the restriction of hybrid poplar by allowing it public land. Regulations restrict exotics such as hybrid poplar on public land for several reasons as discussed in section chapter 2, including the loss of genetic diversity in the natural gene pool.

Policy scenario DBB is identical to DPB, except that hybrid poplars are now permitted on both private and public land. DBB allows the combination of hybrid poplar on private and both native species and hybrid poplar public land to maintain a MSY harvest level and maximize net present value.

3.5. Increase Annual Allowable Cut- Private Land (DPF)

Policy scenario DPF relaxes the constraint on harvest volume by allowing the annual allowable cut (AAC) to increase from MSY levels. A combination of private and public land can be used to maximize the net present value as long as harvest maintains a sustained yield. However, hybrid poplar is only permitted on private land.

In Canada, sustained yield policies require firms to harvest a sustainable AAC. DPF models a scenario where firms are allowed to increase their AAC as long as a sustained yield is maintained. One way of achieving an increase in the AAC is through the allowable cut effect. The allowable cut effect is defined as an immediate increase in today's AAC as a result of expected increase in future yields (Sweitzer et al. 1972).

In scenario DPF, a combination of private and public land may be used to meet a sustained yield where hybrid poplar is permitted on private land. The increase in productivity from the private land using hybrid poplar plantations could activate the allowable cut effect. As a result the AAC of the entire area, both private and public, might increase.

Policy scenario DPF is similar to DPB with exception that the AAC is not constrained to the MSY level. The only restriction on harvest volume is that it must be a sustained yield.

3.6. Increase Annual Allowable Cut- Public Land (DBF)

Policy scenario DBF relaxes the restrictions of exotics on public land and of MSY harvest volume while continuing to maximize net present value. A combination of private and public land is permitted to meet a sustained yield of harvest. Hybrid poplar is now permitted on both public and private land.

Policy scenario DBF differs only from DPF by allowing hybrid poplar on public and private land. DBF is also similar to policy DBB, except that the harvest volume may increase from MSY levels.

3.7 Increase 25% from Maximum Sustained Yield - Public Land (DBA)

Policy Scenario DBA is similar to DBF in that it allows hybrid poplar on both private and public land as well as an increase in AAC from MSY levels. However, where DBF allows an increase in AAC so long as a perpetual sustained yield is attained, DBA only allows the AAC to increase by 25%. As it is uncertain whether or not the government would allow high deviations from the AAC, policy scenario DBA allows an exploration of the impact of raising the AAC by only 25%, which is consistent with work done by McCarney (2007).

3.8. No Harvest Constraints (DBU)

Policy scenario DBU relaxes all constraints on exotics and harvest volume. A combination of private and public land may be used to maximize net present value. Hybrid poplar is permitted on both public and private land without any constraints on harvest volume. The DBU policy is a very unlikely policy as it does not follow sustained yield policies, having no constraints on harvest volume. However, DBU is presented to emphasize the effect restrictions on harvest volume and exotics have on model results.

By allowing the AAC to increase in scenarios DPF, DBF, DBA, and DBU, some assumptions are made. The Alberta- Pacific mill was built in 1991 to a specific capacity which was a function of provincial regulations and forest growth. Increasing the AAC might result in a timber supply that is greater than the capacity of the Alberta- Pacific mill. By allowing scenarios where the AAC can increase, our model assumes that the excess supply could either be accommodated by the mill, in the case of small increases in AAC, or sold.

Chapter 4. Modelling Framework

The methodology used for this project will be outlined in Chapter 4. The model is based on the work of Anderson et al. (2012), using a timber supply model to analyze the result of allowing zoning management using hybrid poplar plantations. Anderson et al. (2012) models a stylized deciduous model of public and private land and analyzes the effect of different policies. The model presented here will use a modified but similar timber supply model which also includes coniferous forest. The rate of caribou population change, a representation of a non-timber value, will also be incorporated into the model to understand how allowing the use of zoning management might affect the costs for their recovery.

4.1 Linear Programing Model Formulation

The basic modelling framework is constructed using a Model II timber harvest scheduling problem as described by Johnson and Sheurmann, 1977. In a Model II formulation, the stands in the forest are separated into those which are harvested and then immediately regenerated and those which are left unharvested at the end of the planning horizon.

The land base is separated into development types which represent the area's ownership type, establishment period, harvest period and management intensities. Two decision variables are created to represent these development types. The first variable (x) represents the area of development type which is harvested from one management intensity and regenerated into another. The second variable (w) represents the hectares of development type which are established into a management intensity and not harvested at the end of the period. The second variable differs from Johnson and Sheurmann (1977) as it represents unharvested area at the end of the period as opposed to the entire planning horizon. Although some aspects of the model presented here differ resulting from reducing the number of development types and to allow the calculation of the rate of boreal caribou population change, much of the notation is adapted from Anderson et al. (2012).

4.1.1 Development Types

The harvested ($x_{o,i,j,m.tm}$) and unharvested ($w_{o,i,j,m.}$) hectares within the forest are grouped into development types which are defined by three attributes which are described below.

*i) Ownership typ*e (o)

Each hectare of the study site is either privately or publicly owned. Private land may consist of agricultural land or hybrid poplar plantations. Public land may consist only of trees depending on the policy scenario. In the model, private land will be designated by the number 1 while public land will be assigned a 2.

ii) Age (i,j)

Forested hectares are assigned a 5 year age class. In the model, age is designated by the period the hectare is established *(i)* and the period the hectare is harvested or left unharvested *(j)*.

iii) Management intensities (m,tm)

Each harvested hectare ($x_{o,i,j,m,tm}$) of the study site is designated with a from-management *(m)* intensity and a to-management intensity *(tm)*. Hectares which remain unharvested ($w_{o,i,j,m}$) are designated with a from-management intensity. A from-management intensity (*m*) is the intensity that the development type was established into. A to-management intensity (*tm*) is the intensity which the development type is re-established as after it has been harvested. The management intensities associated with forested hectares include deciduous, coniferous or hybrid poplar trees. Hectares which are not forested will be designated with a management intensity of agricultural land. The type of management intensities will be defined by numbers within their from and to-intensities. Agricultural land, deciduous trees, coniferous trees and hybrid poplar used in this model will be represented by 1,2,3 and 4 respectively.

Constraints are in the model to control policy aspects such as harvest volume, amount of standing inventory at the end of each period, and the amount of boreal caribou habitat. The model will then maximize either volume or net present value subject to the various constraints over the total length of the planning horizon. GNU MathProg (Makhorin, 2010b) was the program used to implement the model, while GNU Linear Programming Kit (Makhorin, 2010a) was used to solve the model. The code for the GNU MathProg models is available in Appendix 1. The mathematical description of the model is presented in the next section.

4.2 Objective Function

The objective function of this model is to either maximize the volume of timber harvested (equation 1) or the net present value (equation 2) of the total planning horizon depending on the policy scenario in question. The total volume is a summation across all development types of the hectares harvested, $x_{o,i,j,m,tm}$ multiplied by the corresponding yield, $y_{j-i,m}$. The total net present value is the summation across all development types of the hectares harvested, $x_{o,i,j,m,tm}$ multiplied by the corresponding discounted per hectare net revenue, $D_{o,i,j,m,tm}$. The discounted net revenue calculated for each possible development type and is the difference between the revenue from hectares harvested and the costs associated including land procurement, logging and reforestation (equation 3).

$$Max \sum_{o=1}^{O} \sum_{j=1}^{N} \sum_{i=-M}^{j-Z} \sum_{m=1}^{E} \sum_{tm=1}^{TM} x_{o,i,j,m,tm} y_{j-i,m} \tag{1}$$

$$Max \sum_{o=1}^{O} \sum_{j=1}^{N} \sum_{i=-M}^{j-Z} \sum_{m=1}^{E} \sum_{tm=1}^{TM} D_{o,i,j,m,tm} x_{o,i,j,m,tm} \qquad (2)$$

The model choses the amount of decision variable $x_{o,i,j,m,tm}$ where:

O = the number of ownership types

E= the number of from-intensities

TM = the number of to-intensities

-M = the establishment period of hectares of land born before the start of the planning period

N=length of planning horizon in periods

Z=minimum harvest age in periods

$x_{o,i,j,m,tm}$ = hectares of development type of ownership *o,* born in period *i*, from intensity *m*, harvested and regenerated to management intensity *tm* in period *j*.

$Y_{j-i,m}$=the yield curve of the management intensity *m*, in m^3/ha.

$D_{o,i,j,m,tm}$ = the discounted net revenue per hectare of ownership *o,* born in period *i*, harvested from management intensity *m* and regenerated to management intensity *tm* in period *j.*

$$D_{o,i,j,m,tm} = \frac{\left(PY_{j-i,m}\right) - C_{p_{m,tm}} - C_l - C_{r_{tm}} - C_{h_o}}{(1+r)^{d_j}} \qquad (3)$$

$$o = 1,2;\ i = -M, -M+1, \ldots, (N-Z); j = \max(1, i), \ldots, N;$$

$$m = 1, 2, \ldots, E; tm = 1,2, \ldots, TM$$

Where:

P = price of timber ($/$m^3$)

C_l = Cost of logging per hectare ($/ha)

$C_{r_{tm}}$= Cost of reforestation per hectare for each to intensity ($/ha)

$C_{p_{m,tm}}$= Cost of land procurement per hectare ($/ha)

C_{h_o} = Cost of hauling for each ownership type ($/ha)

r = discount rate

As each period is defined by a 5 year period, in order to apply the appropriate discount rate, a midpoint of each period is found (equation 4). All revenues and costs are assumed to occur at the midpoint for each period (Anderson et al. 2012).

$$d_j = \frac{e}{2} + \mathrm{e(j-1)} \tag{4}$$

$$\forall \mathrm{j} = 1, 2, \ldots . \mathrm{N}$$

Where:

d= midpoint of each period, *j*.

e=the length of each period in years

4.3 Area Constraints

There are two area constraints which ensure that all land is assigned an activity in each period and is either harvested or not harvested. The first constraint ensures the amount of land harvested, and left unharvested from the same development type cannot exceed the amount of land in the initial condition (equation 5). The first term, $w_{o,i,j,m}$ represents the amount of land that is born from the initial area $A_{o,i,m}$ which is left unharvested at the end of a particular period, *j*. The second term, $x_{o,i,j,m,tm}$ represents the amount of land that is harvested on or before the same period, *j* that is born from the same initial area. The second area constraint pertains to the regeneration of the forest in each period and ensures that all hectares of land are accounted for (equation 6). In any period *j*, there is an amount which is regenerated into a new development type, $x_{o,l,i,tm,m}$. The summation of future harvests, $x_{o,i,k,m,tm}$ and what is left unharvested, $w_{o,i,j,m}$

from the same period, j cannot exceed what was regenerated, $x_{o,l,i,tm,m}$. In other words, equation 6 ensures that the amount of hectares harvested and left unharvested in each period does not exceed the amount that is regenerated.

$$A_{o,i,m} = w_{o,i,j,m} + \sum_{l=\max(i,1)}^{j} \sum_{tm=1}^{TM} x_{o,i,l,m,tm} \tag{5}$$

$$o = 1,2;\ i = -M, -M+1, \ldots, 0;\ j = 1,2, \ldots, N;\ m = 1,2, \ldots E$$

$$w_{o,i,j,m} + \sum_{k=i}^{j} \sum_{tm=1}^{TM} x_{o,i,k,m,tm} = \sum_{l=-M}^{i} \sum_{tm=1}^{TM} x_{o,l,i,tm,m} \tag{6}$$

$$o = 1,2;\ i = 1,2, \ldots, N; j = i, i+1, \ldots, N;\ m = 1,2, \ldots E$$

Where:

$A_{o,i,m}$ = hectares of initial age classes born into ownership type o in the period i of intensity m.

$w_{o,i,j,m}$= hectares born into ownership type o in period i, left unharvested at the end of period j of intensity m.

4.4 Volume Constraints

Volume constraints are used to control the amount of volume harvested in the first period, and the relationship of the harvest in one period with the harvest in the next. The volume constraints in this model are dependent upon the policy scenario which is being represented. In most scenarios, one or more volume constraints will be applied and are described by equation 7, 8, and 9. Equation 7 calculates the volume of harvest in each period, j through the summation across all development types of the hectares harvested, $x_{o,i,j,m,tm}$ multiplied by the corresponding yield $Y_{j-i,m}$.

Equation 8 and 9 represent an even-flow of timber volume harvests from one period to the next. An even flow constraint is applied for most scenarios in the model. The other flow constraint possible in the policy scenarios is to sustain some level of harvest throughout the entire planning horizon, which is achieved by setting h_1 to the desired level and applying an even-flow constraint.

$$h_j = \sum_{o=1}^{O} \sum_{i=-M}^{j-Z} \sum_{m=1}^{E} \sum_{tm=1}^{TM} x_{o,i,j,m,tm} * Y_{j-i,m} \qquad (7)$$

$$\forall j = 1,2,\dots,N$$

$$h_j - h_{j+1} \leq 0 \qquad \forall j = 1,2,\dots,N-1 \qquad (8)$$

$$h_j - h_{j+1} \geq 0 \qquad \forall j = 1,2,\dots,N-1 \qquad (9)$$

Where

h_j= total volume (m^3) harvest in period j

4.5 Management Transition Constraints

As the policy scenarios differ in whether or not they allow hybrid poplar on private and/or public land, several management transitions constraints are necessary. Equation 10 prevents hybrid poplar from being harvested on private land while equation 11 prevents hybrid poplar harvest on public land. Specifically, equation 10 prevents private land from being converted into hybrid poplar. Equation 11 prevents deciduous species from conversion into hybrid poplar on public land. When hybrid poplar is solely permitted on private land (policy DPF and DPB), equation 10 is no longer required. In policies which permit hybrid poplar on public and private land (DBB, DBA, DBF, and DBU), equations 10 and 11 are no longer required.

$$\sum_{i=-M}^{j-z} \sum_{j=1}^{N} x_{1,i,j,1,4} = 0 \tag{10}$$

$$\sum_{i=-M}^{j-z} \sum_{j=1}^{N} x_{2,i,j,2,4} = 0 \tag{11}$$

4.6 Non-Negativity

In this model, it is not possible in any given period to harvest or not harvest a negative amount of hectares. As a result, non-negativity constraints in the model ensure that the decision variables or the amount of hectares that are harvested, $x_{o,i,j,m,tm}$ or left unharvested, $w_{o,i,j,m}$ at the end of each period of all development types must be equal or greater than 0. The non-negativity constraints are given in equation 12.

$$x_{o,i,j,m,tm} \geq 0,\ w_{o,i,j,m} \geq 0,\ h_j \geq 0 \tag{12}$$

$$\forall\ o, i, j, m, tm$$

4.7 Ending Inventory Constraint

Without a preventative ending inventory constraint, the linear programming model might make harvest decisions that have the most net present value or volume in the last few years of the model. As the planning horizon in this model is set to a finite 40 periods, the most profitable decision might be to harvest a large amount in the final periods because there are no future harvests to consider. As a result, to ensure that some forest remains standing at the end of the planning horizon, an ending inventory constraint will be applied to the model. One way of ensuring that there is forest left standing after the end of the planning horizon is to constrain the amount of hectares left unharvested of the last portion of the planning horizon to be at least the same amount as the previous period as shown in equation 13. This method is consistent with the requirements of the Alberta Forest Management Planning Standard (Alberta Sustainable Resource Development 2006) The amount of standing inventory left at the end of each period is calculated in equation 14 and is the summation across all development types of the hectares left harvested , $w_{o,i,j,m}$ multiplied by the corresponding yield, $y_{j-i,m.}$

$$SI_j \geq SI_{j-1} \tag{13}$$

$$\forall\, j = s, s+1, \ldots, N$$

$$SI_j = \sum_{o=1}^{O} \sum_{i=-M}^{j} \sum_{m=1}^{E} w_{o,i,j,m} Y_{j-i,m} \tag{14}$$

$$j = s, s+1, \ldots, N$$

Where

SI= the volume (m^3) of standing inventory of forest left unharvested at the end of each period.

s = the first period where the ending inventory will be applied.

4.8 Boreal Caribou Habitat Constraint

In order to maintain a self-sustaining level of caribou population the Model II formulation described above is constrained by the rate of caribou population change. Assuming that there is a sufficient amount of animals initially, to maintain self-sustaining caribou populations, their rate of population change must be greater than or equal to 1 in the specified period j. A rate of population change which is equal to or greater than one would imply that the rate of change is stable (λ=1) or increasing ($\lambda \geq 1$). The rate of population change per period is defined by λ_j and is a function of the amount of linear density features on the landscape as well as the amount of young forest as described by Schneider et al., (2010). The linear density features such as roads, seismic lines, and pipelines might increase loss, fragmentation, and alteration of caribou habitat as well as increase predator access. To apply the λ_j constraint, shown in equation 16, the percent of young forest is calculated in each period. As caribou prefer old growth conifer forests, only the conifer species are calculated in the percentage of young trees. The calculation for percentage of young coniferous forest is shown in equation 17 and is a summation across development types which are coniferous and 30 years or younger (Schneider et al., 2010) which are left unharvested, divided by the initial area. The resulting calculation for the rate of caribou population change is shown in equation 15.

$$\lambda_j = 1.10184 - 0.0234 * LDF - 0.0021 * Y \tag{15}$$

$$j = g, g+1, \dots, N$$

$$\lambda_j \geq 1 \tag{16}$$

$$j = g, g+1, \dots, N$$

Where:

g= the first period where the constraint on caribou growth rate is applied, as it may not be possible to restrict harvest to meet the λ from period 1.

