

Evaluating social welfare implications of forestry policies when economic  
and environmental values matter in a British Columbia Context

by

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## **Abstract**

A modified Faustmann equation is used to evaluate the comparative social welfare implications of a set of forestry policies in British Columbia. A one-hectare timber stand is modeled with a timber firm as the licensee and the provincial government as the resource owner and policy-maker. Rotation time and silvicultural investment decisions are the firm's main inputs while revenue, government expenditure, and the values of carbon sequestered and biodiversity accumulated are the components of the social welfare function. The policies include subsidized silviculture, imposed rotation times and compensation for the forest stand's environmental outputs. The social welfare generated from each policy is compared to determine the best policy for a BC forest stand. Heterogeneity is modeled through individual stands' infrastructure costs and unprofitable stands are assumed to accumulate environmental social welfare. Finally, a timber supply area (TSA) in BC's southern interior is used as a case study to explore the model's policy implications in a real-world forestry context. Social welfare was found to be highest under an environmental subsidy policy that compensates the firm for all carbon sequestered in timber biomass and a fraction of the value of biodiversity, soil carbon and wildlife habitat accumulated over the rotation. The BC government's current policy of limited funding for incremental silvicultural activities generated less social welfare than the environmental subsidy policy. When heterogeneity was introduced, the general results held. The unprofitable stands generated very little social welfare compared to the harvested stands. In the case study, if timber quality premiums exist, social welfare is highest when stands are managed under the subsidy policy for timber quality, generating moderate levels of short-term wildlife habitat supply. Where this premium does not exist, all stands should be managed for timber supply. To meet the TSA's stated objectives, timber supply could be managed alongside old growth if only profit and biodiversity matter or in the case where there is a downward-sloping demand for old growth forests.

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# **1 Introduction**

## **1.1 Background**

Forestry policy has historically been focused on timber and profit objectives. Over the past decades, however, there has been an increasing awareness of the role that forests can play in achieving environmental as well as economic goals. Some of the same inputs that enhance timber production can simultaneously generate higher output of various environmental and social amenities. One of the primary inputs into timber production is silviculture, the practice of growing trees (this also includes rotation time or age of the trees at harvest). Specific silvicultural activities can include fertilizing, pruning and thinning. Where these inputs have been carefully managed and implemented, there has been evidence of timber benefits (Jokela et al. 2004, Rotherham and Mooney 1988). The timber benefits include enhanced volume from silvicultural activities such as fertilizing and enhanced value from thinning and pruning. The trade-offs that exist between the outputs created by these activities makes the practice of growing trees complex. For example, a forest that is managed primarily for volume would likely require some fertilizer application. However, without some degree of thinning the increased growth rate of the trees may contribute to a decreased diameter of the timber, potentially compromising the premium captured from the enhanced volume. Investment into timber stands is generally reserved for second growth forests where management practices are applied throughout the rotation on reforested sites. In British Columbia, forestry is transitioning to a second growth industry at a time when there are environmental and economic challenges facing the Province. There has been very little funding for

silvicultural investment from the government, resulting in minimal stand investment (such as pre-commercial thinning and fertilizing) beyond reforestation. Timber companies in BC have not had enough incentive to significantly invest in these practices. The impact of this lack of investment is both economic as timber volume and quality are negatively affected as well as environmental since the investment contributes to more timely and enhanced wildlife habitat and biodiversity in second growth stands. In BC's southern interior timber region, the current mountain pine beetle epidemic will result in timber volume insecurity over the coming decades. The projection for beetle-infested trees is that 57 million cubic meters will be killed by 2015. The harvest levels will increase over the next several decades to capture the mountain pine beetle wood, but will be followed by a ten percent decrease after forty years, with the lowest timber supply in decades to come in seventy to eighty years. More stand investment into second growth forest stands could increase future timber volume and help to mitigate the negative effects of this epidemic. British Columbia's forests are also home to diverse natural ecosystems that are challenged by timber harvesting. Species are being threatened by habitat loss and there are increasing pressures on the forest industry to contribute to biodiversity and carbon sequestration. Appropriate stand management and investment could create more positive environmental externalities within a timber stand. This thesis uses an economic model to evaluate policy alternatives in a lodge pole pine forest in the southern Interior of B.C. A major contribution of this research is the comparative evaluation of relevant policy options as they affect social welfare through timber supply and environmental outputs from a forest stand. The analysis revealed that subsidizing environmental output, instead of silviculture, yields more social welfare overall.

## 1.2 Objectives and Research Questions

The economic and environmental implications of forestry policies that influence a forestry firm's decisions are explored in this thesis through a theoretical economics model. There are also a number of variables that play a potentially important role in a timber firm's behaviour and the outcome of the firm's decisions for society. These variables include the security of the firm's property rights to the resource, prices of key outputs such as timber, biodiversity and carbon stored, as well as other variables that may influence the model such as discount rates. To ground the theoretical economic model of a forestry firm in a realistic context, the volume, cost and price details will reflect a British Columbian forest.

*The following research questions will be explored in the initial simulations:*

- From a set of policies available to forestry policy-makers in a context like British Columbia, given the influence of both tree age (rotation time) and volume-enhancing and environmental quality-enhancing investments on the economic and environmental outputs of a forest, which policies create the most social welfare given the firm's profit maximizing behavior?
- What are the variables that influence the optimality of these policies? Specifically, how do discount rates, prices, social values, property rights and other key variables affect the optimality of these policies?

### **1.3 The Theoretical Model: An Overview**

This analysis will focus on two players, the forestry firm or license holder and the resource owner or manager. The firm has a certain level of tenure security and makes decisions based on a profit-maximizing framework and takes prices as given. The firm's primary output is timber and it chooses a rotation time and level of stand management investment to maximize timber profits. The firm can invest in silviculture, which is assumed to be a bundle of inputs that collectively enhance timber volume. Under certain conditions, the firm may also choose to make environmental investments at the expense of volume. The owner or manager (policy maker) influences the firm's activities on public land by implementing forest policy to maximize social welfare. Social welfare from a forest can be measured as the sum of outputs that have value for society. These can include explicitly market goods and services as well as non-market amenities. A forest stand's primary market value is from timber, however, positive externalities of a well-managed forest stand can include carbon sequestration and biodiversity. As a result, forest managers are in a position to influence the amount of carbon sequestered and the quality of wildlife habitat and biodiversity in forests simply by carefully managing their timber stands. By influencing the firm's input decisions (rotation time and investment) through policy, the resource manager, who in the case of BC is the provincial government, can create positive environmental value.

The model developed in this thesis has two components. A timber company's profit function (maximizing timber profit from a volume function) is maximized given a set of

forestry policies, to determine the firm's "optimal" input choices regarding rotation time and investment. These inputs are then incorporated into a government social welfare function that includes economic and environmental components. Social welfare is then compared across policies.

A modified version of the Faustmann profit maximization model for forestry is used in this analysis. The Faustmann model was chosen as the basis for an evaluation of different policies' effectiveness in meeting multiple forestry objectives in British Columbia.

Faustmann has been used to explore other forestry issues in British Columbia (van Kooten et al 1995) and has been widely used in other forestry contexts as well (Paarsch and Rust, 2004). The Faustmann model uses a timber volume function as the production function which is maximized given prices and costs associated with timber production. The Faustmann model has been modified to incorporate a firm investment decision variable. Thus, the firm is maximizing profits by choosing levels of investment into their timber stand and the length of the timber harvesting rotation.

The stand volume function used in the analysis of the firm is based on two main assumptions: that rotation time and silvicultural investment (fertilizer and possibly thinning) enhance volume, both at a decreasing rate. Timber volume (cubic meters) is simply the result of the relationship between the volume output and the inputs chosen by the firm, namely rotation time and investment. These correlations drive the model's theoretical tree volume function. In this model, a lodgepole pine forest is planted at time zero with varying amounts of silvicultural investment (fertilizing and some degree of pre-

commercial thinning) and then harvested at the end of the rotation and replanted over infinite rotations. Investment that enhances environmental quality at the expense of volume takes place only after the positive volume effects of silviculture investment have been maximized and only given specific incentives.

The two optimal inputs yielded by the firm's profit maximization are used to calculate social welfare. The social welfare function has four components: revenue from the timber firm; government expenditure in the case of subsidy policies; the value of carbon sequestered over a rotation (both in situ and ex situ); and an environmental component (called 'biodiversity-wildlife') that includes biodiversity, soil carbon and wildlife habitat. Each forestry policy will generate a different amount of social welfare depending on the firm's choices of rotation time and investment.

#### **1.4 Context: British Columbia Forestry**

The modified version of the Faustmann model developed for this thesis is based on a British Columbia case study of a lodgepole pine forest. British Columbia was chosen for its unique political and geographical characteristics and lodgepole pine for its hardiness and ubiquitousness across the province. Lodgepole pine is B.C.'s most widespread tree species and provides habitat and food for many wildlife species (Sullivan et al. 2001). As well, lodgepole pine can grow in many different environments and seems to respond very well to intensive management and grow well after disturbances (Koch 1996). Lodgepole pine is a soft wood with many uses such as plywood, paneling, furniture, doors, windows, fence posts, and railway ties.

Each timber firm has a unique contract with the government delineating the amount and area within which harvesting can take place. These contracts range from 5 to 25 years and are either renewable or replaceable. Although the firm theoretically can continue to harvest timber in perpetuity by renewing or replacing their licenses, the Ministry has the ultimate authority to redistribute property rights from tenure holders to other tenure holders or other parties. For example, recently the British Columbia Ministry of Forests undertook a redistribution effort to allocate tenure to small business owners through a market-based auction, auctioning off tenure that had been part of a take back from larger license holders. As well, there was some redistribution from existing tenure holders to other interest groups including first nations. This type of unilateral power to re-distribute the forest resource decreases the security of tenure for the original licence holder/firm and creates a situation where the firm may not reap the long-term rewards from its

investment. Timber firms in BC have the freedom to choose whatever amount of silvicultural investment maximizes volume (profits). Firms can of course also invest in explicit environmental management at the expense of volume. This latter investment decision will only happen if the firm has the right incentives.

BC forestry is characterized by a lack of full property rights to long-term investment returns for the private investor (Zhang and Pearse 1996 & 1997). Thus, silviculture and any other socially optimal investment must be made by the public (or by private licensees as a result of regulation or a modified incentive schedule) since private investors have little incentive to invest beyond their private optimum. Basic silviculture (e.g. tree planting) is generally the responsibility of the tenure holders as outlined in the tenure licenses. There are basic minimum levels of environmental investment that the firms are required to make to ensure adequate timber inventory and basic environmental quality. However, incremental (intensive) silviculture (site rehabilitation, thinning, pruning fertilizing etc...) is generally not part of license agreements nor is more extensive environmental investment. Incremental silviculture has not been a priority for BC governments. Despite BC's lack of investment in post-planting silviculture, the literature suggests that careful investment in the resource will contribute to increased volume and quality of timber (Jokela et al. 2004, Rotherham and Mooney 1988).

## 1.5 Forest Relationships: An Overview

The co-products of a well-managed forest can include environmental outputs such as biodiversity, wildlife habitat and carbon sequestration. Biodiversity and wildlife habitat are essential components to a healthy, thriving forested landscape. Carbon storage and sequestration play an important role in reducing carbon dioxide in the atmosphere.

Terrestrial carbon sequestration occurs when trees remove carbon from the air and store it in the soil and the biomass. The carbon can be stored for long periods particularly if the trees are not harvested for many years and/or harvested and used for long-term timber end uses such as housing. The production of both carbon sequestration and biodiversity “outputs” also involves trade-offs. Since carbon storage is a function of a stand’s volume (the rate of growth), an investment like fertilizer might enhance this output and speed up the growing process, however, trees that are grown more quickly using fertilizer will not necessarily yield biodiversity and wildlife habitat characteristics if the stand is harvested in a shorter time frame. As well, if the goal is carbon storage, then a plantation style forest with fast-growing trees, all at identical successional stages, may be optimal.

However, this type of forest will likely not generate a significant amount of biodiversity and may not accumulate carbon permanently in the soil (Schultze et al. 2000), but instead may provide ample habitat for plant and animal species in young seral stages. An older natural forest landscape with many different seral stages of growth is likely to be high in biodiversity, whereas the rate of carbon sequestration would be less as the trees get older. The economic and environmental trade-offs within a forest present policy makers with a unique policy challenge.

This thesis will incorporate the simplifying assumptions and correlations stated above to evaluate the potential that a forest has to provide economic and environmental outputs. The results provide a starting point for policy-makers to incorporate multiple objectives using only a few specific inputs. Several forestry policies that use rotation time and firm investment into the timber stand are compared. The theoretical economic model used for this comparison can determine the most effective policies for achieving an optimal balance of environmental and economic outcomes from the forest. The framework is economic, as each output is measured monetarily in a social welfare function. The objective is to get an understanding of what role rotation time and investment play in generating different levels of economic and environmental value in society. Both inputs increase timber volume up to a point and also can enhance the environmental outputs of a forest if managed properly. Forestry investment in this chapter is two-pronged. The first investment is into volume-enhancing silvicultural practices that also enhance environmental value. After a given amount of silvicultural investment has been made (and once the volume-silviculture effect is maximized), the investment shifts to practices that enhance environmental outputs (biodiversity, soil carbon and wildlife habitat) at the expense of volume. For example, a forestry firm may respond to a given policy by shortening their rotation time and maximizing their silvicultural investment (to enhance volume) but choose not to explicitly invest in protecting old growth habitat on their forestland. As a result of these choices, the levels of profit, volume, biodiversity and carbon sequestered produced from that particular forest stand will be affected. The assumptions made about the relationships between these inputs and outputs in a forest stand will drive this model.

The challenge that faces forest policy-makers is to effectively manage a multiple output industry using relatively simple and efficient policy tools. The joint production objectives of the forest industry can be managed using a myriad of different price, quantity or hybrid tools. Environmental economics literature has recognized the complexity that joint production brings to policy making (Lichtenstein and Montgomery 2003, Rose and Chapman 2003, Nalle et al. 2004). Competing forest values may further aggravate this complexity, creating a very difficult policy environment. Each forest output may correspond to a social objective, for example, timber corresponds to profit, while biodiversity corresponds to environmental quality, potentially requiring a policy tool for each objective if the objectives are independent or even conflicting.

In the case of a society that values timber, carbon sequestration, biodiversity and employment, there may be a simpler solution. Many of the forest outputs (such as timber and carbon sequestration) can be produced simultaneously given the same inputs (age of the trees and silvicultural investment). The same management strategies (inputs) used for forest production discussed in the previous paragraph, namely rotation time and stand management, can potentially create positive externalities within that forest such as biodiversity and carbon sequestration. The relationships that each of the forest outputs share with the primary inputs create the opportunity for policy makers to employ a single policy tool to achieve multiple objectives. There are many obvious benefits to using a single policy, which include simplicity, accountability, lower administrative and monitoring costs and easier evaluation of the policy. It must be noted that there are circumstances where multiple policy tools are more effective than single tools. When

there are several outputs that are substitutes in the case of harvesting timber and maintaining pristine wildlife habitat, two or more policies to target each of these outputs individually may be the only solution. However, in the economic model outlined below, the symbiotic interactions between the inputs and outputs of the forest allow a number of different single-tool policies to be examined and compared.

## **1.6 Thesis Organization**

The thesis is presented in the "chapter format" which is one of two options available at UBC for theses formats. Unfortunately this results in some duplication of written material. Every effort has been made to reduce any repetition. The thesis consists of 6 chapters. The rest of the thesis will be organized as follows. Chapter 2 includes the general theoretical model. Chapter 3 presents the model's simulation results and sensitivity analyses. Chapter 4 introduces heterogeneity as a variable. Heterogeneous forest stands are added to the original model and their impact is evaluated for each policy. In chapter 5, a BC forestry case study is presented. The economic and environmental objectives for a specific forestry region in the southern interior of BC are examined. Given these objectives, the original model is parameterized to represent the specific region and to evaluate the possibility of improving overall social welfare in BC's southern interior. Chapter 6 highlights the key findings from each chapter and presents overall conclusions and policy implications from the thesis. The appendices present the mathematical simulations and results.

## **2 The Theoretical Model**

### **2.1 Introduction**

This chapter focuses on forestry policy alternatives, within a profit-maximizing context, and addresses the question can social welfare be improved through the production of economic and environmental outputs from a timber stand. Martin Faustmann's (1849) profit equation, as modified to represent a British Columbia second growth timber industry with explicit stand management investment, was chosen because it has been used in previous B.C. economic forestry research (van Kooten et al. 1995, Zhang 2001) and provides a basis to conduct a comparative analysis of forestry policy. In this thesis the focus is how a timber firm, who is faced with a number of different forestry policies that address rotation time, investment and environmental output, can maximize the profit equation. Previous work has been done looking at the impact of policies on rotation age with economic and environmental outputs (van Kooten et al. 1995, Rose and Chapman 2003). The optimal rotation when environmental values are considered has also been explored (Alaouze 2004, Gutrich and Howarth 2007). Faustmann's formulation has been rearranged in many ways to include the influence of tenure, property rights and incentives on conservation and environmental quality (Zhang 2001, Zhang and Flick 2001).

There have been criticisms of the Faustmann model as a result of several limiting assumptions. Some of the limitations of the model include the assumption of an even aged stand, which is often not the case in a forest where certain stands have never been

harvested and thus represent a mixed-age stand. The Faustmann model assumes that forest stands are homogeneous, abstracting from the natural heterogeneity of timber stands. The model also assumes that economic variables, such as prices and discount rates, are constant overtime. These limitations have been identified in the literature (Paarsch and Rust 2004) and the approach taken in this thesis addresses these concerns. In BC, second growth forest stands are becoming more important to the industry, which means that even-aged stands are common. This paper deals exclusively with second growth stands that are even-aged, since planting took place for the entire stand at time zero. The issue of stand heterogeneity is addressed in the fourth chapter. Costs are not always static in the model, for example, in the initial analysis silvicultural costs are a function of stand age and in the case study timber price varies with rotation time. Although the other costs and prices are constant overtime, the sensitivity analysis uses prices and discount rates that have been modified to ensure that the model's results are robust. In the sensitivity analysis two different discount rates are simultaneously applied to the model, to capture the effect of a social discount rate that differs from the firm's discount rate.

The modified Faustmann model used here has a private timber firm maximizing net present value of profits over infinite rotations and in the unconstrained case, the firm chooses both stand level investment and rotation time. The firm's optimization problem will be modified to incorporate a number of different forestry policies. Social welfare from each policy is generated and compared to determine the optimality of the policies. The objective of this analysis is to determine the effect of different policies on a firm's

behaviour and the subsequent impact this behaviour has on economic, social and environmental output. How each policy performs relative to the others is an indication of the potential that a given policy has to achieve society's desired forestry objectives. For the purposes of this analysis, a timber stand is a segment of harvestable land over which a given timber firm has some jurisdiction and which will, as a result of the biological potential of the land and the firm's decisions, produce a given amount of timber volume and environmental output.

One of the most important features of the model is the inclusion of stand management investment as an explicit decision variable for the firm. By allowing the firm to choose the level of investment, the impact of the policy on firm behaviour is captured even in those policies that restrict rotation time.<sup>1</sup> The firm's investment decision is twofold: first whether or not to invest in volume enhancing silviculture and then once this investment maximizes its effect on volume, whether or not to invest in explicit environmental stand management. There is asymmetry of information in this model, which manifests as the government being unable to observe the firm's type of investment. From the government's perspective, the firm's decision is to choose its level of investment in general stand management. Intuition would suggest that an unconstrained firm's privately optimal levels of both rotation time and investment would fall below the socially optimal levels. This is likely to be the case, since rotation time and stand investment enhance carbon and biodiversity-wildlife values beyond the levels that maximize firm profit. Since social welfare is positively correlated with these environmental outputs, it is

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<sup>1</sup> In early simulations of my model, the firm was given the freedom in certain cases to choose rotation time when investment levels were set by policy. The results did not reveal anything insightful beyond what has been gathered from the policies that set rotation time, and thus for simplicity are not included in the paper.

possible that the government would want more of both inputs. The model reveals whether or not there is a role for forestry policy to enhance social welfare by influencing the firm's rotation time and investment decisions.

This thesis extends the previous research by approaching the joint production problem from a broad social perspective that is explicitly integrated into the economic model. Carbon sequestration and biodiversity-wildlife components are included in the model to explore the potential for a single policy to enhance economic and environmental outputs simultaneously. Firm revenue and government expenditure are included in the model to account for the value of the industry to society (e.g. employment) and the cost of the policies on the public and private sector. The policies that are compared in the model include policies in which the government sets rotation time and others where the firm chooses rotation time. In all cases, the firm chooses its level of investment. Under certain policies, the government subsidizes the firm's stand-level investment and with other policies, the firm pays for their investment. The environmental subsidy policies involve the government compensating the firm for any environmental value created on the timber stand through a rotation. These various policy options offer an extension to the existing literature by providing policy makers with a broad selection of policy tools. Political and institutional factors play an important role in policy making, particularly when addressing value-laden issues such as environmental and social objectives. As a result, exploring a wide range of policy options gives additional information about the most efficient policies and also allows policy makers to choose a policy that will be effective given the political and institutional context.