LDF= Linear Density Features expressed as km/km^2 including roads, seismic lines, and pipelines

Y_j= percent of a caribou range that has been harvested in the last 30 years for each period *j*.

$$Y_j = \left(\sum_{o=2} \sum_{i=j-y}^{j} \sum_{m=3} w_{o,i,j,m} \middle/ I\right) * 100 \tag{17}$$

$$j = g, g+1, \dots, N$$

Where:

y= the number of periods considered to be young coniferous forest. In the caribou growth rate constraint, consistent with Schneider et al. (2011), coniferous trees which are 30 years and lower are considered young.

I= the initial amount of coniferous hectares at the beginning of period 1.

The caribou model presented here is a simplification of the true needs of a self-sustaining population. In order for herds to be self-sustaining specific population dynamics are necessary including a sufficient number of reproductive females and density animals. The equation also does not account for the 500m buffer from anthropogenic disturbances which caribou require. (Environment Canada 2012). In addition, the unnaturally high levels predation especially by wolves which has been identified as a major factor in the decline of caribou populations is also not present in the model. It is also important to note that the calculation of the percentage of young forest is restricted to the 33% which is productive forest, not the entire Alberta Pacific FMA. Boreal caribou have habitat which is outside the productive forest which would be important to their self-sustaining status.

The linear density features in the rate of population change equation are adapted from the Alberta-Pacific 2007 Forest management plan. The features included in the calculation from the FMP are seismic lines, pipelines, roads, railways and power lines. The total length in kilometers of the features is summed and divided by the total area of the Alberta-Pacific FMA. The linear density feature used in this linear programming formulation will be 2.12 km/km^2. It is important to note that linear features are dynamic and can be constantly changing. The model presented here uses a static amount of linear features for simplicity and as such might be a conservative estimate. In the sensitivity analysis, a change in linear density features will be analyzed to account for the conservative estimate. Although for simplicity, the linear density features will remain fixed within each model.

Chapter 5. Experimental Design

The forest landscape represented is based on the Alberta-Pacific Forest Products Incorporated's (Alberta-Pacific) 2007 detailed forest management plan (Alberta-Pacific 2007). Using the Alberta-Pacific forest management area (FMA) allows the modelling of a forested area with a prominent population of boreal caribou. By implementing different policy scenarios which have self-sustaining status of boreal caribou populations, the behaviour and resulting revenues and costs of the forestry firm can be studied. The following chapter will describe the experimental design and the data which will be incorporated into the modelling framework in chapter 4.

5.1 Forest Area, Initial Age Class Structure

Public Land

A stylized representation of the mill-site is constructed for this study based on Alberta-Pacific's detailed forest management plan. The Alberta-Pacific FMA is located in north eastern part of Alberta where 98% of the land is in the Boreal Forest Natural Region (Alberta-Pacific 2007). The FMA spans from Lesser Slave lake in the west to the border of Saskatchewan in the east, a distance of approximately 300 km. North to south, the FMA spans 340 km from the Birch mountains wild land provincial park in the north to agricultural land by the Alberta- Pacific mill site in the south. The area of the Alberta-Pacific FMA overlaps the habitat ranges of 6 known caribou herds including: Nipisi, Red Earth, Richardson, West Side Athabasca River, East Side Athabasca River, and the Cold Lake Air Weapons. A map of the Alberta-Pacific FMA and overlapping caribou ranges is shown in Figure 1.

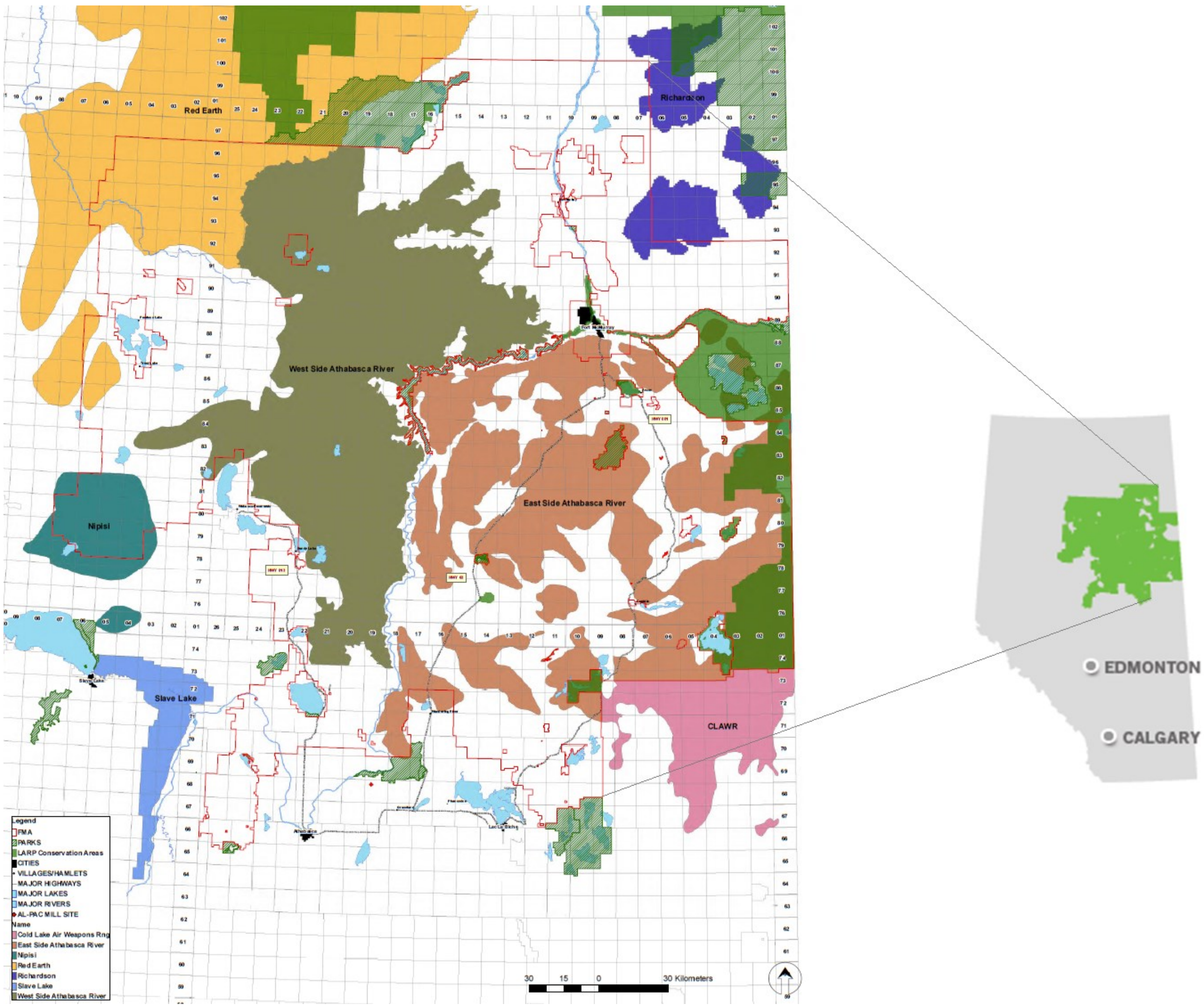


Figure 1. Map of the caribou ranges within the Alberta-Pacific Forest Industries forest management area. (Alberta-Pacific 2012)

Alberta-Pacific's FMA gross land base covers approximately 6.87 million hectares of land (Alberta-Pacific 2007). However, only 33% of this land base consists of productive forest. Various bodies of water, wetlands, and variable uplands, which are unproductive for forestry, make up the remaining portion of the land. Of the productive forest, approximately 57% is comprised of deciduous or deciduous leading forest cover. The remaining 43% of the productive forest consists for coniferous or coniferous leading forest cover. The initial age-class structure is representative of the Canadian boreal forest which predominantly consists of mature forest which has never been harvested. The forest which has been recently harvested makes up the younger portion of the forest, leaving an age gap between the young and old stands. We use this information in modelling the initial area of the forest in public ownership shown in Figure 2.

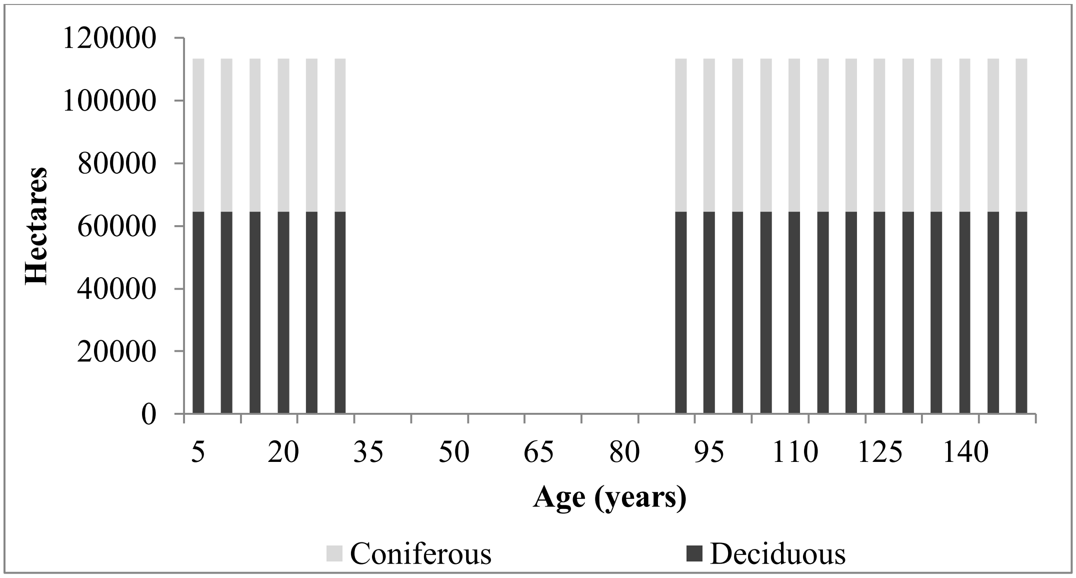


Figure 2. Initial age class and species mix of the forest in public ownership

Private Land

Alberta- Pacific has experimented with intensive management on private land for several reasons including to improve fibre quality and supply in locations close to the mill (Alberta- Pacific 2014). In the next 20 years, Alberta- Pacific has the intention to expand these hybrid poplar "farms" to 25,000 hectares. As such, for this analysis, the initial allocation of private land will be 25,000 hectares (SmartWood, 2005).

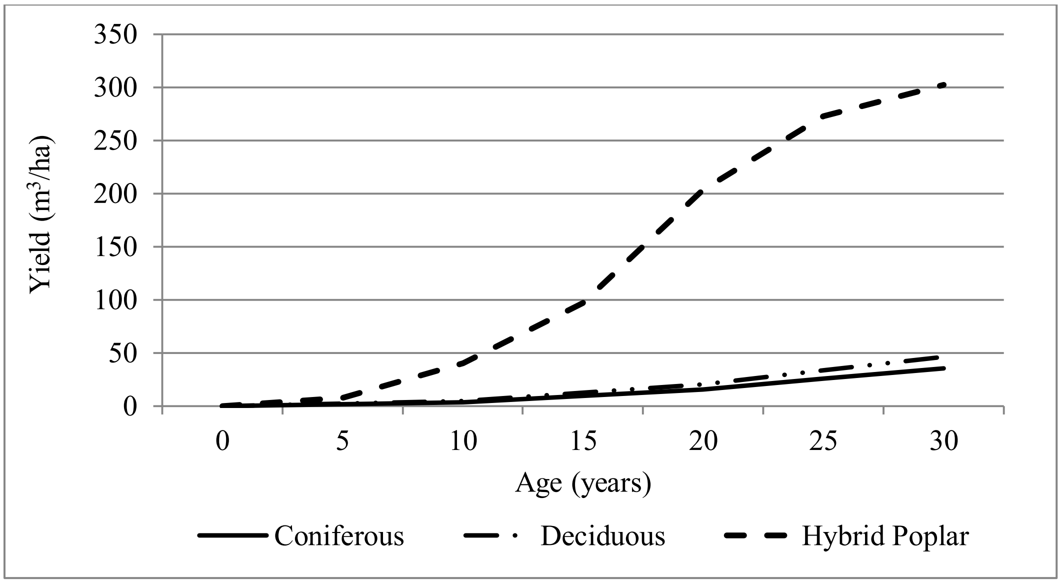
5.2 Species, Growth and Yield

The species mix used in the model includes deciduous, coniferous and hybrid poplar depending on the policy scenario being analyzed. The growth and resulting yields of the native species mix are representative of those found in the Alberta-Pacific FMA. The proportion of deciduous and coniferous was based on the representation within the Alberta-Pacific FMA. The yields of the species are shown in Figure 3.

Both the deciduous and coniferous yield curves are empirical yield curves from the Alberta-Pacific 2007 FMP (Alberta- Pacific 2007). The deciduous yield curve used in the model is the Aw-composite strata which are aspen leading and covers the greatest amount of land base and has a range of fair, medium and good total productivity rating. The coniferous yield curve used is the Sw-O which is white spruce leading and also has a range of fair, medium and good total productivity ratings. White spruce and Aspen are both merchantable and representative of productive trees harvested in the Alberta-Pacific FMA area.

The yield curve for hybrid poplar was developed by the Canadian Wood Fibre Center (Tim Keddy, Canadian Wood Fibre Centre, personal communication, 2013). The data were developed for a location on the British Columbia and Alberta provincial border that is just west of Grande Prairie, Alberta with the coordinates -120.002, 55.479 (e.g., see Joss et al 2008). Using a grid style plantation with an establishment density of 1600 stems per hectare using 2.5m by 2.5m spacing, the data for afforestation was developed. The Canadian Forest Service Site Suitability Index was used to develop a Site Suitability Index (SSI) which could be used to estimate the growth potential. The SSI uses a fuzzy logic and Boolean methodology (Joss et al. 2008) to assess whether a particular site has environmental factors that are suitable for afforestation of hybrid poplar. The environmental factors considered are Canadian Land Inventory Soil Classification, growing season precipitation, climate moisture index, growing degree days, drainage and elevation. The yield curve was developed for a site in the Peace Country of Alberta. However, the criteria SSI and environmental factors for the Peace Country site and the Alberta-

Pacific mill site are similar. A sensitivity analysis on the hybrid yield curve is included in the results and might account for the differences between the SSI and environmental factors between the two sites.



Note: The hybrid poplar yield curve used in this study ends at 30 years. However, the rotation age of hybrid poplar is around 20-25 years as the merchantable timber decreases significantly after 30 years.

Figure 3.Yield curves of deciduous, coniferous, and hybrid poplar trees

5.3 Management Transitions

Each hectare of development type in the model is either regenerated into a new development type with new management intensity or left unharvested at the end of each period. Depending on the policy scenario being considered, there are corresponding permitted transitions from one management intensity to another. Table 2 describes the permitted management transitions. Each cell of this table describes the management transitions which are allowed for in each policy scenario. There are 3 letters which represent whether or not the transition is permitted when hybrid poplar plantations are “N”, not allowed on private or public land, “P’, permitted on private land only, and "B", permitted on both private and public land. Cells which are left blank represent management transitions which are never allowed. As an example, a management transition from deciduous to hybrid poplar on public land is permitted only in scenarios where hybrid poplar is permitted on both private and public land, "B".

Table 2. Permitted Management Intensity Transitions [b]

Ownership	Pre-harvest Management	Post-harvest Management			
		Agriculture	Hybrid Poplar	Deciduous	Coniferous
Private	Agriculture	N,P,B	P,B		
	Hybrid Poplar		P,B		
Public	Deciduous		B	N,P,B	
	Coniferous				N,P,B
	Hybrid Poplar		B		

[b] Adapted from Anderson et al. (2012)

5.4 Data

5.4.1 Timber Price (*p*)

We use a mill-gate price for timber, or the amount the mill is willing to pay for fiber, of $48.69/ m^3 (WRI 2000). The value is adapted from Anderson et al. (2012) and takes the non-conifer price for the third quarter in Alberta in the year 2000 and then adjusts it for and average inflation of 2% to 2004. In 2011, the average price in Canada for pulpwood ranged from \$36/m^3 - \$60m^3 (WRI 2011). Furthermore, the average timber price for the interior of British Columbia from 2003-2014 ranged from \$40/m^3 - \$60m^3 (British Columbia Ministry of Forests, Lands and Natural Resource Operations 2003-2014). As the timber price $48.69 fits into these ranges of prices, it is an appropriate for this model. To allow for the potential changes in price, a sensitivity analysis will be completed in the results.

5.4.2 Discount Rate (*r*)

We express the monetary values in the model in real terms. All the future costs and revenues are discounted using a real discount rate. Since the model is for a long term forestry project, the opportunity costs of alternatives must be considered. Forest resources investments such as plantations have been suggested to have similar returns as AAA corporate bonds (Buongiorno and Gilless 2003). Between 1970 and 1994 in the United States, AAA corporate bonds yielded a nominal rate (R) of 9.1% with an average inflation (π) of 5.2% (Buongiorno and Gilless 2003). Using the formula below, following Buongiorno and Gilless (2003) we calculate the real rate of return, as we use real dollars in this model, which is 3.7%

$$1 + r = \frac{(1 + R)}{(1 + \pi)}$$

5.4.3 Costs

Similar to the timber price, the costs are presented in 2004 dollars. Where necessary, the costs were inflated or deflated to 2004 dollars using Canada's core CPI rates (Bank of Canada 2013).

Land Procurement (C_p)

In order to establish hybrid poplar plantations, there are costs of land procurement. Land could be leased or purchased from private owners. Consistent with Anderson et al (2012), assuming that private land which is converted into hybrid poplar plantations, remains plantation, an annual rental payment can be converted into a lump sum using the 3.7% interest rate. Anderson et al. (2012) found the lump sum lease rate to be similar to the purchase price of the private land. The 2004 average agricultural real estate value in this region was $1480/ha (Government of Alberta, 2013) and is used as the cost of procuring private land for hybrid poplar plantation establishment on private land. On public land, since it is assumed the forest company has rights to harvest the forested land through the specifications of their forest management agreement and plan, there are no costs to procure land.

Establishment / Reforestation Costs (C_r)

Establishment costs for deciduous species are assumed to be $5/ha following Insley et al. (2002). When white spruce regenerate after harvest, site preparation and planting are generally needed as a result of the way their seed is dispersed as well as slow juvenile growth rates (Lieffers et al. 2008). Compared to the minimal preparation required for deciduous trees, the reforestation cost for white spruce is significantly higher at $1500/ha (Armstrong 2014).

Establishment of hybrid poplar requires discing, marking, planting stock, planting and vegetation management. The Canadian Wood Fibre Centre (Tim Keddy, Canadian Wood Fibre Centre, personal communication, 2013) estimates the silvicultural costs for short-rotation high yield afforestation operations such as hybrid poplar plantations over a period of four years. The costs are as follows:

Year 1: $2193/ha

Year 2: $320/ha

Year 3: $240/ha

Year 4: $160/ha

Present Value of Total Cost: $2 765/ha (when discounted at 3.7 percent)

Since, the costs presented in this study are in 2004 dollars, this cost was deflated using Canada's Core CPI from 2004-2012. The resulting cost of hybrid poplar establishment is $2363.77/ha.

Conversion Costs

When converting public land to hybrid poplar plantations, there is a cost incurred from clearing the stumps from the land. Since we assume that deciduous species will cover the public land where hybrid poplar can be established, the land must first be converted to bare land similar to agricultural land. A previous study in Alberta estimates this cost to be approximately \$300/ha (Westworth 1994). We inflate this cost to 2004 dollars using Canada core CPI which results in a conversion cost of \$400.79 /ha. Once hybrid poplar has been established, subsequent post-harvest clearing of stumps will require less work and decreases to \$175/ha (Thomas and Keiser 2003).

Logging (C_l)

Costs of logging are based on estimates from Kuhnke *et al.* (2002) which assumes average logging cost in Alberta to be \$17/m^3 with an average haul of 180 m^3/ha. Multiplying these values together results in logging costs of \$3060/ha.

Hauling (C_h)

Log hauling costs are a cost of \$0.07/m^3/km is used. Assuming an average haul is approximately 180 m^3/ha (Kuhnke et al. 2002), the log hauling costs are \$12.60/km. Since private land is assumed to be close to the mill site, development types of private ownership have no log hauling cost. Anderson et al. (2012) divides the land into 10 haul zones with an average haul distance of 90 km. Using the average haul distance of 90km from Anderson et al. (2012), this model will use a log hauling cost of \$1134/ha for land in public ownership.

5.5 Summary

The study will use a Model II timber supply linear programming model to determine the potential of allowing the implementation of a zoning system using hybrid poplar plantations and the impact on preserving boreal caribou. The timber supply model and constraints presented above will be modified according to the policy scenario which is being analyzed. Key parameters will be further adjusted in a sensitivity analysis to understand how changing the conditions of the model might affect the net present value of the forest company and their cost to achieve self-sustaining caribou habitats.

Chapter 6. Results

The results are divided into 4 sections. The first section provides the results of the 8 policy scenarios described in chapter 3. Next, a series of shadow prices of the constraint on boreal caribou habitat are presented. A sensitivity analysis of the 8 policy scenarios to changes in hybrid poplar yield, timber price, discount rate and linear density feature will follow. Finally, a benefit cost ratio for each policy scenario is calculated.

6.1 Base Model Results:

The net present value (NPV) for each policy scenario for two cases will be discussed in the following results and are shown in Table 3 and Figure 4. The two cases for each policy scenario which will be discussed throughout the results are:

1. The case where caribou populations are self- sustaining (harvesting is constrained by λ to achieve self-sustaining caribou populations, $\lambda \geq 1$). In the model, it is not immediately possible to constrain the harvest to have self-sustaining caribou populations. Attaining self-sustaining caribou populations in the first 4 periods is infeasible as a result of the initial forest conditions. As the forest matures, self-sustaining populations become achievable. As such, the model only achieves self-sustaining caribou populations from period 4 to the end of the planning horizon.

2. The case where caribou populations are not required to be self-sustaining or λ is unconstrained.

Along with these 2 net present values discussed in the results of each policy will be two comparisons.

1. As a result of the federal recovery plan (Environment Canada 2012) and the caribou recovery policy in Alberta (Alberta Environment and Sustainable Resource Development 2014a), a process for species recovery is being developed and it might be assumed that in the future these herds will have to be self-sustaining under the baseline policy. As such, the first comparison describes a scenario where the goals of the recovery plan have been met. The net present value of each new policy where herds are self-sustaining (constrained λ) is compared to a baseline where self-sustaining herd constraints are also met.
2. The second comparison is representative of the current scenario, as only one of the herds in Alberta-Pacific FMA is currently self-sustaining (Alberta Sustainable Resource Development and Alberta Conservation Association 2010). Each policy new policy where herds are self-sustaining (constrained λ) will be compared with the baseline scenario where herds are not self-sustaining (unconstrained λ).

Comparing the baseline where caribou herds are and are not self-sustaining with the new policies where the herds are self-sustaining could show the potential of the new policies in both current and future scenarios. The baseline is explained below and the difference in net present value as a result of implementing alternative policies is presented in Figure 5 (constrained λ) and 6 (unconstrained λ). Finally, the corresponding volumes and tree type harvested in each scenario are presented in table 4 and Figure 7A and 7B.

6.1.1 Maximum Sustained Yield- Volume (VNF)

Policy scenario VNF is representative of the current policy in Alberta, a maximum sustained yield policy. The maximum sustained yield policy ensures that timber production of native species on public land is maximized at a sustained rate. The volume harvested each year in the

VNF case will represent the allowable annual cut (AAC) for a maximum sustained yield that will be used in several policies which follow. For the VNF case, our model maximizes volume, maintains an even flow volume harvest, and does not allow exotics.

The AAC (Table 4) is calculated for the two cases, where harvesting is and is not constrained to achieve self-sustaining status for caribou herds. The AAC is lower when herds are required to be self-sustaining at 19.9 million m^3/period (see Table 4), with a resulting NPV of $ 2.43 billion (see Table 3). In the case that self-sustaining herd status is required, the AAC is 22.3 million m^3/period with a resulting NPV of $2.74 billion. As hybrid poplar is not allowed, the case which meets the conservation status for caribou harvests approximately 25.5% coniferous and 74.5% deciduous species on public land (as shown in Figure 7A). In contrast, when the conservation of caribou is not met, the model harvests more coniferous trees and less deciduous species at 39.2% and 60.1% respectively (Figure 7B). Under the VNF scenario, it would cost the forestry sector approximately $315 million or 11.5 % (Figure 6.) in NPV to meet the conservation requirement for boreal caribou.

6.1.2 Maximum Sustained Yield- Net Present Value (DNB) (baseline)

There is more than one way to harvest the AAC volumes in the VNF scenario. DNB provides comparison for those scenarios which maximize net present value by finding the most profitable method of achieving the MSY AAC. In DNB, the net present value is maximized while maintaining an even-flow volume at MSY that was calculated in VNF.

In DNB, the net present value increases from the VNF scenario but by 7.9% or $200 million when the self-sustaining condition is met and less than 1% or $3 million when it is not. The harvest amount of coniferous and deciduous remains similar to the VNF scenario when herds are self-sustaining. However, when herds are not self- sustaining, the harvest of deciduous trees increases to 68.8 % , while the coniferous harvest decreases to 31.2% The cost to constrain harvest in scenario DNB to meet the constraint on caribou habitat is $105 million. As DNB represents the maximum NPV that can be produced at MSY, we will use $2.63 billion when the caribou herds are self-sustaining and $2.74 billion when they are not as a baseline comparison for the opportunity cost of caribou conservation in the scenarios which follow.

6.1.3 Maximum Sustained Yield- Private Land (DPB)

The DPB scenario allows for zoning in order to meet the 22.3 and 19.9 million m^3/period MSY AACs. In the DPB scenario the model maximizes NPV while allowing intensive hybrid poplar plantations on private land and native species on public land. Under the DPB policy, there is a slight 1.8% and13.7% increase in net present value to $2.69 billion and $3.12 billion respectively when the constraint on caribou populations is and is not met. When herds are self-sustaining, the amount of deciduous harvest increases while the amount of coniferous harvest decreases. Hybrid poplar contributes to less than 1% of the total harvest in both cases, however slightly more is harvested when the model must have self-sustaining herds.

The cost of achieving the caribou constraint as compared to the baseline scenario where the caribou constraint is not met (DNB, unconstrained λ) decreases to $57 million or 2.1% (Figure 6). If both the baseline (DNB, constrained λ) and DPB have self-sustaining caribou populations, policy scenario DPB has the potential to make $48 million or 3.9% more in net present value (Figure 5). Although, scenario DPB can result in an increase in net present value, it is constrained by both the cost to obtain private land and establish hybrid poplar as well as the constraint on volume flow. As a result, there is very little increase in net present value or change in harvest on public or private land relative to the baseline (DNB) case.

6.1.4 Maximum Sustained Yield – Public Land (DBB)

We expand on the DPB scenario by allowing the model to meet the MSY AAC with hybrid poplar plantations on both public and private land. The model may still harvest native species on public land. The net present value increases by 8.3% (to \$2.86 billion) in the case where caribou herds are self-sustaining and 15.1% (to \$3.16 billion), when caribou herds are not self-sustaining. When caribou populations are self-sustaining, hybrid poplar contributes to 12.1% of the harvest, compared to 10.9% in the case where they are not. In order to maintain the status of caribou herds, when the constraint is imposed, the model harvests more hybrid poplar. However, very little hybrid poplar is harvested overall. In fact, no hybrid poplar is established on private land which may result from the expensive combined cost of land procurement and establishment. The establishment costs also affect the harvest of hybrid poplar on public land. Even though the DBB scenario allows hybrid poplar on public land, it is still more profitable for a majority of harvest to be native species. Because of the expensive establishment cost combined with the constraint to harvest a MSY AAC, net present value can only increase by a small amount.

The net present value when self-sustaining herd status is achieved under the DBB scenario (constrained λ), is now higher as compared to both of the baseline scenarios (DNB, unconstrained λ and constrained λ). Compared to the baseline where herds are self-sustaining (DNB, constrained λ), DBB (constrained λ) could result in a net present value that is 8.3% or \$217 million higher. Whereas, compared to the baseline where herds are not self-sustaining (DNB, unconstrained λ), DBB (constrained λ) could result in a net present value which is 4.1%

or $112 million higher. In other words, under this scenario a forestry firm could achieve self-sustaining caribou herds while at the same time increasing net present value.

6.1.5 Increase Annual Allowable Cut- Private Land (DPF)

The DPF policy allows a departure from the MSY by allowing the AAC to increase. The harvest volume in each period may increase from MSY as long as a sustained yield is maintained. Hybrid poplar plantations are allowed on private land but only native species are permitted on public land. In the DPF scenario, the model maximizes NPV while maintaining an even-flow of harvest. The resulting NPV of the DPF policy scenario is almost identical to the DPB scenario. Even though the harvest volume is allowed to increase, it only does by 22, 311 m^3/period , a 0.01% increase in AAC. The minimal changes compared the policy DPB in harvest of each tree species, and in NPV reflect the small change in AAC. The AAC changes only slightly as a result of the high cost of establishing hybrid poplar on private land.

6.1.6 Increase Annual Allowable Cut- Public Land (DBF)

The DBF policy relaxes two of the constraints that were most limiting in the previous policy scenarios. The AAC is not constrained to be at MSY, although it must remain a sustained yield, and hybrid poplar is now allowed on public land. The new AAC can be met with hybrid poplar on private land and a combination of hybrid poplar and native species on public land.

The resulting AAC increases to 46.5 million m^3/period in the case where caribou populations are self-sustaining and 65.0 million m^3/period when they are not. Not surprisingly with such a large increase in harvest volume each year, NPV also increases to $6.28 billion when caribou herds are self-sustaining and $6.28 billion when they are not. In the DBF policy when caribou populations are self-sustaining, relative to both baseline policies (DNB, constrained λ and unconstrained λ), there is a 77.4% and 70.6% increase in net present value respectively. In order to meet the constraint on caribou habitat, coniferous harvest decreases to 9.6%, deciduous harvest increases to 20.5% and hybrid poplar harvest increases to make up the majority of the harvest at 69.9%,

Interestingly, no private land is used for harvest in the DBF policy as a result of the high cost of establishment and land procurement. Hybrid poplar plantations on public land have a much lower total cost of establishment and are more profitable. In all the previous scenarios, as compared to the baseline scenario where herds are not self-sustaining, there was a cost to achieving self-sustaining caribou. Under scenario DBF, as compared to the baseline policy (DNB, unconstrained λ), it is more profitable to the forestry company to achieve self-sustaining status of caribou populations.

6.1.7 Increase 25% from Maximum Sustained Yield- Public Land (DBA)

Policy scenario DBF allows the model to choose the optimal level of harvest so long as it results in a perpetual sustained yield. As seen from the section above, this results in an increase in AAC which is 132% higher than the MSY AAC. As it is unlikely that an increase of that magnitude would be permitted, scenario DBA is included and increases the AAC by 25%. Other than the restriction in how much the AAC can increase, policy DBA is the same as DBF.

The resulting AAC for policy scenario DBA is 25.0 million m^3/period when caribou populations are self-sustaining and 28.0 million m^3/period when they are not. As the AAC may increase but only by 25%, the NPV is $3.47 billion when herds are self-sustaining and $4.00 billion when they are not. When caribou populations are self-sustaining under policy DBA, as compared to the base scenarios where herd are and are not self-sustaining (DNB, constrained λ and unconstrained λ), there is an increase in net present value by 31.5% and 26.4% respectively. As compared to DBF, the harvest of deciduous and coniferous trees increases to 52.1% and 23.4% respectively when herds are self-sustaining. The amount of hybrid poplar decreases to 24.4%. Similar to DBF, as compared to the baseline scenario where herds are not self-sustaining (DNB, unconstrained λ), it is more profitable for the forest company to sustain caribou populations under scenario DBA, as compared to the baseline where herds are not self-sustaining (DNB, unconstrained λ).

6.1.8 No harvest Constraints (DBU)

In the last scenario, we provide a comparison of a case where there are no limiting constraints. There are no constraints on the AAC or allowance of hybrid poplar. Not surprisingly, the resulting NPVs and total volume harvested are the highest. For the case where the constraint on caribou is met the net present value is $6.28 billion, 138% higher than the baseline scenario (DNB, constrained λ). When the caribou constraint is not met, the net present value is $7.36billion, 168% more that the baseline (DNB, unconstrained λ). The total volume harvested is over 2.6 billion $m^{3,}$ which is more than 40% more than any of the previous scenarios. A majority of the harvest in the DBU scenarios is hybrid poplar, with 77.7% of the harvest when herds are self-sustaining and 70.6% when they are not. The DBU scenario is not a realistic policy scenario as it does not harvest at a sustainable rate, however it shows the significant potential hybrid poplar could have financially while still maintaining caribou populations.

6.1.9 Summary of Base Model Results

In comparison to the baseline (DNB, constrained λ) all scenarios which allow the use of hybrid poplar show an improvement in net present value. As compared to the baseline where herds are not self-sustaining, policies which allow hybrid poplar on public land can achieve self-sustaining herd status with a decrease in net present value of less than 3%. In contrast, as compared to the baseline where herds are not self-sustaining (DNB, unconstrained λ), all of the scenarios which allow hybrid poplar on public land have a result where herds can be self-sustaining and at the same time increase their net present value. The largest increase in net present value comes from the scenarios DBF and DBU. There are several limiting factors which prevent a significant increase in net present value. These factors differ depending on whether or not hybrid poplar is permitted on private and public land.

In scenarios where hybrid poplar is allowed only on private land, the competition for land is apparent as the major limiting factor is the cost to procure land. The cost of private land is the current value of private land which is primarily used for agriculture. As the cost of establishing hybrid poplar plantations is so high, it is unlikely that establishing on private land will significantly impact the net present value of a forestry firm. The effects of the establishment and procurement costs are also reflected in the scenarios where hybrid poplar is permitted on public land as private land is no longer used for harvesting. Furthermore, even if the cost of hybrid poplar plantations on private land were to decrease, the limited amount of private land might also limit the potential for higher net present values.

When hybrid poplar is permitted on public land, the limiting factor is the MSY constraint on the AAC. The effect is most apparent in the four scenarios which allow hybrid poplar on public land, DBB, DBF, DBA and DBU. Each of these four scenarios only differs in their constraint on harvest volume. As the constraint on harvest volume becomes more relaxed, the potential for higher net present value increases. Compared to DBB, when caribou populations are self-sustaining, using scenarios DBA, DBF and DBU forestry firms have the potential to make respectively, 21%, 63% and 119% more in net present value.