The model is broken down into two-stages. In the first stage, the resource owner (government) sets the policy to maximise social welfare. Social welfare is assumed to be a weighted sum of firm revenue, value of carbon sequestered, value of biodiversity-wildlife and any net government expenditure from subsidy or tax policies. In the second stage, the firm maximizes profit given a specific policy and depending on the parameters of the policy, the firm chooses both rotation time and investment or just investment. The government then incorporates the firm's choices for rotation time ( $t^*$ ) and investment ( $s^*$ ) into the volume and environmental functions to determine the value of the social welfare function (SWF).

An economic stand-level analysis is used to capture the theoretical results of forestry policy and firm behaviour. There has been some work done highlighting the importance of landscape or forestry-level analysis as opposed to stand-level analysis (Tanz 1998). The issue is that stand level analyses can provide information about specific stand investments and practices and their effect on local environmental outputs. However, a landscape analysis is more effective at understanding the broader impacts of forestry practices on an economic, social and ecological system (Spies 2005). Landscape analyses in BC are rare and complex (personal communication with Thomas Sullivan). However, the two approaches need not be as distinct as some would argue. A forest stand is a recognizable feature of a landscape and from an ecological perspective, the vegetation in a stand should reflect the micro-environmental conditions that helped shape the vegetative community or forest. Thus, for a small enough scale, such as the one used in this study, the stand may be considered a "landscape" unit.

The contribution of this analysis to the current field of study is three-fold: firstly, the traditional Faustmann profit equation is modified to incorporate an investment decision variable for the firm. Secondly, the social impact of the firms' decisions (and the various government policies affecting the firms' decisions) is measured in the accumulation of two environmental amenities: carbon sequestered and environmental output including biodiversity. Thirdly, the research looks specifically at second growth timber to capture the economic and environmental impact of this growing industry at a particularly precarious economic time for B.C. forestry.

## 2.2 The B.C. Example

The British Columbia forestry example motivates the research questions and provides some general base case parameter values for the simulations. B.C. forestry is characterized largely by public ownership and private production. The incentive structure facing BC forestry firms provides a unique context for exploring silvicultural investment-focused policies and their impact on the social welfare of this region. The incorporation of property rights and government-subsidized silviculture are based on BC's forest industry. A firm's choices about investing in intensive silvicultural practices are based on the British Columbia license agreements, which dictate that firms must invest in basic silviculture, which is essentially reforestation or planting of seedlings at the beginning of a rotation. Intensive or incremental silviculture is primarily left to the discretion of the firm but the majority of investments in BC are done by the government. As forestry in British Columbia transitions from old growth dominated timber to an increased reliance on second growth output, even more intensive management of forest stands is required to ensure adequate levels of timber volume (van Kooten and Wang 2001). There are also an increasing number of environmental objectives that are important to British Columbians. Terrestrial carbon sequestration, biodiversity, and other environmental outputs must be managed alongside timber. There is a need for policy to address economic and environmental demands as B.C. forestry transitions to second-growth, at a time of heightened environmental awareness. In chapter five, the BC case study is used to extrapolate the model's theoretical findings to a real world forestry example.

## 2.3 Literature Review: Economics of Silviculture

### 2.3.1 Silviculture and Timber

Increased inputs into timber production, such as rotation time and timber stand investment, contribute to timber volume, which in turn can contribute to positive environmental benefits such as biodiversity and carbon sequestration. Intensive fertilizing and pre-commercial thinning have been shown to increase diameter and wood production of lodgepole pine in British Columbia (Lindgren et al. 2007, Brockley 2005 & 2007). Lindgren et al. (2007) showed that after a ten-year repeated fertilization and thinning project on lodgepole pine in BC, “[a]t the tree level, fertilization treatments significantly increased diameter at breast height (DBH), basal area (BA) and volume growth and [pre-commercial thinning] significantly increased DBH and BA growth” (p. 587). A similar study by Jokela et al. (2004) on intensive management of loblolly pine in several different geographical regions across the southern United States, reported that on average the fertilized stands showed a 2 to 3.5 fold increase in growth response compared to the untreated stands, while the thinned stands had larger diameter. Economists have also evaluated optimal silvicultural strategies and they were found to depend on species type and investment return (Lu and Gong 2005). The combination of fertilization and appropriate thinning (densities should be relatively high to maintain volume) can increase lodgepole pine volume. Although diameter may increase in thinned stands, creating more sawlogs, the effect on volume may not be positive in the short run. As trees are removed from a site, the fewer larger trees likely generate less overall volume than the higher

density stands. In the long run, however, the larger diameter compensates for the loss in height and number of trees and results in greater volume or at least comparable volume (personal communication with Thomas Sullivan<sup>2</sup>).

As tree diameter increases due to thinning, the density of the growth rings inside the tree is reduced, with the rings more widely spaced from one another. This type of tree grown at increased growth rates is called juvenile wood. The advantage of larger stems is a premium for sawlogs as well as increased lumber output, however, the economic implication of juvenile wood is a reduction in the strength of the wood and in construction terms, a reduced mechanical stress rating (MSR) (Jokela et al. 2004, Rotherham and Mooney, 1988). Dimensional (structural-grade) lumber is used for construction and often requires a high MSR (personal communication with Tom Sullivan, 2004). Although pre-commercially thinned stands may increase the size of timber logs and thus may increase total volume in the long run (if increased dbh > decreased height), there is a trade-off in structural quality. Machine stress rated lumber, however, comprises only 5% of the total North American market for timber products (personal communication with Ralph Winter and Rob Kozac)<sup>3</sup>. The other 95% can be used as construction lumber but has limitations as support lumber. Thus, the importance of non-structural rated lumber is possibly more significant for B.C.'s timber industry. There is an optimum stand density according to the Ministry of Forests and Range in B.C., which is between 1200 and 1600 stems per hectare (sph) depending on the species. The MFR determined that these densities would enable higher quality (structural quality) lumber

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<sup>2</sup> Thomas Sullivan, Professor, Faculty of Land and Food Systems, The University of British Columbia.

<sup>3</sup> Rob Kozac, Associate Professor, Department of Wood Sciences, University of British Columbia

while taking advantage of the increased volume from thinning (Middleton et al. 1995). The literature suggests that fertilizer combined with moderate thinning can enhance timber volume, a result that will play an important role in this theoretical analysis.

### 2.3.2 Biodiversity-Wildlife Component

Biodiversity is defined by Hunter as ‘the diversity of life in all its forms and at all levels of organisation including all its processes’ (Hunter 1999). Different seral stages of growth at any one time within a forest landscape may provide the most diverse habitat opportunities for wildlife and the greatest biodiversity (Rose and Chapman 2003). Early, middle and later seral stages provide different types of forest edge and interior habitat for a range of different species, thus creating the most diverse mosaic of biological life (Rose and Chapman 2003, Gustafson 1996, DeLong and Lamberson 1999). Focusing on a single-aged stand at any given time will not maximize the biodiversity-wildlife value. This thesis will assume there is biodiversity-wildlife value in young stands as well as in older stands. The importance of biodiversity and habitat seems evident but the relationship between forestry practices and biodiversity has been a difficult one to measure. As rotation time of a given harvestable area is extended, particularly up to a threshold level, biodiversity is accumulated (Rose and Chapman 2003). There seems to be some consensus that there is an increasing relationship between forest biodiversity and time (Hunter 1990, Sullivan 2000), however, there is debate about the impact of timber management on plant and animal biodiversity (Gamlin 1988, Hunter 1990, Kladtke and

Kenk 1997). There has been some empirical research exploring the impact of intensive management on plant and animal biodiversity and habitat (Sullivan et al. 2000, 2001). In 1993, Sullivan et al. tested the effectiveness of intensive management, including varied degrees of pre-commercial thinning and optimum nutrition fertilization, on timber and environmental outputs at an operational scale on second growth lodgepole pine in B.C.'s Interior (Sullivan et al. 2006a & 2006b, Lindgren et al. 2007). The group measured the effect of thinning and fertilizing on timber yields, stand structure, and biodiversity. Specifically, the study measured the impact of the management regime on plant and animal diversity in order to gauge the extent of the environmental impacts of this type of intensive management. The low density fertilized stands produced old growth characteristics and had more species diversity than the higher density (less managed) stands (Sullivan et al. 2006a & 2006b, Lindgren et al. 2006). The results indicate that intensive silviculture consisting of thinning and fertilizing has a positive effect on biodiversity and wildlife habitat by moving generating characteristics that are associated with later seral stages.

Soil carbon is also enhanced with time (Shultze et al. 2000). The older the stand of trees, the more carbon is stored in both the trees and the soil in a relatively more permanent sink, up to a threshold level since trees will eventually decay or burn and the carbon will be released. Biodiversity, wildlife habitat and soil carbon respond positively to some of the primary timber inputs. There are also other less tangible externalities from timber management that create old growth characteristics in second growth forest stands such as spiritual, recreational and intrinsic natural values (Hunter 1990 & 1999).

### 2.3.3 Carbon Sequestration

As trees grow, they remove carbon dioxide from the air around them and replace it with oxygen. This process is referred to as terrestrial carbon sequestration. The rate of tree growth determines how much carbon is sequestered (van Kooten et al. 1995). Once it is sequestered the tree biomass stores this carbon until it is either released back into the atmosphere, as in the case of fire, decomposition, or harvest for short term ends such as pulp and paper, or it is stored in the timber biomass if the trees are harvested for long term ends such as lumber for construction. Carbon is also stored in the soils and vegetation surrounding the timber. The potential role that forests could play in mitigating adverse climate trends has been extensively assessed and found to be potentially significant because of the low marginal cost of sequestration through forestry (Dixon 1994, Stavins 1995a).