Table 3. Summary of Net Present Value for policy scenarios with and without self-sustaining herds

	Net Present Value ($ x 10^9)	
Scenario	Self-sustaining Caribou populations (λ constrained)	Self-sustaining Caribou populations (λ unconstrained)
VNF	2.428	2.739
DNB	2.638	2.743
DPB	2.686	3.120
DBB	2.855	3.089
DPF	2.711	3.124
DBF	4.678	5.782
DBA	3.468	3.998
DBU	6.281	7.364

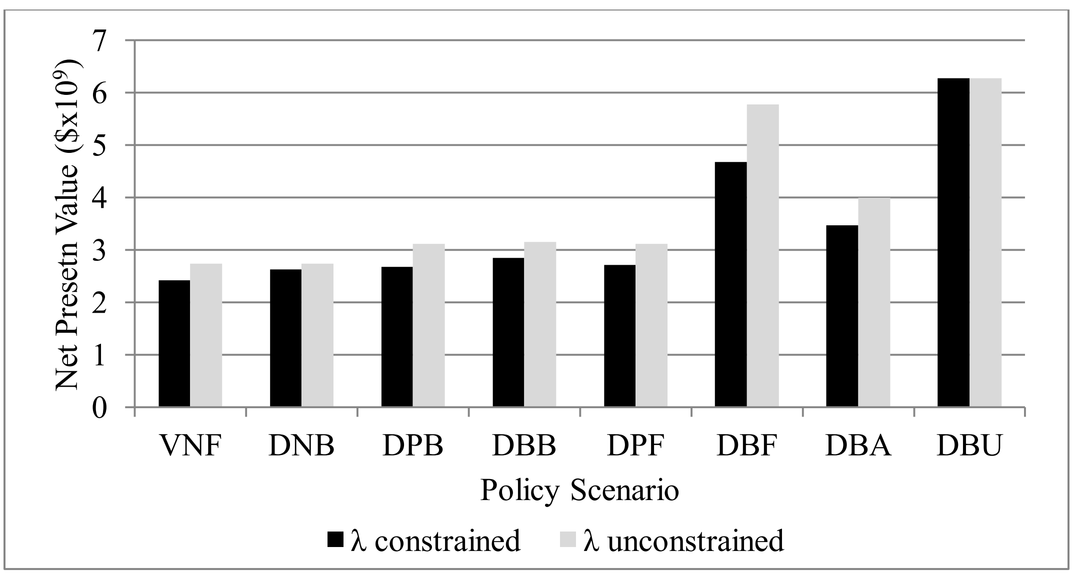


Figure 4. Total net present value of policy scenarios with and without self-sustaining caribou populations.

Table 4. Total and initial harvest volume for policy scenarios with and without self-sustaining caribou populations

	Self-sustaining Caribou populations ($\lambda \geq 1$)		Caribou populations NOT Self-sustaining ($\lambda \neq 1$)	
Policy Scenario	Total Volume ($m^3 x10^8$)	Initial AAC (m^3 $x10^7$/period)	Total Volume ($m^3 x10^8$)	Initial AAC (m^3 $x10^7$/period)
VNF	7.990	1.997	8.936	2.234
DNB	7.990	1.997	8.936	2.234
DPB	7.990	1.997	8.936	2.234
DBB	7.990	1.997	8.936	2.234
DPF	7.999	1.938	9.013	2.256
DBF	18.600	4.650	24.678	6.503
DBA	9.987	2.497	11.170	2.793
DBU	26.084	none	27.30	none

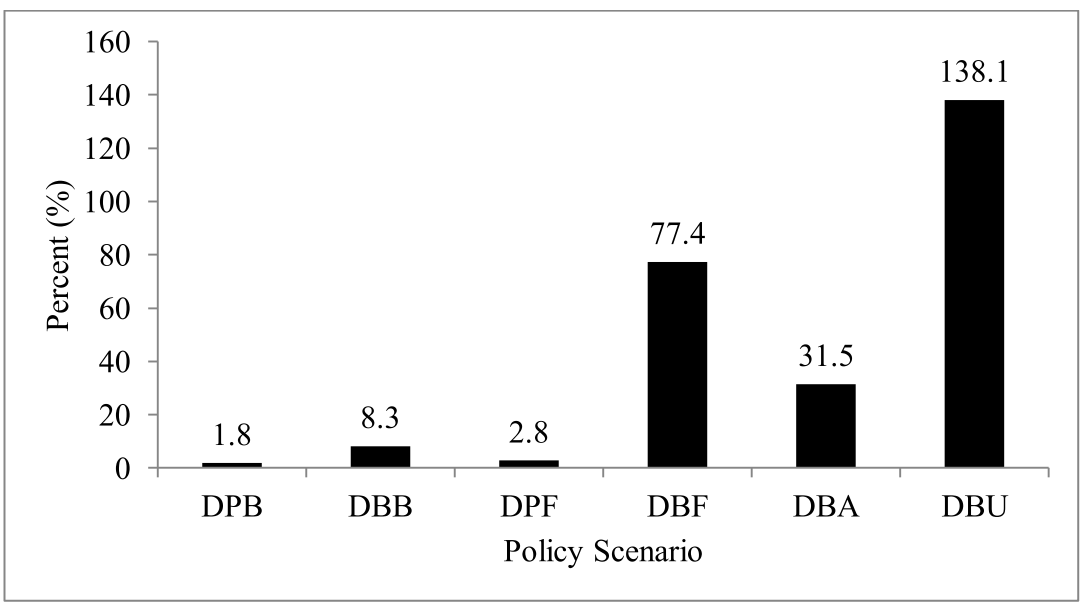


Figure 5. The percent change in NPV, when caribou populations are self- sustaining, for each policy scenario as compared to the baseline scenario (DNB, λ≥1).

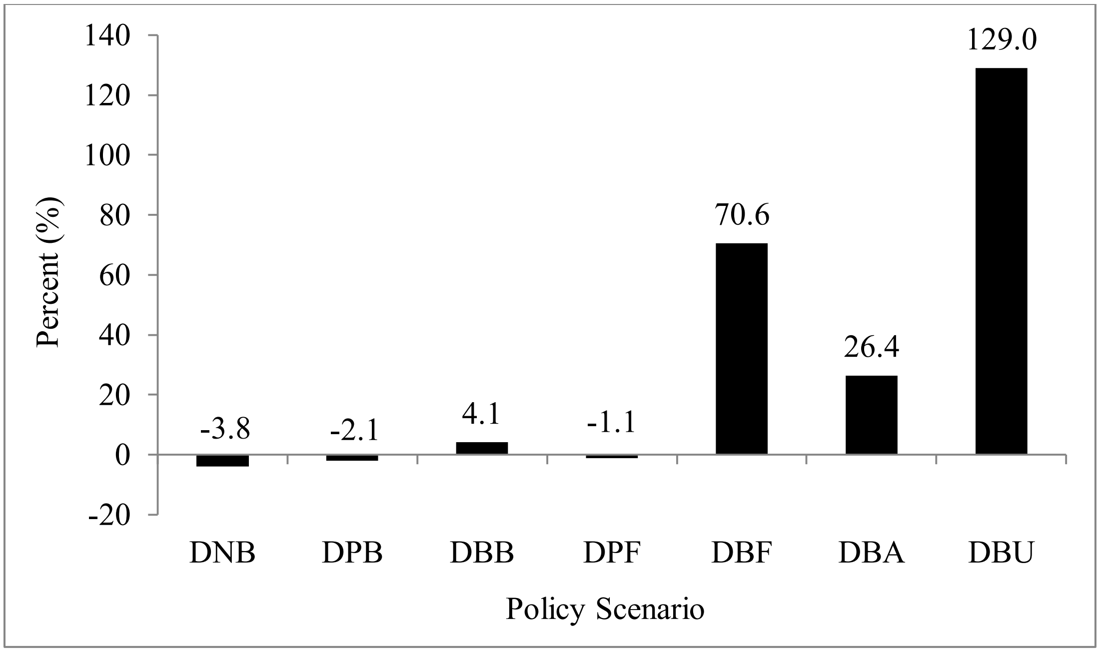


Figure 6. The percent change in NPV, when caribou populations are self- sustaining, for each policy scenario as compared to the baseline scenario (DNB, unconstrained λ).

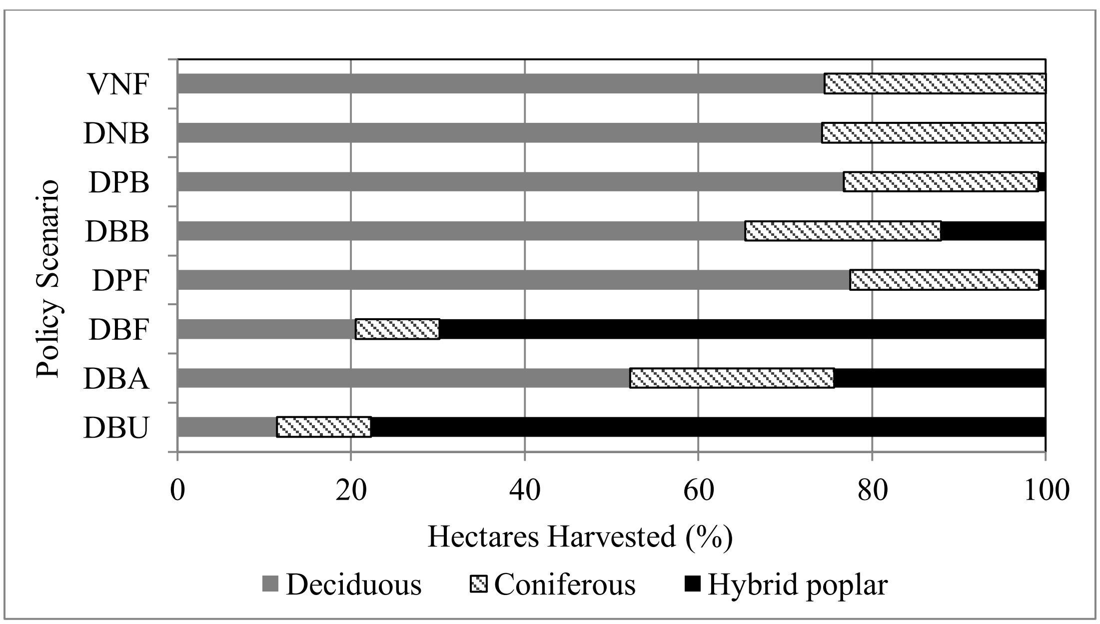


Figure 7A. Percent of hectares of each management intensity harvested over the total planning horizon for each policy scenario when boreal caribou habitats are self-sustaining.

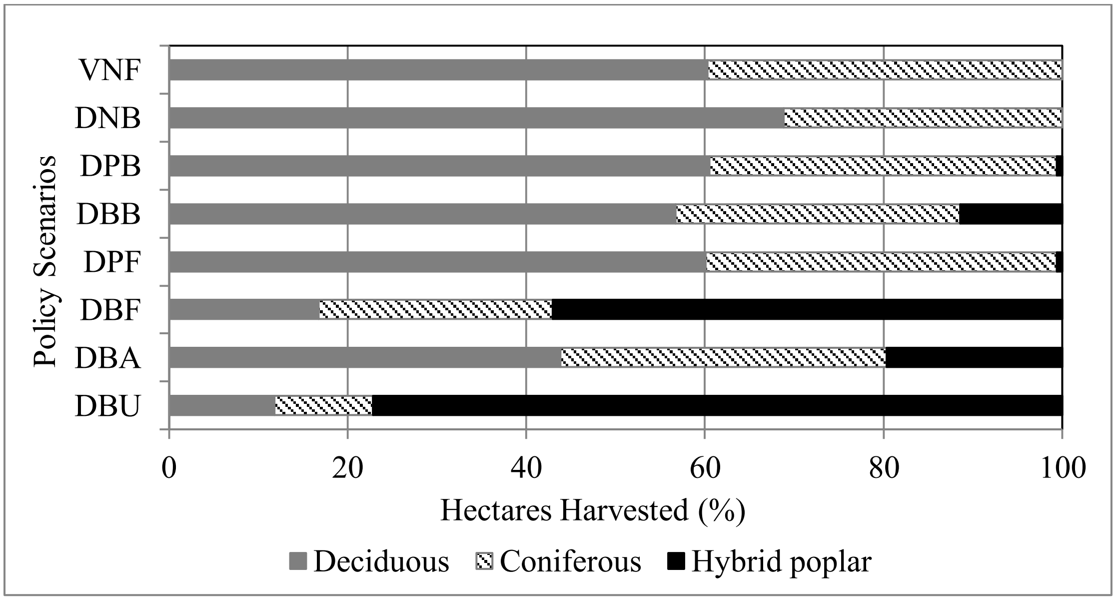


Figure 7B. Percent of hectares of each management intensity harvested over the total planning horizon for each policy scenario when boreal caribou habitats are not self-sustaining.

6.2 Shadow Price Analysis

Shadow price analysis provides a useful method of examining the cost of self-sustaining caribou populations. The shadow price of the constraint on the rate of caribou population change, λ is the cost to the objective function if the constraint was to increase and all other aspects of the model remain the same. In this context, the shadow price represents the cost to increase the constraint on the rate of caribou population change from 1 to 1.01, or a 1% rate of change The shadow price or the cost of meeting the constraint on self- sustaining caribou herds is expressed as the cost to the total net present value in all policy scenarios except VNF. The shadow price of scenario VNF is expressed as the change in total volume as the constraint on rate of population change is increased. As the shadow price for VNF is not a monetary cost comparable to the other scenarios, it is not discussed below. The shadow prices for each policy scenario are shown in table 5. It is important to note that the shadow price describes the impact to the net present value within each scenario. It represents the cost to the objective function within each scenario to increase a constraint. As a result, comparing the shadow prices across scenarios can be difficult. All policies which maximize net present value are included in Table 5 to give an idea of their shadow prices. However, since the revenue potential of the policies are so different from each other, it might not be appropriate to compare shadow prices across scenarios.

In the shadow price analyses, first, we will discuss those scenarios where harvest each year is constrained to be at MSY, as calculated in VNF and maximize NPV including DNB, DPB, and DBB. After which, those scenarios with only an even flow or no constraint on harvest volume will be discussed.

The effect of the various hybrid poplar scenarios on the cost of achieving self-sustaining caribou populations is shown clearly when comparing shadow prices for policy scenarios DNB, DPB, and DBB. In DNB, where hybrid poplar is not allowed on public or private land, the cost of increasing the constraint on caribou populations each period is in the billions. As you allow hybrid poplar on private land, the shadow price decreases significantly to the millions each period. Furthermore, allowing hybrid poplar on private and public land decreases the shadow prices of the constraint on caribou populations by even more. As the constraint on hybrid poplar plantations' allowance on private and/or public land is increasingly relaxed, the shadow price of the constraint on self-sustaining caribou population decreases.

The scenarios which maximize NPV but do not have a MSY constraint on the AAC have much different revenue potentials from each other. As a result, comparing the shadow prices of these policy scenarios is more difficult. The shadow prices of DPF are similar to those of DPB, as their revenue potential is very similar. In the DBF scenario, the shadow prices are high at the beginning of the planning horizon and become lower as time proceeds. If the DBF scenario did not have to maintain self-sustaining caribou herds, the model would harvest conifer species at the beginning of the planning horizon, to make net present value while deciduous trees are being harvested and re-establish as hybrid poplar. Forcing the model to have enough old growth forest for caribou populations, means the initial conifer harvest cannot occur resulting in very high shadow prices. As time progresses, the cost to meet the constraint becomes smaller. Shadow prices for the constraint on self-sustaining caribou populations are lower in the later the period, as hybrid poplar has now replaced conifer harvest.

In DBA, there is only a 25% increase from the MSY AAC, meaning the revenue potential is not too much higher than scenario DBB. As a result, the shadow prices closely resemble those of scenario DBB. The shadow prices are initially high, then decreases as more hybrid poplar is harvested.

For the scenario DBU, the impact of increasing the caribou constraint is initially high and decreases with time. Similar to the DBF scenario, the model initially harvests large areas of conifer species and then switches to harvest mostly hybrid poplar. When a majority of the harvest is hybrid poplar, the shadow prices of increasing the constraint on caribou populations are smaller.

One interesting result is that there are periods which have a shadow price of zero. In policies DNB, DPB, and DPF the periods near the beginning of the planning horizon have $0 shadow prices. In these four scenarios, there is little conifer harvest initially and as a result the shadow price of the constraint on caribou populations is 0. The exception to this is in scenario DNB where there is a pattern of a large amount of conifer harvest in the first periods, then no harvest in the next few periods, where the shadow prices are 0. The pattern seen in DNB may result because the constraint on caribou habitat is not present until period 4. Scenarios, DPB, DPF, and DBB initially have no shadow prices, as much of the harvest is deciduous species, in preparation of reforesting hybrid poplar.

There are other \$0 shadow prices which occur throughout the planning horizon of the policies which allow hybrid poplar on both private and public land, including DBB, DBF and DBU. These 3 scenarios have harvesting patterns where some periods harvest no conifer species and result in periodic \$0 shadow prices throughout the planning horizon.

The shadow prices of the policy scenarios describe the cost to the total net present value to the forestry firm to increase the constraint on caribou populations. The effect of hybrid poplar on the shadow prices is clear in two situations. The first is the decreasing shadow prices associated with the relaxation of the constraint on harvesting hybrid poplar, when all other constraints are held constant, as shown by comparing scenarios DNB, DPB, and DBB. The second is the decrease in shadow price within policy DBB, DBF and DBU. Within each of these 3 scenarios, as the model transitions to harvest more hybrid poplar further into the planning horizon, the shadow prices become smaller.

Table 5. Shadow Prices ($\$x10^6$) for policy scenarios resulting from increasing the constraint on the rate of caribou population change (λ).

	Policy Scenario						
Period	DNB	DPB	DBB	DPF	DBF	DBA	DBU
4	-9989	0	0	0	-44.58	0	-84.30
5	0	0	0	0	-37.80	0	-13.82
6	0	0	0	0	-29.88	0	-11.61
7	0	0	0	0	0	0	-8.18

Table 5. Continued

Period	Policy Scenario						
	DNB	DPB	DBB	DPF	DBF	DBA	DBU
8	0	0	0	0	-9.14	-6.45	0.00
9	-2118	0	-2.09	0	-7.60	-7.88	0.00
10	-2292	0	-2.60	0	-8.14	-6.64	0.00
11	-12792	-13.77	-2.68	-3.30	-1.32	-5.09	-22.08
12	-4511	-12.63	-2.43	-11.53	-1.80	-4.57	-3.73
13	-2705	-11.00	-2.94	-10.40	0	-3.71	-3.05
14	-5746	-9.99	-2.44	-9.33	0	-0.91	-1.07
15	-3254	-9.71	-0.05	-8.58	0	0	0
16	-10610	-6.62	0.00	-1.14	0	-1.81	0
17	-4718	0	0	0.00	0	-1.50	-1.24
18	-22036	-10.73	0	-1.85	0	-0.65	-2.28
19	-7886	-10.17	0	-3.09	0	-0.42	-0.72
20	-14976	-7.67	-0.43	-6.05	0	-0.78	-0.63
21	-10826	-8.57	-0.17	-5.89	-0.13	-0.35	-0.45
22	-17892	-9.65	0	-6.32	-0.07	-0.26	0
23	-17125	-7.52	0	-1.16	-0.02	-0.40	0
24	-19543	-3.81	0	-0.46	0	-0.31	0
25	-30338	-14.13	0	-1.47	0	-0.30	-1.57
26	-20100	-12.59	-0.01	-2.28	0	-0.08	-0.14
27	-18842	-7.82	0.00	-5.63	0	-0.30	-0.25
28	-23487	-9.18	-0.05	-4.29	-0.05	-0.06	-0.10
29	-21545	-9.29	0	-5.64	-0.01	0	0
30	-24017	-6.04	0	-0.20	-0.01	-0.15	0
31	-22409	-1.73	-0.01	-0.51	-0.02	-0.06	-0.54
32	-29415	-12.83	0	-0.41	-0.01	-0.04	-0.01
33	-18872	-11.05	0	-1.25	0	-0.05	-0.01
34	-21199	-7.02	0	-4.40	0	-0.03	-0.14
35	-22943	-9.10	-0.03	-3.54	0	-0.03	0
36	-8355	-8.15	0	-4.30	0	0.01	0
37	-21368	-2.04	0	-0.02	0	-0.01	0
38	-17074	-0.29	0	0.00	0	-0.02	0
39	-27711	-3.99	0	0.00	0	-0.01	0
40	0	0	0	0	0	0	0

6.3 Sensitivity Analysis

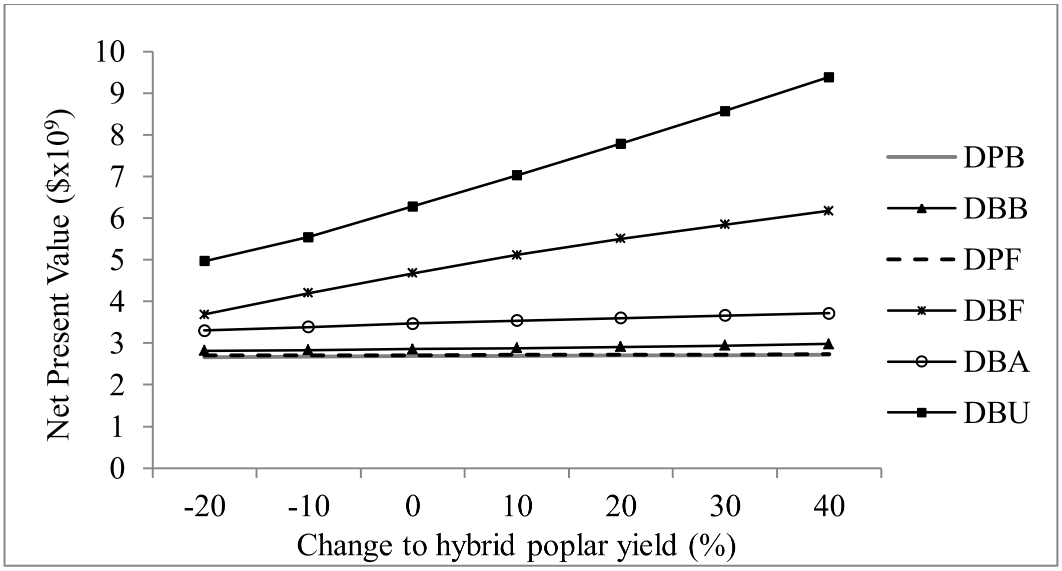
We conduct a sensitivity analysis to explore how changes to key parameters in the model might affect the net present value of a forestry company. The following sensitivity analysis is conducted: 1) Changes to the hybrid poplar yield curve, 2) Changes to the discount rate, 3) Changes to the timber price, and 4) Changes to linear density features. In each of the three analyses, one parameter is changed (i.e.: hybrid poplar yield, discount rate, timber price, or linear density feature) while the remaining aspects of the model remain unchanged as compared to the scenarios described in the base results above (section 6.1). In the analyses for each policy scenario, only the case where caribou populations are constrained to be self-sustaining will be discussed. Each sensitivity analysis is presented by two figures. The first figure describes the absolute change in net present value as the parameter changes. The second figure will show the percentage change in net present value of each scenario in comparison to the baseline scenario where the self-sustaining status of caribou is met (DNB, $\lambda \geq 1$). The results in the second figure will give a sense of the impact of the change in the costs of achieving self-sustaining caribou populations that occurs if parameters were to change.

6.3.1 Yield Curve of Hybrid Poplar Plantations

The potential for the hybrid poplar yield curve to vary over different conditions will affect the value and level of harvest of the forestry firm. In the sensitivity analysis on hybrid poplar yield, the change of the yield curve will range from 20% less than the base yield curve to 40% more. There has been significant work done on hybrid poplar which may increase the yield (Derbowka et al. 2012). The use of technologies such as genetic markers may have the potential to increase hybrid poplar's resistance to pests and diseases, as well as significantly increasing the yield. To account for the potential of these technologies, hybrid poplar yield is increased up to 40% more than the base curve. Decreasing the hybrid poplar yield by up to 20% from the base may account for potential changes to the environmental factors which the yield curve is modelled for as described in Chapter 5. The results of changing the yield curve are shown in Figure 8 and 9.

Changing hybrid poplar yield makes no difference to those policies (VNF, DNB) that do not allow hybrid poplar and will not be discussed in these results. In those scenarios which do allow hybrid poplar, as the yield increases or decreases the net present value of each scenario moves in the same direction (Figure 8). The policy scenarios which permit hybrid poplar on private land (DPB and DPF) increase in NPV as the hybrid poplar yield increases, but by less than 1%. In scenario DPB and DPF, there is little private land resulting in a limit to the amount of hybrid poplar that can be harvested. Although, hybrid poplar is permitted on public land in scenario DBB, the harvest is constrained to the MSY and as a result, the increase in NPV is also less than 1% for every increase in yield. In the scenarios DPB, DPF and DBB, as the hybrid poplar yield increases, the amount of deciduous and coniferous harvest does decrease to allow for greater harvesting of the hybrid poplar, however not by a significant amount.

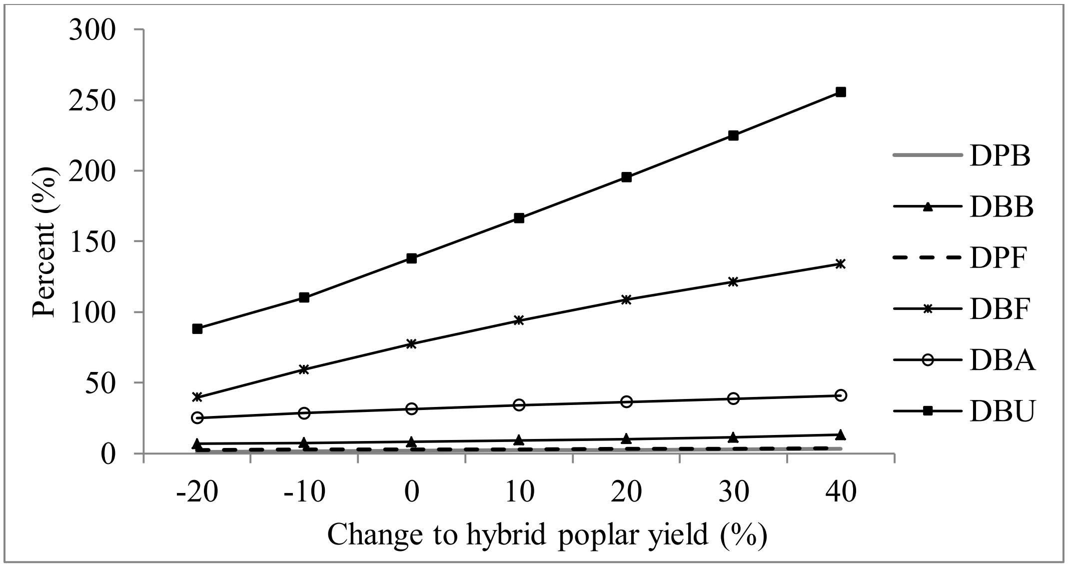
The most significant change in net present value as hybrid poplar yield changes comes from scenario DBF, DBA, and DBU, where the constraints on harvest volume are relaxed.



Note: Policy DPB and DPF yield similar net present values as a result of the constraints imposed. Although DPF yields slightly higher net present value than DPB, they appear as one line in Figure 8.

Figure 8. Sensitivity of the net present value to a change in hybrid poplar yield for policy scenarios DPB, DBB, DPF, DBF, DBA, and DBU.

Figure 9 shows the percent difference in each scenario's NPV as compared to the base scenario (DNB, constrained λ) as the hybrid poplar yield changes. Similar to Figure 8, large differences are only observed in scenarios DBF and DBU where there is no MSY volume constraint on harvest and hybrid poplars are permitted on public land. Even at the lowest yield in scenarios DBF, DBA, and DBU, the net present value is respectively 39.6%, 25.2% and 88.3% higher than the base scenario. However, allowing hybrid poplar in any of the other scenarios (DPF, DPB, DBB) even at the lowest yield, results in an increase in net present value as compared with the baseline by 1.0% - 6.9%. Permitting the use of hybrid poplar has a positive effect in every scenario, even if the yield decreases 20 % from the base.

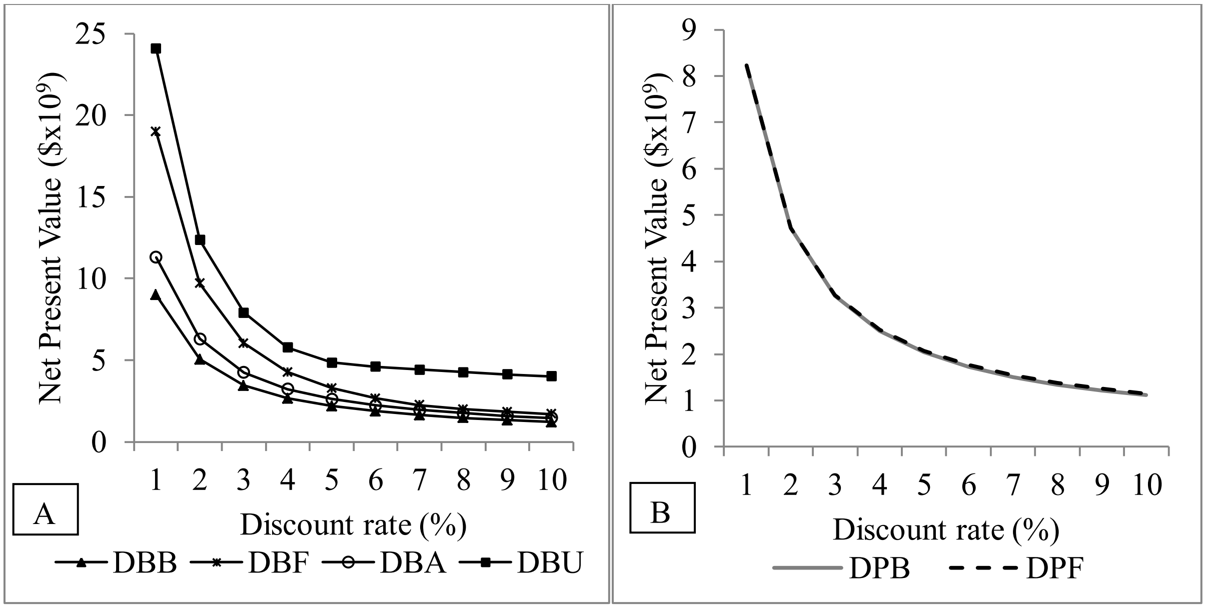


Note: Policy DPB and DPF yield similar net present values as a result of the constraints imposed. Although DPF yields slightly higher net present value than DPB, they appear as one line in Figure 9.

Figure 9. Sensitivity of the net present value to changes in hybrid poplar yield expressed as percent change from the base scenario (DNB, where λ is constrained) for policy scenarios DPB, DBB, DPF, DBF, DBA, and DBU.

6.3.2 Discount Rate

Changing the discount rate has the expected resulting change in net present value. As the discount rate increases, the net present value decreases for every scenario. High discount rates result in harvests later in the planning horizon to have lower values. When the discount rate is high, a majority of the net present value comes from the time periods at the beginning of the planning horizon. In contrast, scenarios with lower discount rate have a net present value per period which still decreases with time but to a much smaller degree. The results are shown in Figure 10.



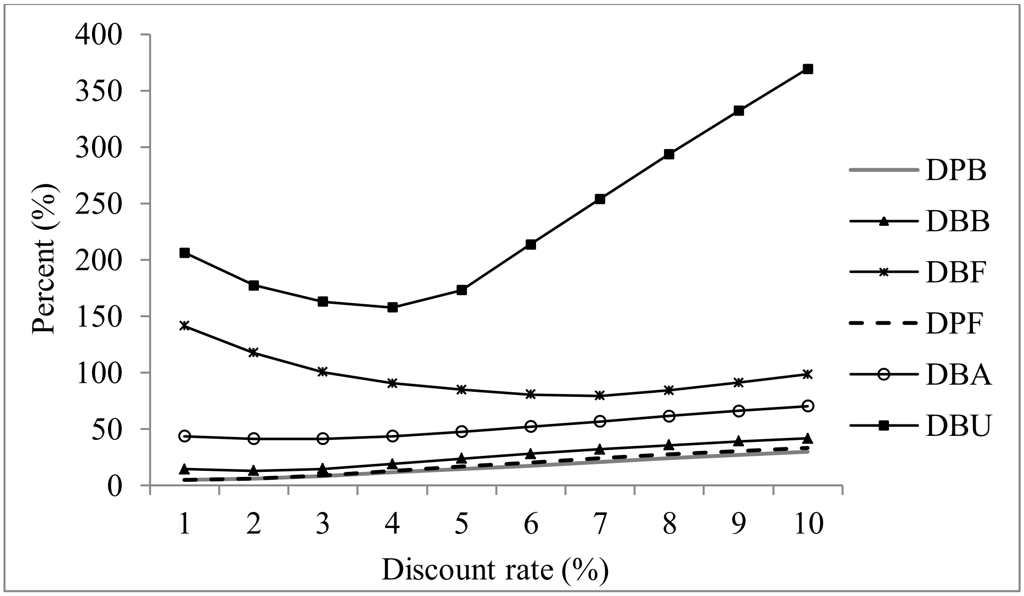
Note: Figures.10A and 10B use different scales for net present value.
Policy DPB and DPF yield similar net present values as a result of the constraints imposed. Although DPF yields slightly higher net present value than DPB, they appear as one line in Figure 10B.

Figure 10. Sensitivity of the net present value to a change in discount for policy scenario A) DBB, DBF, DBA, and DBU, B) DPB and DPF.

The change in net present value as compared to the baseline scenario is shown in Figure 11. There are two main impacts, depending on the conditions of the policy scenario. The first impact is the increase in the difference from the baseline as the discount rate increases, which is shown by scenario DPF, DPB, and DBB and DBA. The baseline scenario has a strict even flow volume it must harvest every year and may only achieve it through using native species. As a result, the amount of harvest of each type of tree does not change in the base scenario as discount rate increases. In contrast, although DPB, DBB, DPF and DBA also have volume constraints, the amount and type of tree harvested changes as discount rate changes. In particular, in the three scenarios DPB, DPF, DBB, and DBA, hybrid poplar harvest increases and the harvest age becomes younger as discount rate increases. By adjusting the amount, type, and age of trees harvested, the percent difference from the base scenario increases in scenario DPB, DBB, DPF, and DBA as the discount rate increases.

The second impact is in the two scenarios where hybrid poplar is allowed on public land and the harvest volume is not constrained to MSY. The change as compared to the base for scenarios DBF and DBU both decrease until the discount rate reaches 7 % and 4% respectively, and after this begins to increase. The pattern of hybrid poplar harvest changes at 7% in scenario DBF and 4% in scenario DBU. For scenario DBF the harvest of hybrid poplar decreases until the 7% discount rate before beginning to increase. Once the hybrid poplar harvest begins to increase, the difference from the base begins to diverge upwards. In DBU at discount rates higher than 4%, harvesting of hybrid poplar stops altogether as it becomes more profitable to increase the harvest of deciduous species (Note: harvest of coniferous stays constant to achieve self-sustaining status of caribou herds), as there is no constraint on flow. In other words, the establishment cost of deciduous species is significantly lower than that of hybrid poplar. As a result, at discount rates higher than 4%, hybrid poplar is no longer harvested.