The relationship between stand age, harvesting and carbon sequestration is complex but scientists have raised several key points. There is a loss of carbon during the harvesting process and, according to Schulze et al. (2000), old growth forests store carbon for a much longer period than forest products. This loss due to harvesting may result in second growth stands sequestering little carbon, increasingly with the greater frequency of harvesting and other disturbances (Brainard 2006). Schulze et al. (2000) also argue that “terrestrial forest ecosystems do not reach an equilibrium of assimilation and respiration and act as net carbon sinks until high ages” (Ibid, pg. 2059). These authors claim that

carbon accumulation in a permanent pool (compared to a temporary pool in younger stands) increases exponentially over time. By harvesting old growth and replacing it with second growth, there will be a large net loss of carbon into the atmosphere (Schulze et al. 2000, Harmon et al.1990, Vitousek 1991). Intensively managed second growth stands provide an alternative to old growth sites for harvest, thus avoiding the carbon loss from converting old growth stands, and also potentially increasing total terrestrial carbon sequestration through increased biomass, soil carbon and a larger inventory of long-term end-use wood products. Younger managed stands have been shown to have higher rates of carbon fixation while unmanaged old growth stands store much larger quantities of carbon (Vitousek 1991). There could be a net gain in total carbon stored if second growth stands are intensively managed for higher carbon sequestration rates and more timber production, while remaining old growth stands are left untouched. Thus, as managed stands increase productivity and biomass through fertilization and other investments, they simultaneously take on more carbon. As a result, even second growth stands, the focus of this research, are able to store carbon both in situ and ex situ and can contribute to a reduction in atmospheric carbon levels.

#### 2.3.4 Tenure Security and Investment

Timber volume and revenue increase with silvicultural investment and rotation time creating positive environmental co-products such as carbon sequestration and biodiversity. However, the incentive for a timber company to invest in more than reforestation is a function of the magnitude and security of the returns on this investment.

There have been studies exploring the relationship between tenure security and silvicultural investment (Zhang and Pearse 1996, Luckert and Haley 1990) as well as tenure and reforestation (Zhang and Pearse 1997). Each of these studies points to a positive correlation between tenure security and forestry-related investment. There have also been studies exploring the effect of policy uncertainty on investment behaviour (Zhang 2001) that found policy uncertainty to have a similar effect to tenure insecurity on investment behaviour. The government's environmental objectives are incorporated into the analysis to account for the specific environmental externalities associated with this investment. To ascertain the effect of tenure security on investment decisions, a property rights variable will be incorporated and manipulated in a sensitivity analysis later in the thesis. Explicit environmental investment by the firm also impacts volume and environmental quality and is a function of incentives and the firm's level of tenure security.

### 2.3.5 Forest Policy

Over the past several decades, environmental awareness has prompted a significant body of work exploring the economics of environmental regulations including standards, incentive-based policies and market policies. Standards generally include direct regulation dictating a quantity quota that must be met by the firm. This can be an input such as a design standard or an output quota, such as a performance standard. Incentive-based policies give firms incentives, either positive or negative, to meet certain guidelines or targets, while market-based policies create a market (with a given target or quota for

the industry as a whole) for a given externality. This allows the firms to efficiently distribute the externality amongst themselves. Thomas (1980) conducted a welfare analysis of performance vs. design standards and found that welfare costs of a direct restriction were lower than for input requirements. Besanko (1987) examined performance standards, which regulate pollution directly with a quota, versus design standards, which regulate indirectly requiring a minimum usage of a given emissions control input. Price controls or incentive controls have also been compared to direct quantity controls in the literature. Economists tend to favour taxes/subsidies over quantity controls. Taxing emissions or subsidizing abatement instead of regulating an across-the-board reduction in emissions or output allows each firm to make decisions that are least cost for their particular cost structure, thus achieving an efficient industry-wide reduction. The firms with the lowest abatement costs will reduce the most and receive the greatest tax break or subsidy, while the firms who find abating prohibitively costly will reduce less and pay the tax (Baumol and Oates 1988; Hanley et al. 1997). Despite the appeal of using an optimal tax strategy, there is information required to implement the system that is often very difficult to obtain. For example, the marginal net damages caused by a given polluting activity corresponding to the optimal solution must be known for the tax or subsidy rate to be optimal. Baumol and Oates (1988) suggest setting an acceptability limit for environmental damage and then charging taxes based on achieving this limit, as opposed to trying to identify the optimal limit. This approach requires getting much more easily accessible information and is thus more easily implemented.

Despite the efficiency arguments in favour of price controls (once the informational requirements are met), governments in North America have consistently favoured

quantity controls (Glaeser and Shleifer 2001; Buchanan and Tullock 1975). Glaeser and Shleifer 2001 offer an explanation for this discrepancy. Although quantity regulations may constrain firms from making efficient choices, it is more costly for law enforcers to identify violators under a tax program than with quantity control (Glaeser and Shleifer 2001). The authors outline a clear example of this cost differential in the case of taxing liquor sales on Sunday vs. mandating liquor stores to close on Sunday. The difficulty and thus greater cost in identifying tax violators vs. observing whether or not a given store is closed, illustrates their point. Buchanan and Tullock (1975) give another reason that policy makers may have traditionally favoured quantity controls. The authors point out that when a specific type of quantity control is imposed, firms may experience less short-term loss than if a certain tax were imposed and thus will always prefer a quantity regulation (Buchanan and Tullock 1975). They argue further that the pressure exerted by these firms on policy makers, although ideally inconsequential, is influential and affects policy.

In the context of regulating terrestrial carbon sequestration as a positive environmental externality or carbon emissions as a negative externality, policy makers have several choices. Dales (1968) was the first to formally introduce the idea of creating property rights to efficiently deal with environmental externalities. Dales proposed that property rights be defined for a given environmental output (positive or negative) and that these rights be sold to the highest bidder (Dales 1968). Gutrich and Howarth (2007) evaluated the optimal management strategy for timber firms when carbon sequestration is a function of timber growth and rotation time. The authors found that the optimal forest

rotation is extended when the social value of carbon is recognized. Pollution permits would ensure that a given environmental target be met, whereas with taxes, the optimal level required to meet that target is difficult to estimate. As well, because the permits will be managed in a market context, prices will automatically be adjusted for inflation and economic growth. Another potential advantage of a permit system would be that if the permits were “grandfathered”, there would be no initial cost to firms, unlike under a tax system. Finally, permits are essentially quantity controls that are managed by the market and thus are a familiar form of policy, resulting in potentially lower implementation and administration costs (Baumol and Oates 1988). However, there are significant transactions costs associated with a permit system (Montero 1997, Stavins 1995B) as well as a loss of revenue if permits are grandfathered, relative to a tax.

The simulations discussed include both policies that regulate the firm’s rotation time and others that allow the firm to freely choose its’ rotation time. Regulating rotation time, which is an input to timber production, can also be thought of as a design standard. By regulating the rotation time for a firm’s harvesting, forestry managers are allowing the firm to make certain other input decisions, such as investment. These input decisions are driven by the firm’s profit maximizing behaviour and subsequently determine the forestry outputs. The information required to implement effective design standards for forestry is the correlation between rotation time input and volume and also potentially between rotation time and environmental outputs. Science suggests that time is positively correlated with both carbon sequestration (Schulze et al. 2000) and biodiversity accumulation (Hunter 1990 & 1999) and volume. This would imply that given policy

makers' specific economic and social objectives, they could set a rotation time to maximize their social welfare. Since the firm's other decision variable, stand management investment, is also initially positively correlated with volume, and thus profit, and indirectly with the environmental outputs, the firm may be able to reinforce the policy makers' desired outcome by choosing a profit maximizing level of investment. The outputs or performance results in this case are timber volume, net carbon sequestration and biodiversity accumulation. A performance standard in the case of forestry would require a significant administrative and implementation cost since the firm's cost structure would have to be ascertained by the policy makers in order to accurately assess the correct profit-maximizing output. As a result, for this study, design standards are implemented and compared to unconstrained profit maximizing behaviour as well as to price policies.

This chapter focuses therefore on two main policy types, standard input policies with and without government subsidy and price policies. Input policies allow firms to choose their levels of investment, with and without a government subsidy, but the firm is restricted to a certain rotation time. These input policies were chosen because in B.C., the government pays for the majority of the incremental silvicultural activities that takes place on tenured land. As a result, the input policy tool that sets rotation time with and without a subsidy will explore the impact of subsidies on the firms' decision-making in a similar setting to B.C.. As well, setting a rotation time is a much simpler policy to monitor and enforce than setting levels of investment and thus a more realistic policy option. To explore the impact of a price policy when there are positive environmental externalities from a firm's

behaviour, subsidy and taxation policies were implemented following van Kooten (1995). For simplicity and ease of administration and monitoring, price policies were chosen instead of permits in the forestry industry. The carbon and environmental subsidy (and carbon tax) are used to determine the social welfare benefit of compensating a firm for its net environmental outputs. Taxes and subsidies are not equivalent in this case for carbon since carbon accumulation is subsidized through a rotation and carbon is only subject to tax after it is released at the end of the rotation, which is only equivalent if there is no carbon stored in timber products. As well, the carbon subsidies offer incentive for firms to enter the industry whereas taxes offer no such incentive (Baumol and Oates 1988). An output policy was initially implemented in the model, setting a firm's timber harvesting at a percentage of its total harvestable output, however, the results indicated that this policy was never preferred to any other policy and is not included in the results.

#### 2.3.6 Faustmann Equation

Standard economic theory postulates that a firm's objective is to maximize the net present value of its profits, defined as discounted total revenues minus total costs. Assuming that the firm is free to modify inputs and outputs as it chooses (a long run scenario), the firm will maximize profits by choosing from a set of non-fixed inputs subject to certain constraints. In a perfectly competitive market where firms are price takers, the profit maximizing result is that price (marginal revenue) minus marginal cost must be equal to zero in the long run, or that marginal revenue must equal marginal cost (Varian 1996). In the timber industry, the production function is essentially a biological

or natural growth function and is defined by the relationship between timber output (volume), input (investment) and time (harvest cycles). The relevant variables for a timber production function include age of the stand, quality of the land and level of management effort (Wear and Parks 1994). Management effort includes an initial establishment input (e.g. planting or regeneration) and then subsequent investments over time.

The traditional economic formulation of the profit function taking into account this optimal harvesting problem was prepared by Martin Faustmann (1849). The Faustmann model determines the optimal rotation length for an even-aged stand and maximizes the discounted timber revenues less the discounted production costs, assuming constant prices and a known timber yield function. The firm's optimal harvesting and profit maximization problem can be solved using unconstrained maximization. The partial derivatives of the objective function with respect to the two decision variables, namely rotation time and input, are set equal to zero and solved simultaneously (Jackson 1980).