In scenarios DPB, DPF, DBB, DBF and DBA the difference from the baseline only increases when the harvest of hybrid poplar also increases. The harvest of hybrid poplar could be driving the divergence in net present value from the baseline scenario.



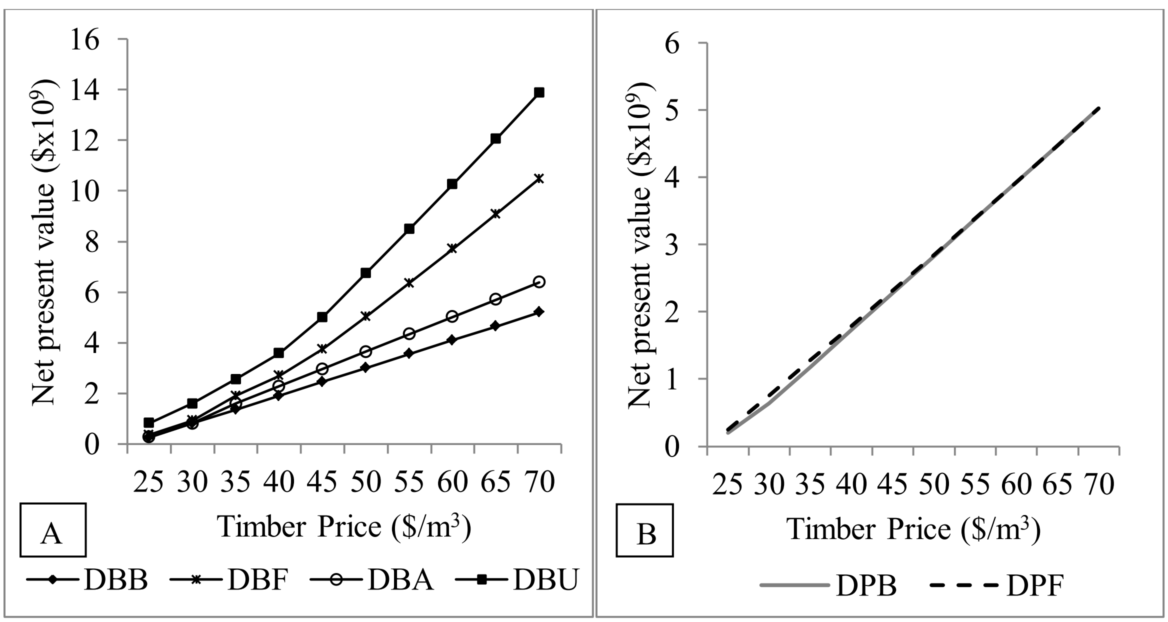
Note: Policy DPB and DPF yield similar net present values as a result of the constraints imposed. Although DPF yields slightly higher net present value than DPB, they appear as one line in Figure 11.

Figure 11. Sensitivity of net present value to changes in discount rate expressed as percent change from the base scenario (DNB, where λ is constrained) for policy scenarios DPB, DBB, DPF, DBF, DBA, and DBU.

6.3.3 Timber Price

Given the uncertainty surrounding the future of timber prices, we conduct sensitivity analysis on the potential impact timber prices might have on the net present value. There is potential for timber price to increase with the future demand that might arise from various industries such as housing or bioenergy. Anderson et al. (2014) calculated the maximum residual price that could be passed to the price developer from fast rotation plantations to be \$55/m^3 according data compiled by the Canadian Wood Fibre Center (Sidders 2011). The potential for rising demand and a higher hybrid poplar yield could increase this price even higher. The impact of timber prices from \$25/m^3 to \$70/m^3 is analyzed.

As expected in all scenarios, net present value increases as timber price increases as shown in Figure 12. The greatest increases in net present value are for scenarios DBF, DBA, and DBU, which allow hybrid poplar on public land without an MSY constraint on harvest volume. Although, DBA does not increase to the extent of DBF and DBU, as the volume is only allowed a 25% deviation from MSY AAC. The remaining scenarios (DPF,DBB,DPF), which have a land and/or a MSY volume constraint rise in a similar pace to each other as the timber price increases. For scenarios DPB, DBB and DPF, even if the price increases significantly, harvest volume cannot increase and the corresponding net present value will not increase significantly.



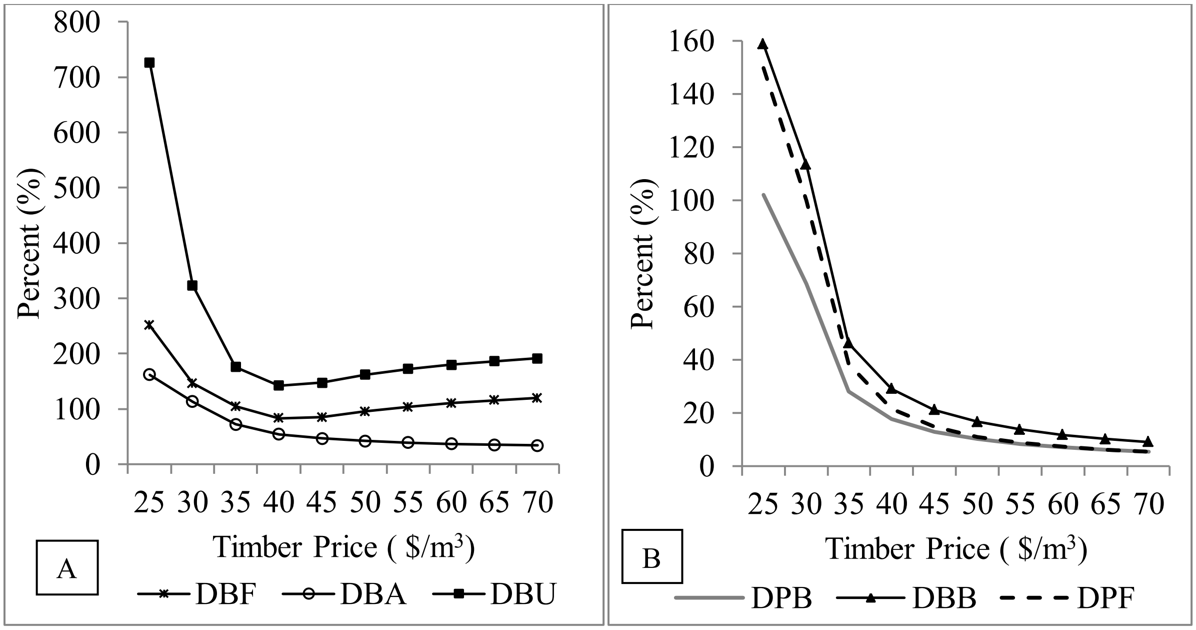
Note: Figures.12A and 12B use different scales for net present value.

Policy DPB and DPF yield similar net present values as a result of the constraints imposed. Although DPF yields slightly higher net present value than DPB, they appear as one line in Figure 12B.

Figure 12. Sensitivity of the net present value to a change in timber price for policy scenario A) DBB, DBF, DBA, and DBU, B) DPB and DPF.

Figure 13 shows the difference in net present value as compared to the base scenario as the timber price changes. For scenarios DPB, DBB, DPF, and DBA the difference is initially higher, and then decreases as the timber price increases. The harvest volume constraint the AAC prevents the scenarios DPB, DBB, and DBA from harvesting more even though price is increasing. Scenario DPF faces a similar harvest constraint in the limited amount of private land. As a result, the harvest amount and type does not change in each of the scenarios, DPB, DBB, DPF, and DBA as price changes, both in the amount and the type of trees. When price is lower, the net present value of policies DPB, DBB, DPF, and DBA differ from each other as the impact of the procurement and establishment costs of hybrid poplar is more pronounced. However, the unchanging harvest amount and type eventually results in net present values that converge in the difference from baseline in scenarios DPB, DBB, DPF and DBA as price increases.

Changing the timber price in scenario DBF and DBU, which allow hybrid poplar on public land without an MSY constraint on AAC, has an interesting impact on the net present value of the forestry firm. In the DBF and DBU scenario, the percent difference in net present value initially decreases, then increases at $40/m^3 . At prices above $40/m^3, both scenarios begin to harvest hybrid poplar. At prices lower than $40/m^3, no hybrid poplar is harvested as the cost of establishment is too high. Once DBF and DBU begin to harvest hybrid poplar, there is a significant divergence from the base scenario as timber price increases. This interesting result highlights that even increases in timber prices does not have a significant impact on net present value unless hybrid poplar can be harvested on public land.



Note: Figures 13A and 13B use different scales for percent.

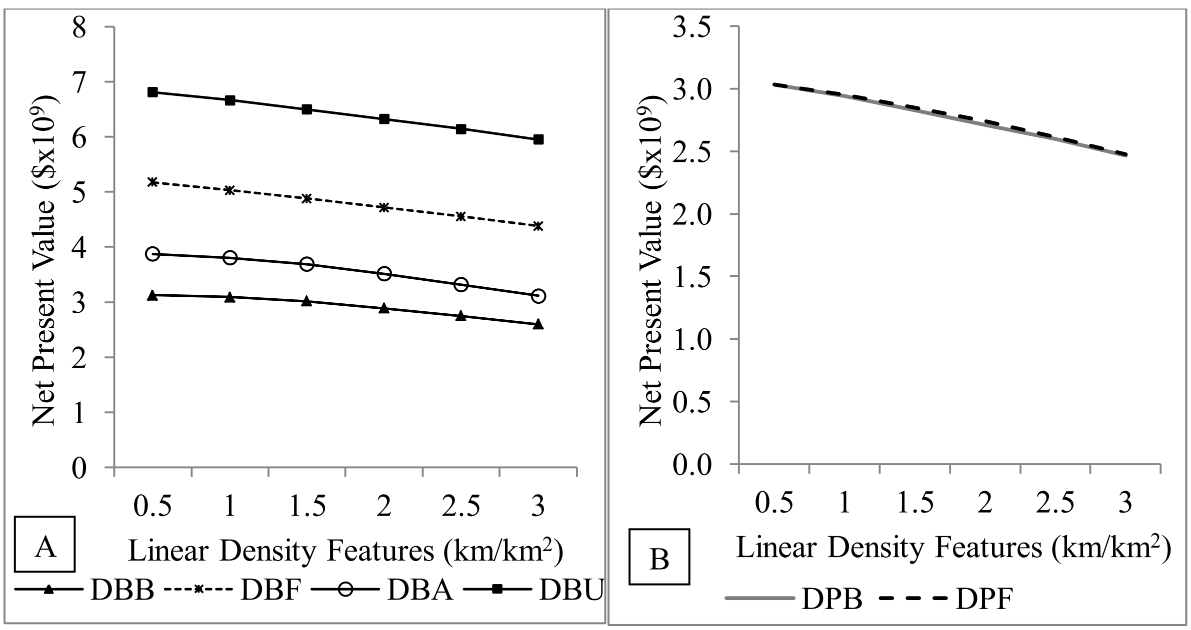
Figure 13. Sensitivity of net present value to changes in timber price expressed as percent change from the base scenario (DNB, where λ is constrained) for policy scenario A) DBF, DBA and DBU, B) DPB, DBB, and DPF.

6.3.4 Linear Density Features

In the caribou model, the assumption that linear features remain at the same level throughout the entire planning horizon is made. Since Alberta has an active energy sector in the caribou range studied in this thesis, the linear features have the potential to increase. At the same time, as concern for caribou and other ecological aspects increases, reclamation of these linear features also may occur. As a result, a sensitivity analysis of the linear density features is conducted. The sensitivity analysis of the linear features will continue to remain static throughout the planning horizon, however it will be increased and decreased. Schneider et al. 2003 has estimated that there is potential for the linear features in the energy regions of Alberta to change in a range of

1.8 km/km^2 – 8 km/km^2. Considering the potential for reclamation projects to decrease linear features, the sensitivity of net present value is analyzed from 0.5 km/km^2 to 8 km/km^2.

Decreasing the amount of linear features on the landscape reduces the need to constrain harvest in order to achieve self-sustaining herds of caribou. Conversely, increasing the amount of linear features increase the need to constrain harvest to achieve self-sustaining herds of caribou. As a result, the net present value of all scenarios decreases as the linear density features increases, which is shown in Figure 14. Interestingly, when linear density features are increased beyond 3km/km^2, it is no longer feasible in any scenario to continue harvesting at a profitable level while at the same time maintaining self-sustaining herds of caribou.

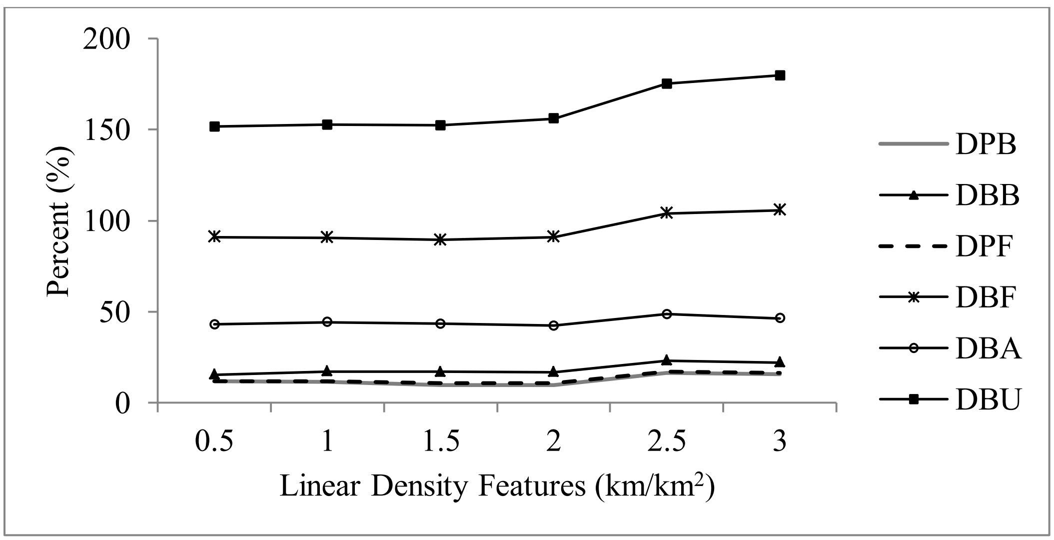


Note: Figures.14A and 14B use different scales for net present value.

Policy DPB and DPF yield similar net present values as a result of the constraints imposed. Although DPF yields slightly higher net present value than DPB, they appear as one line in Figure 14B.

Figure 14. Sensitivity of net present value to changes in linear density feature for policy scenario A) DBB, DBF, DBA and DBU, B) DPB and DPF.

Figure 15 compares each the net present value of each policy scenario as the linear density features increase and decrease, as compared to the baseline scenario (DNB, where $\lambda \geq 1$). In all scenarios, the larger the linear density features are, the greater the percent difference is in net present value as compared to the baseline scenario. For the 2 larger linear density features that were analyzed, which are 2.5 km/km^2 and 3.0 km/km^{2,} for all policy scenarios, as compared to the baseline, there is a larger increase in net present value. The baseline scenario is constrained by both harvest volume and only native species. As a result, the other policy scenarios may have a greater increase from the baseline scenario when the linear density features are higher because one or more of the constraints are relaxed. In addition, the largest increase in net present value from the baseline occur when the linear density features are greater than 2km/km^2 are in the scenarios where the constraints are most relaxed, DBF and DBU.



Note: Policy DPB and DPF yield similar net present values as a result of the constraints imposed. Although DPF yields slightly higher net present value than DPB, they appear as one line in Figure 15.

Figure 15. Sensitivity of net present value to changes in linear density features expressed as percent change from the base scenario (DNB, where λ is constrained) for policy scenarios DPB, DBB, DPF, DBF, DBA, DBF, and DBU.

6.3.5 Summary

The sensitivity analysis on the yield curve, discount rate, timber price, and linear density features support the conclusions made in the base results section. Even with these parameter changes, a significant change to the net present value is only seen in those policies which allow hybrid poplar on public land and relax the constraint in volume harvested. However, through the comparisons with the baseline scenario, the sensitivity analysis also gives us further insight into the role of hybrid poplar. Increases in net present value from the baseline are only observed when the amount of hybrid poplar harvest also increases within most policy scenarios as yield, discount rate, and linear density features increase. In other words, hybrid poplar harvest is one of the driving forces of net present value change in the model regardless if they are permitted on private of public land.

6.4 Benefit Cost Analysis for Sustaining Caribou Population.

Another way of assessing whether or not it would be appropriate to undergo a new forest management approach which allows zoning and hybrid poplar is to calculate the benefit cost ratio of each policy scenario. A benefit cost ratio is a measure of the total benefits of a project, compared to the total costs of a project. Generally, projects which have a benefit-cost ratio greater than 1 are considered efficient investments.

As the benefit of caribou was not directly calculated in this study, we transfer benefits calculated in an existing study. In 2011, a study was conducted which elicited the value of caribou in Alberta through stated preference techniques (Harper 2012). The study found that respondents were willing to pay $184.02 and $330.36 per household per year to move from the current management strategy of 2 self-sustaining herds to 3 and 13 self-sustaining caribou herds.

As there are only 6 caribou herds in the ALPAC forest management area, which is being used as the stylized base for this case study, the willingness to pay for 6 self-sustaining herds, $255 per household per year is used in this analysis. Aggregating the willingness to pay from a household to a provincial level, the willingness to pay is multiplied by the number of households in Alberta in 2011, which is 1,390,275 (Statistics Canada 2011). As the value for caribou was elicited for populations being self-sustaining for the next 50 years, the provincial value is then aggregated and discounted at a rate of 3.7% over 50 years. The total benefit of maintaining 6 self-sustaining caribou herds for 50 years in Alberta is $8,378,382,247.

By having to achieve self-sustaining caribou populations, firms might face an opportunity cost of lost profits due to a change in their optimal harvest. As such, the costs are the loss in net present value associated with constraining harvests to have self- sustained caribou population as a result of the forest operations. Here, the cost is calculated by taking the difference between the net present values of the baseline scenario where the caribou population is not met (DNB, unconstrained λ) with the various other scenarios where the constraint on caribou populations is met. A benefit cost ratio will then be calculated for each scenario and are shown in Table 6.

When compared with the business as usual scenario, the greater the net present value in each scenario, the greater the benefit. The cost of moving to alternative scenario (from DNB, unconstrained λ) and achieving the self-sustaining caribou population are all significantly lower than the benefits with ratios ranging from 79.6 to 267.3. In fact the three scenarios which allow hybrid poplar on public land and have no base volume flow constraints (DBB, DBF, DBA, and DBU) do not have any costs. In the DBB, DBF, DBA, and DBU scenarios it is costly not to meet the self-sustaining herd constraint as compared to the baseline scenario.

Table 6. Benefit and Cost (from the baseline scenario) of meeting the caribou constraint

Scenario	Cost ($\$x10^9$)	Benefit ($\$x10^9$)	Net Benefit ($\$x10^9$)	Benefit Cost Ratio
DNB	0.11	8.38	8.27	79.6
DPB	0.06	8.38	8.32	148.3
DPF	0.03	8.38	8.35	267.3

Note: Scenarios DBB, DBF, DBA and DBU do not have any costs as their net present values are higher relative the base scenario (DNB, λ is constrained). In these cases there are negative costs to achieve the self-sustaining constraint

Chapter 7. Policy Discussion

The results of this study show that by allowing the use of intensive plantation forestry using hybrid poplar as well as extensive forestry using native species in an optimization model could result in zoning forest management. Some areas can be left "protected" in the sense that old growth forest which would aid in caribou conservation is left unharvested and others are designated for hybrid poplar. By allowing zoning a forest firm could increase their net present value while at the same time reduce the cost of achieving self-sustaining caribou populations. Under relaxed restrictions on AAC and the allowance of hybrid poplar on public land, the forestry firm had the potential to have the highest net present value. Through sensitivity analysis, the results show that increasing the price only makes a significant difference as compared to the baseline scenario (DNB, constrained λ) if hybrid poplar is allowed on public land without a MSY constraint. Furthermore, even at the lowest hybrid poplar yield analyzed, the net present value as compared to the baseline was still 25% higher in scenarios which allowed hybrid poplar on public land without an MSY AAC constraint. This chapter will discuss the policy implications of allowing the implementation of a zoning system using hybrid poplar.

7.1. Hybrid Poplar on Public land.

Most of Canada does not permit the use of exotics or genetic modification in forestry on public land. However, our results indicate that the benefits of allowing hybrid poplar on public land could far exceed the costs to the forestry firm to conserve caribou populations. The main reason for the lack of use of exotics on public land is the fear of compromising the genetic diversity of the natural boreal forest which could lead to several issues including limited local adapting ability of the native forest (Talbot et al. 2012). Allowing exotics on public land could further lead to the trees rapidly spreading and outcompeting native species and invasion to adjacent ecosystems. Although, these reasons are given for restricting the deployment of hybrid poplar, few studies have studied the movement of genes from exotic to native populations in North America. Of those studies which do exist, the conclusions seem to be mixed. Some studies report a high risk with negative implications of gene transmission between exotic and native populations (Cairus 2008, Thompson et al. 2011). While others suggest that the risk is very low (Talbot 2012) or extensive but can be maintained or prevented with appropriate management techniques (DiFazio et al. 2011). Furthermore, the trajectory of hybrid poplar research is heading in the direction of genetic modification. Similar fears of the unknown negative effects on the genetic diversity of the native forest will prevent the use of genetics on public land and are provincially and federally enforced (Alberta Environment and Sustainable Development 2006).

Another potential limitation behind the use of exotics on public land is their perception by the public. In general, plantations and the use of exotics on public land have a negative perception. There are studies which have shown that the public are largely not in favor of the plantations on forested land (Harshaw et al. 2012, Neuman et al. 2007). Furthermore, the use of exotics might result in fears of loss of genetic diversity (Hallman et al. 2003). However, information regarding improved growth technology in forestry may not be well known among the public. As such, there is opportunity for an increase in information regarding public perceptions.

The constraints on exotics in Canada might be decreasing the effectiveness or amount of studies on research of hybrid poplar and their potential benefits. Perhaps increasing the knowledge surrounding public perceptions and genetic threats imposed by hybrid poplars might be able to highlight rather than diminish their potential benefits. Indeed, initiatives have already begun on increasing the knowledge of hybrid poplar including Forest 2020 (Dominy et al. 2010), an initiative of the federal government which seeks to find the role of plantations forestry in the reduction of greenhouse gases, and the POPCan initiative (Genome Canada 2014). A clearer understanding of the threats which cause restrictions of the implementation of hybrid poplar on public land could lead to an increased adoption.

7.2. Non-timber Values

The results of this study show how hybrid poplar plantations might reduce the cost to a forestry firm to protect boreal caribou populations in north eastern Alberta. Preserving old growth boreal forest and implementing hybrid poplar plantations might have several other non-timber values which could be considered which may further reduce the cost. Two examples of non-timber values discussed here which might be associated with the implementation of hybrid poplar plantations are carbon and fire protection.

Forests in Canada are a large carbon sink. As such, they have been recognized for their potential to mitigate the effects of climate change. In Canada hybrid poplar has been recognized for their potential role in sequestering carbon in the Forest 2020 initiative (Dominy 2010). Carbon emissions could be reduced in through hybrid poplar plantations through afforestation or avoided conversion/deforestation.

Afforestation is directly relevant to hybrid poplar as establishing plantations could sequester carbon. However, afforestation in most cases only applies to those lands which were not originally forested (Alberta Environment 2011), or in the case of our study, private lands. As there is little private land planted, carbon sequestration by hybrid poplar on private land might not make a large difference. Carbon sequestration could be more of a consideration if public land is taken into consideration. By planting hybrid poplar on public land through a zoning system, our results show a portion of land left conserved as it is no longer needed for timber revenue. As such, old growth forest which stores a larger amount of carbon is no longer harvested, or conversion/deforestation is avoided. If hybrid poplar is to be used in bioenergy, there is also potential for a reduction in carbon emissions through avoided use of fossil fuels, a higher emitting fuel source.

Alberta has a mandatory carbon reduction program which was implemented in 2007 which allows companies to use of carbon offsets to meet targets (Alberta Environment and Sustainable Development 2014b). However, within the Alberta offset system, there are currently no carbon protocols pertaining to afforestation, avoided conversion, or bioenergy as a result of the difficultly in accounting. Although, there is currently a draft for afforestation in Alberta (Alberta Environment 2011). Canada has stated an intention to develop a carbon program which would align closely with the United States (ecoAction 2008). California has recently implemented the first industry wide mandatory by regulations carbon reduction program in North America. Their program includes protocols for afforestation, avoided conversion and bioenergy (California Environmental Protection Agency, Air Resources Board 2011). As this is the first mandatory program, aspects of this program could be adopted federally. If Canada is to also adopt this type of carbon program, adding carbon to the potential revenue of a forestry firm might increase the adoption of hybrid poplar. Even in the absence of a mandatory program, firms could participate in a voluntary carbon programs which could further reduce the cost to achieve self-sustaining herds.

Another non-timber value of hybrid poplar which could be considered is the potential for hybrid poplar to act as fire protection. Fire Smart is a program which uses management practices in a pre-planned manner to reduce the amount of area affected by undesirable fires. The intention of Fire Smart is to reduce the negative socioeconomic effects of fire such as public safety, and job security (Hirsch et al. 2001). With disasters such as the Slave Lake fire in 2011, the use of exotics such as hybrid poplar in programs like Fire Smart could become increasing important and valuable. In fact the town of Hinton, AB has a Fire Smart Mitigation Strategy to protect against the significant risk posed by fire (Town of Hinton 2011).

Considering the added benefit of hybrid poplar from non-timber sources such as carbon and fire smart might could further reduce the cost of meeting a self-sustaining status for caribou populations by adding to the net present value of a forestry firm. As such, the viability and adoption of hybrid poplar in a zoning type management such as triad might increase with consideration of other non-timber values.

7.3. Increasing the Annual Allowable Cut

The results from this study indicate that the greatest increase in net present value is only achieved if hybrid poplar can be used on public land and the harvest volume is allowed to increase from a MSY AAC. The determinations of AAC's take into account many aspects in response to social, economic and environmental considerations to ensure sustainable levels of timber are harvested. As a result, they are an important and widely used management tool in forestry. Although, increases in AAC have been considered such as the allowable cut effect, such policies may not be effective in encouraging silvicultural activity (Luckert and Haley 1995). Furthermore, considering the potential risks of extensive establishment of hybrid poplar (including water and nutrient needs Joss et al. 2008, Jassal et al. 2013), increasing the harvest levels to beyond MSY levels to accommodate more hybrid poplar may not be supported by government policies. Increasing the AAC to beyond MSY levels might increase the viability of hybrid poplar plantations and further reduce the cost of self-sustaining caribou herds. However, considering the future risks and benefits of increasing the AAC in the context of using a fast rotations trees such as hybrid poplar in a zoning system should be explored further.

7.4 Linear Density Features

The results of the sensitivity analysis on the amount of linear density features on the land indicate that in order to achieve self-sustaining levels of caribou as well as have increase net present values for forestry, linear density features may not increase beyond 3 km/km^2. By utilizing hybrid poplar on the land, the pressure on the extensive forest could be reduced. However, the survival of caribou is highly dependent on the amount of linear density features which exist in their habitat. If linear disturbances continue to increase, the potential of hybrid poplar used in zoning to reduce the cost of achieving self-sustaining caribou populations will significantly diminish. In order to understand the full impact of hybrid poplar and zoning on reducing costs of caribou conservation, future studies should include the modelling of linear density features.

Chapter 8. Limitations

There timber supply and caribou population models used in this study have limitations associated with them. These limitations include a static energy sector, lack of spatial information, and assumptions on the forest structure, boreal caribou population dynamics, and the hybrid poplar yield curve.

8.1. Static Energy Sector

The equation for the rate of boreal caribou population change is a function of not only amount young forest but also the amount of linear density features. In our model, the linear density features are assumed to be static. Realistically, with an active and growing energy industry in Alberta, the linear density features will be dynamic in nature. Using the Alberta-Pacific Forest Management Area, Schneider et al. (2003) estimated the potential of disturbances of human-origin could increase from 1.8 km/km^2 to 8.0 km/km^2. These disturbances are estimated to increase most rapidly in the next two decades and result from industrial features such as roads, pipelines, well site and most prominently seismic lines. There is also potential for the improvement in density features from integrated-landscape management including reducing the impact of new disturbances as well as reclaiming existing ones (Alberta-Pacific 2014). Although our model does allow for the linear density features to increase in the sensitivity analysis, they remain static in nature and as such may underestimate the impact of the potential for dynamic changes from the energy industry.

As the industrial features on the landscape are so dynamic in nature and subject to the cycles of boom and bust (Schneider et al. 2003), they are difficult to predict. In order to include the dynamics of the features in this study, a more complex modelling strategy would have been necessary. Further efforts should be made in future studies.

The model presented also lacked representation of the impact on forest fire. Fires are a natural feature of the boreal forest. However, they are also very varied, dynamic and require complex modelling to predict. In Alberta, fires 2 hectares and smaller account for approximately 74% of all fires from 1961-1998 on the Alberta-Pacific FMA and represent a small impact (Alberta-Pacific 2007). Although, they are rare, large and more damaging fires could occur which have much larger impact on the landscape and the boreal caribou. However, major efforts towards reducing the impact of fire have been taken since the 1950's in the Alberta-Pacific FMA. The dynamic nature of fire also makes its incorporation into a programming model complicated. For these reasons, we do not consider fire in our model.

8.2. No Spatial Information

Several spatial components are missing in the above analysis. The results of this study show that it is possible to attain enough old growth for self-sustaining caribou populations. However, little detail is given as to where the old growth forest is. Boreal caribou require continuous tracts of old growth forest as well as a sizable buffer from the nearest disturbance. The model presented lacks information regarding each of these aspects.

Anderson et al. (2012) presents a similar study establishing a zoning system on a stylized forest landscape. The results of their study showed that across all policies examined the areas which were conserved were often the oldest. The preserved areas occurred across many haul zones (of 10 km to 190 km distances from the mill site), but as a result of increasing log-haul costs from further distances, much of the preserved landscape was further from the mill site. The study presented above might have similar results regarding location of preserved caribou habitat. However, more complex modelling and information of where and how continuous the old growth forest is should be considered in future work.

8.3. Stylized Forest and Initial Age Class Structure

The location of this study was chosen because of the existing mix of the forestry sector and the presence of threatened caribou populations. However, the forest is highly stylized and although does give an idea of the landscape, does not give and fully accurate representation of the area. The model presented used two yield curves which were representative of an average of the Alberta-Pacific FMA. However, a more complex model could consider the many different yield curves and productivity levels of species in the area. The model presented here also used an age class distribution typical of the boreal forest including a gap in the middle of young and old forest with each age class in the initial inventory was evenly distributed. The initial age class structure of the Alberta-Pacific FMA is not evenly distributed and does not have a gap in between young and old age classes (Alberta-Pacific FMA 2007).

The initial distribution and age class could have a large impact on the constraint of the caribou population change as well as the increase in AAC. Meeting the constraint to create self-sustaining caribou herds could result in a significantly different harvest pattern if there was no "gap" in the initial amount of coniferous forest. The ability to have enough old forest for the caribou was aided in our model by the large amount of initial mature coniferous forest. The increase in allowable cut in our model was also generated as a result of initial age class distribution. The allowable cut effect is activated allowing increases in AAC if increases in yield are expected in the future. When hybrid poplar is planted, a future increase in yield may occur and activate ACE. However, the starting inventory of our model used a stylized, evenly distributed age class with a substantial amount of mature forest. Without this initial stock of mature forest to harvest, there likely would not have been an increase in AAC. If the initial age class had instead a large portion of juvenile inventory with few mature trees, then the allowable cut effect may not have occurred (Hegan and Luckert, 2000). For simplicity reasons, we used a stylized age-class distribution. However, given the large effect that the initial age class inventory probably had on our model, alternative structures should be considered for future work

8.4. Boreal Caribou population dynamics

It is also important to mention that the model presented shows that enough caribou habitat can be set aside to achieve self-sustaining caribou habitats. A large assumption is made that if there is enough habitat for self-sustaining caribou habitats that the correct population dynamics would also exist. Crucial to the survival of caribou populations is the number of actively reproductive females in each herd. Further studies could include this aspect to improve the results of the study.

8.5. Non-timber Values

The thesis incorporates a non-timber value in the optimization problem through the constraints of the problem. By doing this, the opportunity costs to the forestry firm of maintaining a specific level of caribou population change can be analyzed. However, incorporating the non-timber value of caribou in this manner is a rather indirect method as the actual value provided by the caribou is not directly accounted for. Incorporating the value of caribou into the objective function is difficult as it is a passive use value which could be elicited through complex valuation studies. In the event that the values are elicited, difference in units between the multiple objectives could be mathematically complex. Future work could consider adding the value of non-timbers into the objective function.

8.6. Yield Curve on Public land

Knowledge of the growth potential of hybrid poplar in Canada has been studied in depth in Canada (McKenney and Yemshanov 2004, Joss et al. 2008,Yemshanov and McKenney 2008, Laroque et al. 2013). The research indicated the prairie provinces as very suitable land with high potential for hybrid poplar (McKenney and Yemshanov 2004, Yemshanov and McKenney 2008). Most studies indicate the high potential of hybrid poplar in Canada. However, there has been a lack of adoption of hybrid poplar projects in Canada (McKenney et al. 2014). The lack of adoption might be related to the costs of production, the future prices of energy and other environmental improvements, and the need for strong integrated biological and economic models (McKenney et al. 2014).

Unfortunately, most studies have been contained to agricultural or marginal lands. Our results indicate that the benefits of hybrid poplar are higher if they are allowed on public land. Further studies on the growth rate of hybrid poplars on public land might be essential to the future adoption of public land plantations.

Chapter 9. Conclusions

The objective of the thesis presented is to understand the effect of allowing the model to choose a zoning system using hybrid poplar plantations, on the net present value of a forestry company and boreal caribou populations in the study area.

The results are important because of the concern for boreal caribou populations and the forestry industry in Alberta and Canada. Boreal caribou are listed as threatened provincially and federally. Their preferred habitat represents an ecologically, socially, and culturally important ecosystem. The preservation of boreal caribou could have positive effects for the ecological integrity and natural capital of the boreal forest and the many species which live there. The integrity of the boreal forest will result in other numerous benefits in terms of the ecosystem services provided and could also lead to spill over cultural and social values. Culturally and historically, the boreal caribou are an integral piece to many Aboriginal peoples in Canada. The caribou provide important holistic and ceremonial practices as well as subsistence, knowledge and relationships acquired from hunting (Natural Resources Canada 2014). Socially, it has been shown that there is value in Alberta from knowing that caribou and old growth forest exist (Harper 2012).

The ability to convert from traditional to plantation forestry in Canada might have positive implications for the viability of forestry in Canada. The trend in forestry globally is shifting towards short rotation high yield plantations. If Canada is to remain globally competitive, plantation forestry should be considered.

Similar to the work of Anderson et al. (2012), the model presented uses a linear optimization model of the forest to determine the effect of different policy scenarios of the net present value of a forestry firm. However, the model presented here includes the non-timber aspect of the old-growth forest not accounted for the in Anderson et al. (2012).