There have been several efforts over the past hundred years to move beyond Faustmann's formulation to capture more of the complexities motivating real timber harvesting decisions, including multi-objective forestry management (Hartman 1976), uneven aged stands (Adams and Ek 1974), input costs (Hyde 1980) and stochastic prices (Norstrom 1975). The Faustmann equation has also been modified to account for silvicultural investment by Jackson (1980) and Zhang (2001) and to incorporate specific environmental values within the forest (van Kooten et al. 1995 and Creedy and

Wurzbacher 2001). Luckert (1998) conducted a comprehensive study comparing different policies' effect on silvicultural investment behaviour by firms. The approach taken here differs from Luckert's in that a Faustmann equation is employed in this thesis to explore firm optimality conditions, both investment amount and rotation length, under different policy scenarios. Thus the Faustmann model is used as a comparative tool to evaluate alternative forestry policies. The Faustmann equation provides the necessary link between forest input, output and profit for a forestry firm.

There are several criteria for determining the optimal rotation time for the firm. One can maximize the physical volume of biomass to be harvested (maximum sustained yield overtime (MSY)). MSY is the maximization of the average volume function with respect to time.

$$\text{Max} \frac{v(T)}{T}$$

$$\frac{v'(T)}{v(T)} = \frac{1}{T}$$

The firm's timber profit from harvesting can also be maximized (generally referred to as the Fisher equation for one rotation only and the Faustmann equation for infinite rotations). There are other formulations of the firm's profit function as well including maximizing a combination of timber and non-timber values (Hartman 1976). For the purposes of this analysis a modified Faustmann model will be used, however, a brief overview of the traditional Faustmann equation is presented to initiate the research using

a more simplified intuitive case. The traditional Faustmann equation does not explicitly include silvicultural investment as a separate input from rotation time to include such things as thinning and fertilization. This has been integrated into the modified model.

Time is the only decision variable for the firm:

Fisher Equation (one rotation):

$$\text{Max}\pi(t) \rightarrow \text{Max}(p - c)v(t)e^{-rt}$$

$$\frac{v'(t)}{v(t)} = r$$

Faustmann (infinite rotations):

$$\text{Max}\pi(t) \rightarrow \text{Max}(p - c)v(t)\frac{e^{-rt}}{1 - e^{-rt}}$$

$$\frac{d\pi}{dt} \rightarrow \frac{(p - c)v'_t}{(p - c)v(t)} = \frac{r}{1 - e^{-rt}} \leftrightarrow \frac{v'_t}{v(t)} = \frac{r}{1 - e^{-rt}}$$

Where p is the price of logs sold at the mill, c is the cost of harvesting, v (t) is the output of logs as a function of time and r is the discount rate. This problem can be solved for the optimal Faustmann rotation age (t\*) by taking the derivative of  $\pi$  with respect to time (t) and setting it equal to zero.

## **3 An application of the Modified Model in a BC Context**

### **3.1 Methods**

#### 3.1.1 Simulations and Parameterization

The profit maximizing simulations and subsequent social welfare calculations were done using Mathematica 6.1©. Mathematica was chosen because it is a comprehensive mathematical program that has the capability to evaluate multiple functions within a single simulation. The program itself is relatively simple to program and has been used widely for complex simulations (Varian 1992). The simulations were set-up to first solve the firm's profit maximizing problem. The firm maximizes profit subject to a set of prices and costs and a given forestry policy. The firm chooses rotation time ( $t$ ) and investment ( $s$ ) levels to maximize profit. To check whether or not the maximization simulations were generating reasonable results, intuitive robustness checks were done. As timber prices rose or harvesting costs fell, *ceteris paribus*, the simulations showed higher revenue. As prices and weights of the environmental outputs rose, *ceteris paribus*, the value of these outputs also rose. As discount rates fell, *ceteris paribus*, revenue and profit increased, and the opposite happened when these rates increased. These checks were reassuring in that the model was operating correctly within the economic paradigm of profit maximization.

The optimal rotation time ( $t$ ) and investment level ( $s$ ) chosen produced an amount of timber output. This initial 'volume' was effectively a numeraire, meaning that the

magnitude was without units. To model a lodgepole pine timber stand in British Columbia, the output was calibrated, which essentially applied units of volume (cubic meters) to this output to reflect the size of an average lodgepole pine stand given rotation time and silvicultural investment (Dempster and Huang 2006a & 2006b and Lotan and Critchfield 1990). It was important for the volume function to be calibrated to capture the impact of investment and rotation time on timber output and for the actual units to reasonably represent a one-hectare timber stand. The rotation time chosen by the firm is in years and is a function of the relationship between volume and stand age. The optimal rotation time generates stand volume for a one-hectare stand. Firm investment units are consistent with a one-hectare timber stand. Once the firm's maximization produced optimal values of  $t$  and  $s$ , these values were used to calculate the social welfare's four components. The four components were all discounted at the same rate as the firm's problem. Revenue, government expenditure and carbon were calibrated the same way as volume, to keep the units and magnitudes associated with volume consistent.

Biodiversity-wildlife values were also calibrated. This calibration was done to provide a biodiversity-wildlife value that was reasonable within the timber stand context. The amount of biodiversity-wildlife value in a timber stand was assumed to be less than revenue and in the ballpark of the carbon value. This is clearly arbitrary since this environmental output is an aggregate of many different components, many of which are difficult to measure and price. The results from a sensitivity analysis on the price and weight of the biodiversity-wildlife value are presented to ensure that the calibrated value is not unreasonably affecting the results.

The firm's rotation time and investment levels were chosen based on a set of parameter values that reflect an average timber area in a region such as British Columbia.

Investment cost is a function of rotation time, since the older the stand the more investment takes place. For example, when fertilizing a timber stand, the optimal application frequency is every six years or less (BC FS 1995). The cost of silviculture was based on a range given by Thomas Sullivan for costs of thinning and fertilizing a stand of lodgepole pine in British Columbia (personal communication with Thomas Sullivan). Sullivan's average cost was approximately \$400/hectare for fertilizing and thinning. Since the cost of stand investment in this model includes not only incremental silviculture but also environmental stand management, the investment cost was higher.

The total cost depends on both the amount of investment and the rotation time and for the unconstrained firm making 7 units of investment for a 52-year rotation, the cost was around \$600 per hectare. The timber price of \$120/cubic meter was chosen based on data from the Ministry of Forests and Range where a range for timber prices was between \$0 and \$150/cubic meter (BC MFR 2001 & 2002). van Kooten et al. (1995) used a timber price within this range and a similar carbon price to the one used in this model (\$20/unit). Harvesting cost was set at \$80/cubic meter, which is higher than that set by Thompson et al. (1992) and van Kooten et al. (1995). BC's interior has average harvesting costs of roughly \$10,000 per hectare including harvest cost, tree to truck cost and hauling costs (BC MFR 2004). Depending on the volume within a one hectare stand (for this model it ranges from 100 to over 500 cubic meters), the cost then ranges from \$20 to \$100 per cubic meter. The harvesting cost in this model also includes the cost of basic silvicultural investments including planting and select seed investment. Select seed planting involves

choosing genetically superior seeds to increase timber supply. Basic silvicultural costs in BC's interior range from \$25 to \$3000 per hectare (BC Forest Service, 2004). When converted by timber volume, basic planting costs range from basically zero to \$30 per cubic meter. The total harvest plus planting costs could range from \$20 to \$130 per cubic meter of timber. The harvesting cost underwent a sensitivity analysis to determine its effect on rotation time and investment levels and the overall policy ranking. The carbon-volume ratio was set following Jessome (1977), and was also used by van Kooten (1995). The pickling rate for the initial simulations was set at 50%, the rate used by van Kooten et al. 1995, and a similar rate was found by Harmon et al. (1990). A sensitivity analysis evaluates the impact of all of these parameter values on the policy ranking and choices of rotation time and investment.

### 3.1.2 Firm's Profit Function

The profit maximizing timber company will be modeled using a traditional Faustmann formula extended to include a silvicultural investment decision variable for the firm. The Faustmann model assumes that the land is bare before the first stand of trees is planted, that the land is used only for timber, that there are no non-timber values and constant prices through time. This model sets up an optimization problem for the firm who maximizes the net present value of their profit over an infinite number of harvesting rotations. The forest area depicted represents an average lodgepole pine stand in British Columbia. An economic report on British Columbia's Coastal forests (Coast Information

Team 2004) indicates that the base case for timber volume in one of the Coastal timber regions is in the ballpark of 2 to 4 million cubic meters per year. The theoretical firm is managing a timber stand of around one hectare, which produces around 300 to 400 cubic meters of lodgepole pine timber (if timber volume is maximized as opposed to profit) at a rotation time of around 140 years with nominal incremental silviculture investment. Our model uses a base case discount rate of 3%, compared to the British Columbia Ministry of Forests' discount rate of 3.5%.

The production function (volume) for the firm is a function of time (t) and investment (s). The desired properties for the functional form of production are that it is increasing in both variables at decreasing rates up to a threshold level, and that the cross partial derivatives are positive. In other words, timber volume increases with both time and investment but at a decreasing rate (diminishing marginal returns) up to a threshold level of each input at which point volume falls in rotation time and investment. Both time and investment have a reinforcing effect on one another on volume.

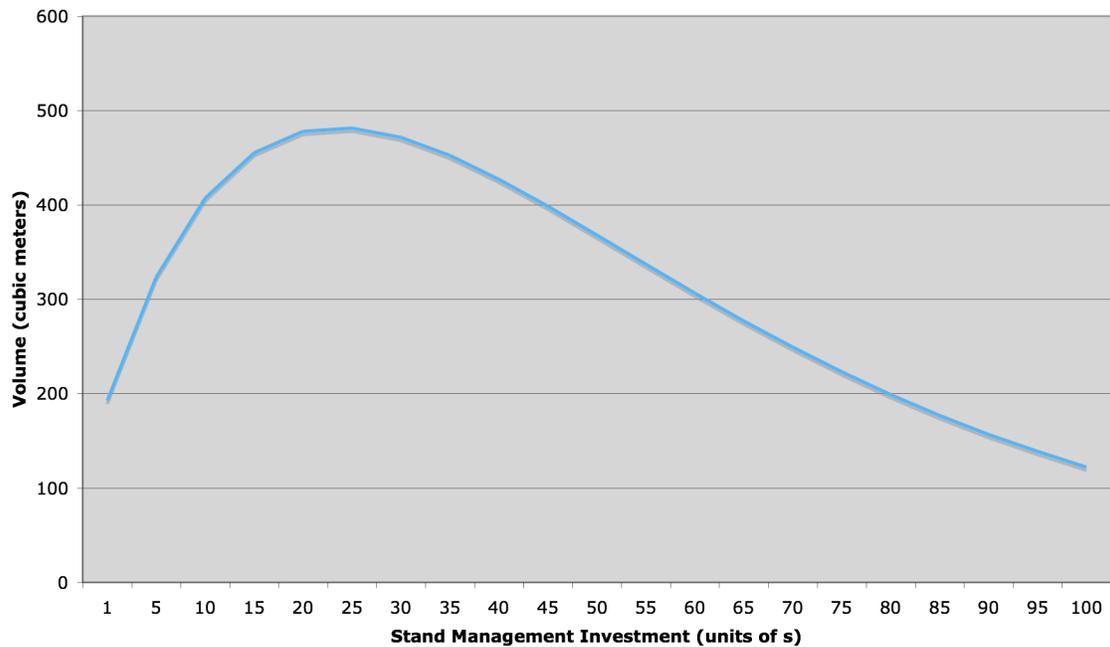
Any functional form that satisfies these criteria will be adequate for conducting the various manipulations on the model. The functional form of volume is a function of stand management investment (s) and rotation time (t):

$$v(t,s) = (st^5)e^{-0.035(t+s)}$$

Where  $v$  is stand volume,  $t$  is rotation time and  $s$  is investment in the form of fertilizer and pre-commercial thinning (and environmental investment after a certain point). The volume function used in the simulations generates a theoretical timber volume output for a lodgepole pine stand as a function of investment ( $s$ ) and stand age or rotation time ( $t$ ). The volume function is based on one used by van Kooten et al. (1995) which comes from a functional form used by Thompson et al. (1992) to represent a general timber growth curve for British Columbia. The function has been modified to reflect a lodgepole pine stand and to incorporate firm investment (see section 3.1 for more on parameterization and calibration). The volume function generates timber output in cubic meters ( $m^3$ ) as a function of rotation time ( $t$ ) and investment ( $s$ ).

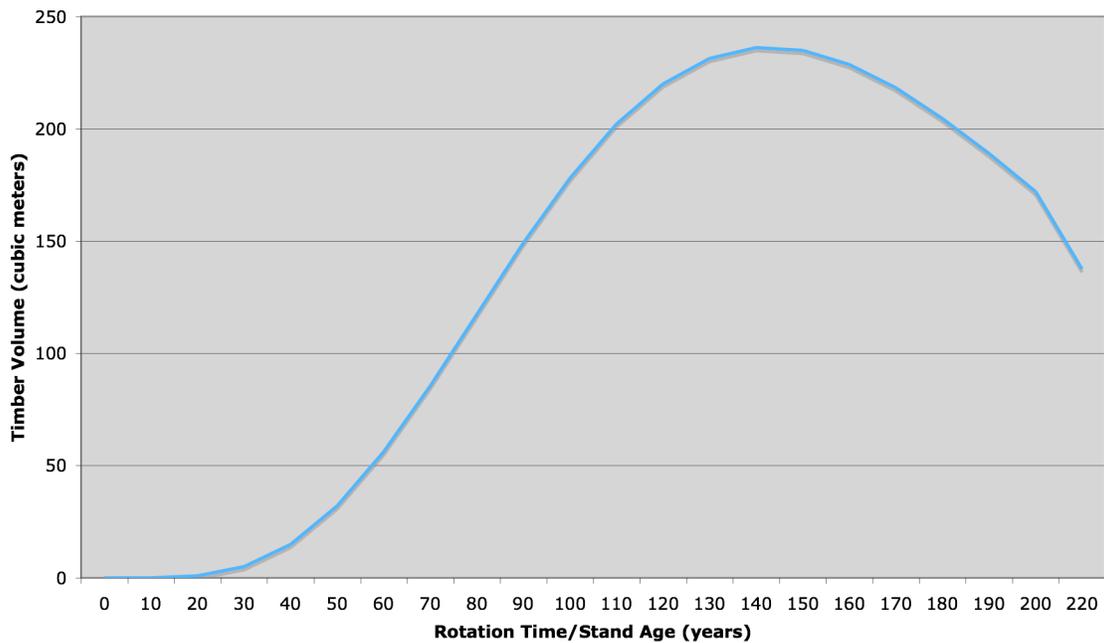
Figures 3.1 and 3.2 show the relationships between volume and inputs. The firm investment in the stand increases volume for the first 30 units, which are assumed to be silvicultural investment, such as fertilizer and thinning. For the rest of the investment, the firm becomes an environmental steward and invests in stand management that enhances the environmental quality of the stand at the expense of volume. Clearly, this environmental stewardship will only take place if there are proper economic incentives.

**Figure 3.1: Timber volume as a function of stand management investment (with constant rotation time)**



Timber volume peaks at just over 450 cubic meters when the rotation time is set within the range that the unconstrained timber firm would choose and there is a maximum amount of silvicultural investment. Rotation time increases volume up to a peak of approximately 140 years (Figure 3.2). This is reflecting an average lodgepole pine stand's volume function. Without any significant stand investment, timber volume peaks at around 230 cubic meters, less than the maximum achieved for a 70-year (not the volume-maximizing rotation length) rotation with more stand investment.

**Figure 3.2: Timber volume as a function of rotation time  
(with constant nominal investment)**



The firm's profit function is a function of  $s$ ,  $t$ , timber price  $p$ , harvest cost  $c$ , and unit cost of investment,  $w$ , a property rights variable  $\alpha$ , pickling rate (percentage of harvest that goes into long term storage)  $\lambda$ , and unit cost of pickling  $w_\lambda$ . The profit function is discounted over each rotation for infinite rotations with discount rate  $r$ . Note that the stand management investment is a one time lump cost at  $t = 0$  and thus is only discounted over infinite rotations, not within each rotation. The firm's modified profit function is as follows:

$$\text{follows: } \pi(t,s) = \frac{\alpha(p - c - \lambda w_\lambda)v(t,s)e^{-rt} - sw}{1 - e^{-rt}}$$

The profit function is maximized by the firm  $t$  solve for their optimal levels of  $t$  and  $s$ .

The first order condition is as follows:

$$\frac{d\pi(t,s)}{dt} = \frac{-e^{-rt}r(\alpha(p-c-\lambda w_\lambda)(v(t,s))e^{-rt} - sw)}{(1-e^{-rt})^2} + \frac{e^{-rt}\alpha(p-c-\lambda w_\lambda)\frac{dv(t,s)}{dt} - e^{-rt}r(\alpha(p-c-\lambda w_\lambda)(v(t,s)))}{1-e^{-rt}}$$

This simplifies to:

$$\frac{d\pi(t,s)}{dt} = \frac{e^{-rt}}{(1-e^{-rt})^2} \alpha(p-c-\lambda w_\lambda) \left( (1-e^{-rt}) \frac{dv(t,s)}{dt} - r(v(t,s) - sw) \right)$$

Which means that  $t^*$  is found by solving the above for the firm's optimal rotation time.

For investment (s):

$$\pi(t,s) = \frac{\alpha(p-c-\lambda w_\lambda)v(t,s)e^{-rt} - sw}{1-e^{-rt}}$$

$$\frac{d\pi(t,s)}{ds} = \frac{e^{-rt}\alpha(p-c-\lambda w_\lambda)\frac{dv(t,s)}{ds} - w}{1-e^{-rt}}$$

Which simplifies to:

$$w = e^{-rt}\alpha(p-c-\lambda w_\lambda)\frac{dv(t,s)}{ds}$$

and so  $s^*$  is found where  $\frac{dv(t,s)}{ds} = \frac{e^{rt}w}{\alpha(p-c-\lambda w_\lambda)}$ , or in other words the firm's

unconstrained optimal level of silvicultural investment.

### 3.1.3 Social Welfare Function

Once the firm solves its profit function, the values for  $t$ ,  $s$ , volume and revenue are incorporated into the government's social welfare function. Each policy motivates a unique solution from the firm and then the corresponding social welfare function values are compared across policies. The social welfare function is a summation of four components: firm revenue, government's net expenditure from a subsidy or tax policy, the value of carbon sequestered from standing biomass and harvested long-term timber products, and the value of biodiversity-wildlife that is meant to capture any residual environmental value from the forest in terms of biodiversity, wildlife habitat, soil carbon and other intrinsic values.

After social welfare is calculated for each policy, the relative ranking of the policies can be determined for a government who includes the biodiversity-wildlife value as a significant priority and for one who does not. The results of this model will reveal the impact of each policy on social welfare. This is essentially just the relationship between the rotation time and investment for a given policy and the environmental output accumulated at that stand age. A policy that requires a forestry firm to harvest only after 100 years would likely create more biodiversity or soil carbon than a policy that allows the firm to choose its own rotation age unconstrained, which could be around 60 or 70 years. Thus, a forestry manager who cares only about biodiversity would favour a policy with a longer rotation time. The relationship between rotation time (stand age) and environmental output accumulated may produce a different ranking of policies. This

ranking may illuminate (for environmentally-focused policy makers) the impact of using rotation time and/or investment as policy tools for increasing social welfare. Each component in the social welfare function is also weighted to allow for a comparison of policies given different social priorities. A simplified version of the social welfare function is presented first and then followed by the more complex version:

SWF =

Firm Revenue + Net gov't expenditure + Value of Carbon Sequestered + Biodiversity-Wildlife Value

The actual social welfare function is as follows:

$$swf(t,s) = aP_t v(t^*,s^*) + bGE + cP_c c(t^*,s^*) + dP_e e(s^*,t^*)$$

$$v(t^*,s^*) = (st^5)e^{-0.035(t+s)}$$

$$c(t^*,s^*) = \frac{\gamma(\lambda)v(s^*,t^*)e^{-rt^*} + \int_0^{t^*} \gamma r v(t^*,s^*)e^{-rt} dt}{1 - e^{-rt^*}}$$

$$e(t^*,s^*) = (st^5)e^{-0.01(t+s)}$$

Where  $a, b, c, d$  are weights and  $P_t, P_c, P_e$  are prices on timber (for revenue), carbon sequestered, and the biodiversity-wildlife component respectively.  $v(t^*,s^*)$ ,  $c(t^*,s^*)$  and  $e(t^*,s^*)$  are the value of the volume, carbon and biodiversity-wildlife outputs at the firm's optimal  $t^*$  and  $s^*$ , discounted over infinite rotations. The revenue component is taken directly from the firm's profit maximization. Government expenditure is a function of the

policy implemented and the cost of any subsidy or tax for firm investment, carbon and/or biodiversity-wildlife output.