The key result of this thesis is the ability of the forestry firm to not only increase net present value but also maintain self-sustaining caribou populations if certain constraints are relaxed. The potential for the highest net present value comes from converting a large portion of the forest on public land to hybrid poplar plantations. Such a conversion is not without risks. Hybrid poplar plantations require a significant amount of water and nutrients (Joss et al. 2008, Jassal et al. 2013), face a negative perception by the public on the landscape, and are a potential risk to the genetic diversity of the forest. Supplying the plantations with adequate nutrients might also lead to increased use of chemicals which may not be permitted on public land (Fortier et al. 2012). The trade-off is the potential benefits which could come with self-sustaining caribou populations.

It is unknown if governments, firms and the public would be willing to make the trade-off between the benefits to boreal caribou and the risks of hybrid poplar. There are policies which allow for a smaller amount of hybrid poplar on the public land (DBB, DBA) which could reduce the risks. However, these policies do not show a significant increase to the net present value from current management (see: Figure 5.). In order to use hybrid polar to increase the amount of "protected area" or old growth forest for boreal caribou as well as increase the net present value by a significant amount as compared to current management, major regulatory changes would be necessary.

Considering the significant regulatory changes that would be needed and the trade-off between the real and perceived risks of hybrid poplar and the benefits of boreal caribou, a zoning system using hybrid poplar might not be an optimal solution. At a cost to the forestry firm (see Figure

6.), using the current management system it is possible to sustain boreal caribou populations. Rather than take the risks and regulatory changes that come with hybrid poplar, perhaps the current management regime may be more appropriate. In order to consider zoning using hybrid poplar on the public land to reduce the cost of boreal caribou conservation, more information surrounding the risks of hybrid poplar is required.

There are many assumptions made in this thesis which are not representative of a real world scenario. As such, there is significant room to refine aspects of the model to make it more representative. However, the results could be a tool used in the decision making process and lead towards seeing the benefits of zoning and hybrid poplar.

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Appendix

This appendix contains the input files for the GNU Linear Programming Model presented in chapter 4. The input files are nearly identical for all of the policy scenarios analyzed. The only major differences between the policy scenarios are the commands for optimization, management transitions, and harvest volume flow. The code presented here will be of the base model scenarios as they are described in chapter 3. Notes are provided where the code differed between the policy scenarios. In the sensitivity analyses hybrid poplar yield, discount rate, timber price and linear density features were also adjusted. As only specific numbers were changed for sensitivity analysis, the code will not be shown in this appendix.

/*BASIC MODEL PARAMETERS***/**

```
param M; /* birth period of oldest existing age class */

param N; /*planning horizon length in periods */

param Z; /* minimum final harvest age */

param y{age in 0..70, m in 1..4}; /* yield (m^3/ha) at age in periods*/

param A{p in 1..2, bp in -M..0, m in 1..4}; /* area of initial age classes (ha) */

param r;/* discount rate */

param gamma :=  (1 + r);

param price; /* price of wood ($/m^3) */

param logcost ;  /* logging cost ($/ha) */

param pcost{m in 1..4, tm in 1..4}; /*land procurement cost*/

param rcost{tm in 1..4}; /* reforestation cost ($/ha) */

param haulcost {p in 1..2}; /*hauling costs ($/ha)*/

param perlen; /*period length (years) */
param midpoint{n in 1..N} := perlen/2 + perlen * (n - 1); /* midpoint of each period */
```

*/*discounted net harvest revenue */*
param D{p in 1..2,i in -M..(N-Z), j in max(1,(i+Z))..N, m in 1..4, tm in 1..4} :=
(price * y[j-i,m] - logcost - rcost[tm]- haulcost[p]-pcost[m,tm])/(gamma^midpoint[j]);

/*** **DECISION VARIABLES** ***/
var x{p in 1..2, i in -M..N, j in max(1,i)..N, m in 1..4, tm in 1..4} >= 0;;

var w{p in 1..2, i in -M..N, j in i..N, m in 1..4} >= 0;

*/*to ensure that harvest age is always greater than Z*/*
s.t. forcezero{p in 1..2, j in 1..N,i in j-Z..j, m in 1..4, tm in 1..4} : x[p,i,j,m,tm] = 0;

/* **OBJECTIVE FUNCTION** */

/*1. Maximize Total Volume*/
maximize totvol:
sum{p in 1..2, j in 1..N, i in -M..(j-Z), m in 1..4, tm in 1..4} x[p,i,j,m,tm] * y[j-i,m];/*total volume*/

var npv;
s.t. npvcalc: sum{p in 1..2, j in 1..N,i in -M..(j-Z), m in 1..4, tm in 1..4} D[p,i,j,m,tm] * x[p,i,j,m,tm] = npv; /*total NPV*/

/* **or** ***2.Maximize Net Present Value*/***
maximize npv:
sum{p in 1..2, j in 1..N,i in -M..(j-Z), m in 1..4, tm in 1..4} D[p,i,j,m,tm] * x[p,i,j,m,tm];

var totvol;
s.t. totalvolcalc: sum{p in 1..2, j in 1..N, i in -M..(j-Z), m in 1..4, tm in 1..4} x[p,i,j,m,tm] * y[j-i,m]=totvol; /*total volume*/

/* **AREA CONSTRAINTS** */

s.t. standingareacalc1{p in 1..2,i in -M..0,j in 1..N, m in 1..4}:
A[p,i,m] = sum{l in max(i,1)..j, tm in 1..4} x[p,i,l,m,tm] + w[p,i,j,m];

s.t. standingareacalc2{p in 1..2,i in 1..N, j in i..N, m in 1..4}:
w[p,i,j,m] = sum{l in -M..i, tm in 1..4} x[p,l,i,tm,m] - sum{k in i..j,tm in 1..4}x[p,i,k,m,tm];

/*** **MANAGEMENT TRANSITIONS*****/

*/*These transitions manage whether hybrid poplar is permitted. They differ depending on the scenario. Shown here is the baseline (DNB) transitions*/*

*/*private land management transitions*/*
```
s.t. mgmttransition1 {i in -M..N, j in max(i,1)..N}: x[1,i,j,1,2]=0;
s.t. mgmttransition2 {i in -M..N, j in max(i,1)..N}: x[1,i,j,1,3]=0;
s.t. mgmttransition3 {i in -M..N, j in max(i,1)..N}: x[1,i,j,1,4]=0;
s.t. mgmttransition4 {i in -M..N, j in max(i,1)..N}: x[1,i,j,2,1]=0;
s.t. mgmttransition5 {i in -M..N, j in max(i,1)..N}: x[1,i,j,2,2]=0;
s.t. mgmttransition6 {i in -M..N, j in max(i,1)..N}: x[1,i,j,2,3]=0;
s.t. mgmttransition7 {i in -M..N, j in max(i,1)..N}: x[1,i,j,2,4]=0;
s.t. mgmttransition8 {i in -M..N, j in max(i,1)..N}: x[1,i,j,3,1]=0;
s.t. mgmttransition9 {i in -M..N, j in max(i,1)..N}: x[1,i,j,3,2]=0;
s.t. mgmttransition10 {i in -M..N, j in max(i,1)..N}: x[1,i,j,3,3]=0;
s.t. mgmttransition11 {i in -M..N, j in max(i,1)..N}: x[1,i,j,3,4]=0;
s.t. mgmttransition12 {i in -M..N, j in max(i,1)..N}: x[1,i,j,4,1]=0;
s.t. mgmttransition13 {i in -M..N, j in max(i,1)..N}: x[1,i,j,4,2]=0;
s.t. mgmttransition14 {i in -M..N, j in max(i,1)..N}: x[1,i,j,4,3]=0;
s.t. mgmttransition15 {i in -M..N, j in max(i,1)..N}: x[1,i,j,4,4]=0;
```

*/*public land management transitions*/*
```
s.t. mgmttransition16 {i in -M..N, j in max(i,1)..N}: x[2,i,j,1,1]=0;
s.t. mgmttransition17 {i in -M..N, j in max(i,1)..N}: x[2,i,j,1,2]=0;
s.t. mgmttransition18 {i in -M..N, j in max(i,1)..N}: x[2,i,j,1,3]=0;
s.t. mgmttransition19 {i in -M..N, j in max(i,1)..N}: x[2,i,j,1,4]=0;
s.t. mgmttransition20 {i in -M..N, j in max(i,1)..N}: x[2,i,j,2,1]=0;
s.t. mgmttransition21 {i in -M..N, j in max(i,1)..N}: x[2,i,j,2,3]=0;
s.t. mgmttransition22 {i in -M..N, j in max(i,1)..N}: x[2,i,j,2,4]=0;
s.t. mgmttransition23 {i in -M..N, j in max(i,1)..N}: x[2,i,j,3,1]=0;
s.t. mgmttransition24 {i in -M..N, j in max(i,1)..N}: x[2,i,j,3,2]=0;
s.t. mgmttransition25 {i in -M..N, j in max(i,1)..N}: x[2,i,j,3,4]=0;
s.t. mgmttransition26 {i in -M..N, j in max(i,1)..N}: x[2,i,j,4,1]=0;
s.t. mgmttransition27 {i in -M..N, j in max(i,1)..N}: x[2,i,j,4,2]=0;
s.t. mgmttransition28 {i in -M..N, j in max(i,1)..N}: x[2,i,j,4,3]=0;
s.t. mgmttransition29 {i in -M..N, j in max(i,1)..N}: x[2,i,j,4,4]=0;
```

/* HARVEST VOLUME CONSTRAINTS ***/**
```
var h{j in 1..N} >= 0; /* harvest volume by period */
s.t. volcalc{j in 1..N}:  sum{p in 1..2, i in -M..(j-Z), m in 1..4, tm in 1..4} x[p,i,j,m,tm] * y[j-i,m]
= h[j];
param alpha;
param beta;
```

/ the following four constraints differ depending on the policy scenario. Shown here is the baseline (DNB)/**
```
s.t. flowupper{j in 1..N-1}: (1 - alpha) * h[j] <= h[j+1];
```

```
s.t. flowlower{j in 1..N-1}: (1 + beta) * h[j] >= h[j+1];
s.t. initvol: h[1] = 19980963.43; /*initial volume, λ≥1*/
#s.t. initvol: h[1] =  22340587.40;  /*initial volume, λ≠1*/

/***HECTARES HARVESTED***/

var xs {j in 1..N}; /*amount of ha that has been harvested in each period*/
var conhar {j in 1..N} >= 0; /*amount of coniferous harvested in each period*/
var dechar {j in 1..N} >= 0; /*amount of deciduous harvested in each period*/
var hphar {j in 1..N} >= 0; /*amount of hybrid poplar that has been harvested in each period*/
var oldha {j in 1..N} >=0; /*amount of coniferous older than 6 periods*/
s.t. oldhacalc{j in 1..N}: oldha[j] = sum{p in 1..2,i in -M..j-7,m in 3..3} w[p,i,j,m];
s.t. conharcalc {j in 1..N}: sum{p in 1..2, i in -M..(j-Z), m in 3..3, tm in 3..3} x[p,i,j,m,tm] =
conhar[j];
s.t. decharcalc {j in 1..N}: sum{p in 1..2, i in -M..(j-Z), m in 2..2, tm in 2..4} x[p,i,j,m,tm] =
dechar[j];
s.t. hpharcalc {j in 1..N}: sum{p in 1..2, i in -M..(j-Z), m in 4..4, tm in 4..4} x[p,i,j,m,tm] =
hphar[j];
s.t. xscalc {j in 1..N}: sum{p in 1..2, i in -M..(j-Z), m in 1..4, tm in 1..4} x[p,i,j,m,tm] = xs[j];

/***ENDING INVENTORY CONSTRAINT***/

var standinginv{j in 1..N} >= 0;
s.t. standinvcalc{j in 1..N}: sum{p in 1..2, i in -M..j, m in 1..4} w[p,i,j,m] * y[j-i,m] =
standinginv[j];
s.t. ndinv{j in 30..N}: standinginv[j] >= standinginv[j-1];
param young;
var youngarea{j in 1..N} >= 0; /*amount of young forest*/
s.t. youngareacalc{j in 1..N}: sum{p in 2..2, i in j-young..j,m in 3..3} w[p,i,j,m] = youngarea[j];

/***BOREAL CARIBOU GROWTHRATE***/
param Con:= 1.10184;
param LDF:=0.0234;
param YG:= 0.0021;
param Initial:= 850375;
param LDFx:= 2.12
var lambda{j in 1..N}>=0;
s.t. lambdacalc {j in 1..N}: Con-LDF*LDFx-YG*((youngarea[j]/Initial)*100)=lambda[j];
s.t. lambdaconstrain {j in 4..N}:lambda[j]>=1;
solve;

/*** DATA ***/
data;

param alpha := 0.0;
param beta := 0.0;
```

```
param M := 29;
param N := 40;
param Z := 2;
param perlen := 5;
param price := 48.69;
param rcost := [1] 0 [2] 5 [3] 1500 [4]2538.77;

param pcost    [1,1] 0 /*cost of changing management type*/
                [1,2] 0
                [2,1] 0
                [2,2] 0
                [1,3] 0
                [2,3] 0
                [3,3] 0
                [3,1] 0
                [3,2] 0
                [1,4] 1655.06/*private land cost + cost to clear stumps(perha)*/
                [4,4] 0
                [2,4] 400.79 /*cost to clear stumps from public land (perha)*/
                [3,4] 0
                [4,1] 0
                [4,2] 0
                [4,3] 0;

param logcost := 3060;

param haulcost:= [1] 0 [2]1134;

param young := 6;

param r := 0.037;

param y := [*,*]: 1 2 3 4:=
0       0       0         0        0
1       0       2.245     1.705    7.629906886
2       0       4.49      3.41     39.88517924
3       0       12.5      9.47     96.78882291
4       0       20.51     15.53    203.5110215
5       0       33.24     25.45    272.4534697
6       0       45.97     35.38    302.0009198
7       0       61.48     47.255   0
8       0       76.99     59.13    0
9       0       93.46     71.325   0
10      0       109.93    83.52    0
11      0       125.91    95.265   0
```

12	0	141.88	107.01	0
13	0	156.34	117.61	0
14	0	170.8	128.2	0
15	0	183.1	137.2	0
16	0	195.4	146.2	0
17	0	205.2	153.39	0
18	0	215	160.58	0
19	0	222.21	165.9	0
20	0	229.41	171.22	0
21	0	231.88	174.73	0
22	0	234.34	178.24	0
23	0	229.85	180.08	0
24	0	225.35	181.91	0
25	0	215.64	182.24	0
26	0	205.94	182.58	0
27	0	189.26	181.64	0
28	0	172.58	180.69	0
29	0	151.46	178.66	0
30	0	130.35	176.64	0
31	0	107.63	173.74	0
32	0	84.91	170.85	0
33	0	63.47	167.28	0
34	0	42.03	163.72	0
35	0	21.015	159.65	0
36	0	0	155.59	0
37	0	0	151.18	0
38	0	0	146.78	0
39	0	0	142.17	0
40	0	0	137.56	0
41	0	0	0	0
42	0	0	0	0
43	0	0	0	0
44	0	0	0	0
45	0	0	0	0
46	0	0	0	0
47	0	0	0	0
48	0	0	0	0
49	0	0	0	0
50	0	0	0	0
51	0	0	0	0
52	0	0	0	0
53	0	0	0	0
54	0	0	0	0
55	0	0	0	0
56	0	0	0	0
57	0	0	0	0

```
58	0	0	0	0
59	0	0	0	0
60	0	0	0	0
61	0	0	0	0
62	0	0	0	0
63	0	0	0	0
64	0	0	0	0
65	0	0	0	0
66	0	0	0	0
67	0	0	0	0
68	0	0	0	0
69	0	0	0	0
70	0	0	0	0;

param A:=
[1,*,*]: 1  2 3 4:=
-29	0	0	0	0
-28	0	0	0	0
-27	0	0	0	0
-26	0	0	0	0
-25	0	0	0	0
-24	0	0	0	0
-23	0	0	0	0
-22	0	0	0	0
-21	0	0	0	0
-20	0	0	0	0
-19	0	0	0	0
-18	0	0	0	0
-17	0	0	0	0
-16	0	0	0	0
-15	0	0	0	0
-14	0	0	0	0
-13	0	0	0	0
-12	0	0	0	0
-11	0	0	0	0
-10	0	0	0	0
-9	0	0	0	0
-8	0	0	0	0
-7	0	0	0	0
-6	0	0	0	0
-5	0	0	0	0
-4	0	0	0	0
-3	0	0	0	0
-2	0	0	0	0
-1	0	0	0	0
0	25000	0	0	0
```

```
[2,*,*]: 1  2 3 4:=
-29     0       59070   42518.75        0
-28     0       59070   42518.75        0
-27     0       59070   42518.75        0
-26     0       59070   42518.75        0
-25     0       59070   42518.75        0
-24     0       59070   42518.75        0
-23     0       59070   42518.75        0
-22     0       59070   42518.75        0
-21     0       59070   42518.75        0
-20     0       59070   42518.75        0
-19     0       59070   42518.75        0
-18     0       59070   42518.75        0
-17     0       59070   42518.75        0
-16     0       59070   42518.75        0
-15     0       0       0               0
-14     0       0       0               0
-13     0       0       0               0
-12     0       0       0               0
-11     0       0       0               0
-10     0       0       0               0
-9      0       0       0               0
-8      0       0       0               0
-7      0       0       0               0
-6      0       0       0               0
-5      0       59070   42518.75        0
-4      0       59070   42518.75        0
-3      0       59070   42518.75        0
-2      0       59070   42518.75        0
-1      0       59070   42518.75        0
0       0       59070   42518.75        0;

end;
```