The carbon component is modeled after van Kooten et al. 1995. The value of carbon sequestered is the discounted sum of carbon stored in long-term timber products after harvest,  $\gamma$  is the conversion ratio of timber volume to carbon sequestered, and  $\lambda$  is the pickling rate and the accumulated carbon in biomass during the rotation period. The biodiversity-wildlife function is an inverted-u shaped curve, accumulating value up to its peak at roughly 450 years after which point it starts to drop off. This biodiversity-wildlife function closely mimics the form of the timber volume curve, however it peaks much later, at around 500 years. The function is based on the assumption that as the stand ages and is not harvested, environmental value is accumulated (Hunter 1990). The functional form suggests a positive correlation between environmental output and both rotation time ( $t$ ) and stand management investment ( $s$ ). The little research that has been done looking at silvicultural investment and its impact on habitat and biodiversity suggests that there is a positive correlation between silviculture and biodiversity (Sullivan 2006a, 2006b). This positive correlation between biodiversity and silviculture is used to support an assumption in the model that firm investment enhances the environmental output at a decreasing rate.

The biodiversity-wildlife function is increasing in rotation time at a decreasing rate overtime. However the relationship between this environmental output and stand management is less intuitive and equally important. The assumption from the

biodiversity-wildlife function itself is that environmental output is increasing in investment at a decreasing rate. In the model, the environmental function increases in both inputs and is maximized at a rotation time of 500 years. The biodiversity value at low values of  $t$  is a function of the habitat provided by the young seral stages. The absolute magnitudes of the environmental value are arbitrarily set due to the difficulty in determining a level accumulated in a forest stand without specific data. A sensitivity analysis is performed to determine the model's sensitivity to these parameter values. Since the magnitudes for the biodiversity-wildlife function are arbitrarily chosen without site-specific and/or species-specific data, it is the relative accumulation that will matter given each policy implemented. To ensure that the biodiversity-wildlife function is not unfairly biasing the results, there will be two versions of the social welfare function, with and without the function. Both carbon and biodiversity-wildlife generate use value from the total amount of the amenity available at a given time. The entire function is discounted over infinite rotations. Depending on society's value system, each component can be given a higher or lower weight to emphasize those components that are the most important according to the forest managers.

The concept of acceptable maximum versus optimum is of significance when discussing social welfare. The government's ability to capture the optimal social welfare in society is very different from their capturing the maximum possible. The optimum amount of environmental, social and economic output may very likely be much greater than the maximum attainable given societal constraints. In this scenario, the government is attempting to capture some balance of the outputs from the forest given different policy

channels. The social welfare captured at the end of the rotation is the maximum attainable given the constraints of the profit maximizing firm, the policy implemented and the geographic and biological constraints within the forest.

#### 3.1.4 Policies

The second-best policies described in the following analysis were chosen for a number of reasons. The unconstrained policy (u) was chosen as a base-line for comparison, to explore what the economic and environmental outcome would be if a timber firm were unconstrained in their profit maximizing input and output decisions, given a policy with little if any implementation, monitoring and enforcement costs. The status quo (sq) policies were chosen to reflect what is currently happening in British Columbia today in terms of publicly-funded silvicultural investment, and to extend this current practice to include even more funding by the province. The sq policies explore what the co-products from the forest are in the case where the government funds the majority of incremental silviculture, and timber firms choose the amount to be funded. These sq policies would be fairly straightforward to implement in theory given the current trends in the province, however, the magnitude of investment is presently very low in B.C., and any significant investment would be expensive for the province and likely not politically palatable. As long as the government actually implements the silviculture, monitoring and enforcement are not an issue. However, if the government moved to a situation where they funded firms to undertake the silvicultural investment, the firm might have an incentive to primarily implement those practices that enhanced yield, placing less emphasis on those

that primarily enhance habitat. The input policies (in), which set rotation time and require the firm to choose and pay for their own investment, are implementable since they require only determining the appropriate rotation time and monitoring this outcome. However, regulating rotation time may not be acceptable to forestry companies who prefer to maximize their profits by choosing the most efficient inputs.

Finally, the incentive policies (sub and tax) allow the firm to make their own input decisions and compensate the firm's environmental contribution each rotation. These policies may be more acceptable from the firm's perspective, however, politically it may be difficult to convince the public to pay for environmental output that essentially belongs to British Columbians and that is only a co-product of a timber company's profit maximizing timber investment decisions. To implement the incentive policies, there would be a significant initial implementation cost since the environmental output must be quantified and valued to set up the appropriate subsidy (or tax). In the case of the carbon subsidy and tax, measuring and pricing the output would likely be less costly since estimates and measures are currently being used. However, for the biodiversity subsidies, the implementation costs could be significant since biodiversity and wildlife habitat are less tangible and may be difficult to measure and price. Therefore, I assume a maximum feasible biodiversity subsidy of 20% of biodiversity value.

These five policy types are used in the simulations. The first policy is the unconstrained case (u) where the firm chooses rotation time (t) and investment (s) and pays 'w' dollars

per unit for the investment (total cost is then:  $s \times w$ ). The firm's profit function under this policy is as follows:

$$\pi(t,s) = \frac{\alpha(P_t - c - \lambda w_\lambda)v(t,s)e^{-rt} - sw}{1 - e^{-rt}}$$

*Note: in this case the government expenditure is zero.*

The second policy is the subsidized unconstrained investment case (sq) (called status quo since it resembles most closely the British Columbia example) has the firm choosing  $t$  and  $s$  but the investment ( $s^*w$ ) is paid for by the government. In B.C, anywhere from 60 to 100% of incremental silviculture is paid for by the government. In most cases, however, this number is closer to 100%. In the initial simulation, an sq policy was run where the government only paid for 60% of the incremental silviculture and the results suggested that it was never a preferred policy. For simplicity and realism, the policy is not included in the following analysis.

The firm's profit function under the 100% sq policy is as follows:

$$\pi(t,s) = \frac{\alpha(P_t - c - \lambda w_\lambda)v(t,s)e^{-rt}}{1 - e^{-rt}}$$

*Note: in this case the government expenditure is  $s^*w$ .*

The subsidized restricted case (sq90, sq100, and sq110) has the firm choosing investment (s) given a set rotation time (either 90, 100 or 110 years) with the investment subsidized by the government. For these three status quo policies, rotation times are imposed on the firm. A maximization of the social welfare function was performed to determine the government's first best solution for rotation time and investment. This first best solution gives an indication of what the socially optimal levels would be for these variables if the firm was not an active participant in the process. The government chooses longer rotation times when environmental values are incorporated. As a result, rotation times of 90, 100 and 110 years were used in the following policies to gauge whether or not, under various conditions, longer rotation times could generate higher social welfare. The firm's profit function under these status quo policies (using t=90 as an example) is as follows:

$$\pi_{90}(90,s) = \frac{\alpha(P_t - c - \lambda w_\lambda)v(90,s)e^{-r90}}{1 - e^{-r90}}$$

*Note: in this case the government expenditure is  $s^*w$ .*

The input policies (in60, in70, and in75) have the firm choosing investment (s), given a set rotation time (60, 70 or 75 years) with no subsidy for the investment. For the inputs policies, firms were not able to capture positive profits if the rotation times were set as high as the status quo policies, so rotation times for input policies were set at 60, 70 and 75 years. The firm's profit function under this policy (using t=70 as an example) is as follows:

$$\pi(70,s) = \frac{\alpha(P_t - c - \lambda w_\lambda)v(70,s)e^{-r70} - sw}{1 - e^{-r70}}$$

*Note: in this case the government expenditure is zero.*

The following two policies are price policies, one using a tax on carbon released and one subsidizing carbon captured. The tax policy (tax) levies a tax on the firm at the time of harvest (end of each rotation) for the carbon that is released from the biomass. This means that all timber going into non-long term products, such as paper or pulp will be taxed at the rate of the social value for carbon (Pc). The firm's profit for this tax policy is the unconstrained profit less the tax as follows:

$$\pi_{gross}(t^*,s^*) = \frac{\alpha(P_t - c - \lambda w_\lambda)v(t^*,s^*)e^{-rt^*} - s^* w}{1 - e^{-rt^*}}$$

$$tax(s^*,t^*) = \frac{P_c \gamma (1 - \lambda)v(s^*,t^*)e^{-rt^*}}{1 - e^{-rt^*}}$$

$$\pi_{tax}(s^*,t^*) = \pi_{gross}(s^*,t^*) - tax(s^*,t^*)$$

*Note: The government expenditure for this policy is the negative of the tax(s,t).*

Where  $\gamma$  is the conversion ratio of timber volume to carbon sequestered and  $\lambda$  is the pickling rate of timber into long-term end uses. The carbon subsidy policy (sub) rewards firms for sequestering carbon over each rotation as well as for the carbon that remains

sequestered in long-term timber products at the time of harvest. Only the timber going into long-term products (housing, other construction lumber) is subsidized. The timber that is used for paper, pulp or other short-term end uses is assumed to release any stored carbon back into the atmosphere almost immediately. Both the yearly carbon accumulation and the pickled carbon is subsidized at the rate of the social value for carbon. The carbon accumulation integral runs from time zero to  $t^*$  (rotation age). In reality, there are carbon losses at the time of harvest as well as on the reforested stand until the stand reaches an equilibrium and begins to act as a carbon sink. This feature is not built into the model, since it requires a complex scientific understanding of the geographical and ecological nature of a specific forest stand and has not been built into other economic models (van Kooten et al. 1995). The implication is that the amount of biomass carbon sequestered in this model is an upper limit. The firm's profit for this policy is the unconstrained profit plus the sum of the carbon accumulated over the rotation and the carbon stored in long term timber products as follows:

$$\pi_{gross}(t^*, s^*) = \frac{\alpha(P_t - c - \lambda w_\lambda)v(t^*, s^*)e^{-rt^*} - s^* w}{1 - e^{-rt^*}}$$

$$sub(s^*, t^*) = \frac{P_c \gamma(\lambda)v(s^*, t^*)e^{-rt^*} + \int_0^{t^*} P_c \gamma r v(t^*, s^*)e^{-rt} dt}{1 - e^{-rt^*}}$$

$$\pi_{sub}(s^*, t^*) = \pi_{gross}(s^*, t^*) + sub(s^*, t^*)$$

*Note: The government expenditure for this policy is the  $sub(s, t)$ .*

In addition to the carbon subsidy policy described above, there are two other variations on this policy. These two policies include a full subsidy for carbon (as above) and a partial subsidy for the biodiversity-wildlife value that is accumulated over the rotation by the firm. The firm is subsidized for the value of this output at the biodiversity-wildlife price ( $P_e$ ). The first carbon and environmental subsidy policy (sub1) subsidizes the firm for 10% of the biodiversity-wildlife value accumulated, and the second subsidy (sub2) compensates the firm for 20% of the biodiversity-wildlife value accumulated over the rotation. For these two comprehensive subsidy policies (sub1 and sub2), social welfare will always include the biodiversity-wildlife component since this component is being subsidized. No administrative, monitoring or enforcement costs are included in any of the above policies.

## 3.2 Results

In a two-stage game, the player in the first stage solves for what the player in the second stage would do in any given situation. In this case, the government first determines the firm's reaction to any given policy. Then, taking that reaction into account, the government chooses the policy that maximises its welfare function. Each simulation begins with the firm maximizing its profit function given whatever policy is imposed. The output from this maximization ( $t^*$ ,  $s^*$ , volume, revenue) is then entered into the social welfare function to determine the amount of social welfare created by that given policy under the particular set of assumptions and parameter values. This is done for each policy given the parameter values. Social welfare is compared across policies to determine the ranking of the policies. A sensitivity analysis is conducted for the relevant variables in both the profit function and the social welfare function and repeated for each policy to ascertain which variables shift the policy ranking.

### 3.2.1 Government's "First Best"

Before getting into the two stage simulations which are motivated by the firm's profit maximization, it is interesting to note what the government's first best choice would be for rotation time ( $t$ ) and investment ( $s$ ). In order to ascertain this, the social welfare function itself is maximized with respect to the two input variables. In the maximized social welfare function, volume, net revenue, carbon sequestration, and the biodiversity-wildlife component are formulated the same as they are in the social welfare function

described above. The first best choice was evaluated in two stages. First, the government maximizes total revenue (which is maximizing volume with constraints). Next, revenue plus the environmental components are maximized. The results indicate that when the government maximizes revenue as its only component to social welfare,  $s^*$  and  $t^*$  are chosen to be nearly identical to those chosen by the unconstrained firm, somewhere around 73 years for rotation time and 29 units of silvicultural investment (the volume-maximizing amount). When the government maximizes social welfare taking into account the environmental components that include carbon and the biodiversity-wildlife component, a rotation time of 120 years is chosen along with 90 units of investment, which comprises both silviculture and environmental management investment. When environmental values matter to society, social welfare increases when longer rotation times are accompanied by the maximum amount of silvicultural investment and environmental stand management investment. These results give an idea of what a command and control type policy would look like for a government who cares about economic and environmental values in a forest. The government would choose rotation times that are exactly the same as those chosen by the firm under a profit maximizing framework when revenue is the priority. This makes intuitive sense, since both parties are essentially just maximizing volume, subject to economic constraints. If the government was maximizing timber volume as its only objective, the rotation time would reflect the peak of the volume function, around 140 years for lodgepole pine. When environmental components are taken into account, the government realizes higher social welfare by increasing investment and rotation times.

To reach the government's "first best", economics would suggest that if the firm is fully compensated for its environmental outputs, the firm would independently choose the government's first best rotation time and level of silvicultural investment. To explore this further, a first best subsidy policy simulation was run. The firm is compensated for 100% of the value of carbon accumulated in the biomass and 100% of the biodiversity-wildlife value accumulated at the end of a rotation. The simulation results show that if the firm is not paying for their investments and is being compensated for the full value of their environmental outputs, they do in fact choose the government's "first best" solution of a 120 year rotation time and nearly 100 units of investment.

This result, although interesting and informative, does not give a simple answer to the policy question. The reality is that it is not economically or politically feasible for the British Columbia government to either pay for 100% of the biodiversity-wildlife value or to pay for the very costly silvicultural inputs when the firm is choosing almost 100 units of s. The intangible nature of biodiversity and wildlife habitat as well as the BC public's overarching feeling of ownership of the forests' outputs, creates a politically sensitive situation when implementing policy that compensates a timber company for these difficult to measure values. However, this "first best" does serve as a baseline for comparison with the other second best policies. For a policy to be successful, it must not only provide for the desired output but also be implementable, cost effective and politically viable. As a result, the policies discussed below represent second best policies in a world where the first best is unattainable under the initial set of parameter values. It

is important, however, to refer back to the first best as the baseline to which these second best policies are compared.

### 3.2.2 Government's "Second Best"

To reiterate briefly, the profit function is the following:

$$\pi(t^*, s^*) = \frac{\alpha(P_t - c - \lambda w_\lambda)v(t^*, s^*)e^{-rt^*} - s^* w}{1 - e^{-rt^*}}$$

and the social welfare function:

$$swf(t, s) = aP_t v(t^*, s^*) + bGE + cP_c c(t^*, s^*) + dP_e e(s^*, t^*)$$

$$v(t^*, s^*) = (st^5)e^{-0.035(t+s)}$$

$$c(t^*, s^*) = \frac{\gamma(\lambda)v(s^*, t^*)e^{-rt^*} + \int_0^{t^*} \gamma r v(t^*, s^*)e^{-rt} dt}{1 - e^{-rt^*}}$$

$$e(t^*, s^*) = (st^5)e^{-0.01(t+s)}$$

GE is net government expenditure on any subsidy or tax policy, and firm revenue will include the environmental subsidy for the subsidy policies.

The parameter values for the initial simulation are as follows:

*TenureSecurity/PropertyRights*(1 = 100%) :  $\alpha = 1$

*TimberPrice*(\$/m<sup>3</sup>) :  $P_t = 120$

*HarvestCost*(\$/m<sup>3</sup>) :  $c = 80$

*PicklingRate*(0.5 = 50%) :  $\lambda = 0.5$

*PicklingCost*(\$/m<sup>3</sup>) :  $W = 10$

*DiscountRate*(0.03 = 3%) :  $r = 0.03$

*SilvicultureCost*(\$/unit(s)) :  $w = t^2 / 10^{1.5}$

*PriorityWeight*(revenue) :  $a = 1$

*PriorityWeight*(biodiversity – wildlife) :  $b = 1$

*PriorityWeight*(carbon) :  $c = 1$

*PriorityWeight*(profit) :  $d = 1$

*CarbonPrice*(\$/m) :  $P_c = 20$

*Biodiversity(Wildlife)Price*(\$/m) :  $P_e = 20$

*CarbonConversionRatio* :  $\gamma = 0.2$

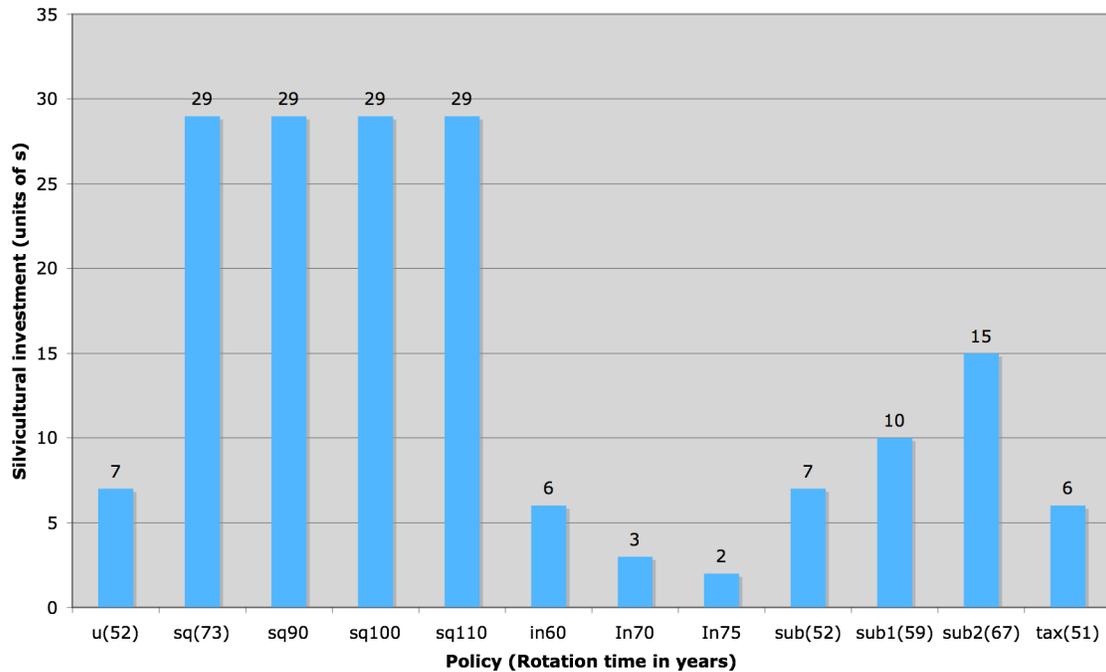
The cost of investment is a function of rotation time in this simulation. As the stand ages, more and more stand management must be done, such as thinning and fertilization. Also, the older the stand gets, the more investment is made into environmental stand management, which requires increasing effort for such things as habitat preservation and protection. Although this cost is paid upfront at time zero, the firm accounts for the fact that the cost is increasing in time, so the more investment, the longer the rotation, and the more costly it will be for the firm upfront. The model is run using the above base case parameters and the resulting optimal rotation time  $t^*$ , and investment  $s^*$ , are chosen accordingly. For the values to represent a realistic timber stand for a British Columbian forestry firm, the outputs are calibrated for a one-hectare timber stand.

### 3.2.3 Base Case Results

A simulation was run for the initial model using the above parameters. The unconstrained firm chooses a rotation time of 52 years and minimal investment. The firm chooses only to invest in silviculture that will enhance volume (fertilizing) and not to invest explicitly in environmental management (as we can see from the low level of  $s^*$ ). When the policy includes a full investment subsidy from the government (a so called status quo policy in British Columbia), the firm chooses a rotation time of 73 years (more than 20 years longer) and four times more investment (however, at this level of  $s^*$ , the investment is still primarily volume-enhancing silviculture as opposed to environmental stand management). Refer to Appendix A for the base case simulations and results.

It is interesting to note the relationship between rotation time ( $t$ ) and investment ( $s$ ). The firm is always free to choose at least one of these timber inputs in every policy. Figure 3.3 shows the dynamic between these two inputs.

**Figure 3.3: A timber company's silvicultural investment decisions by policy**



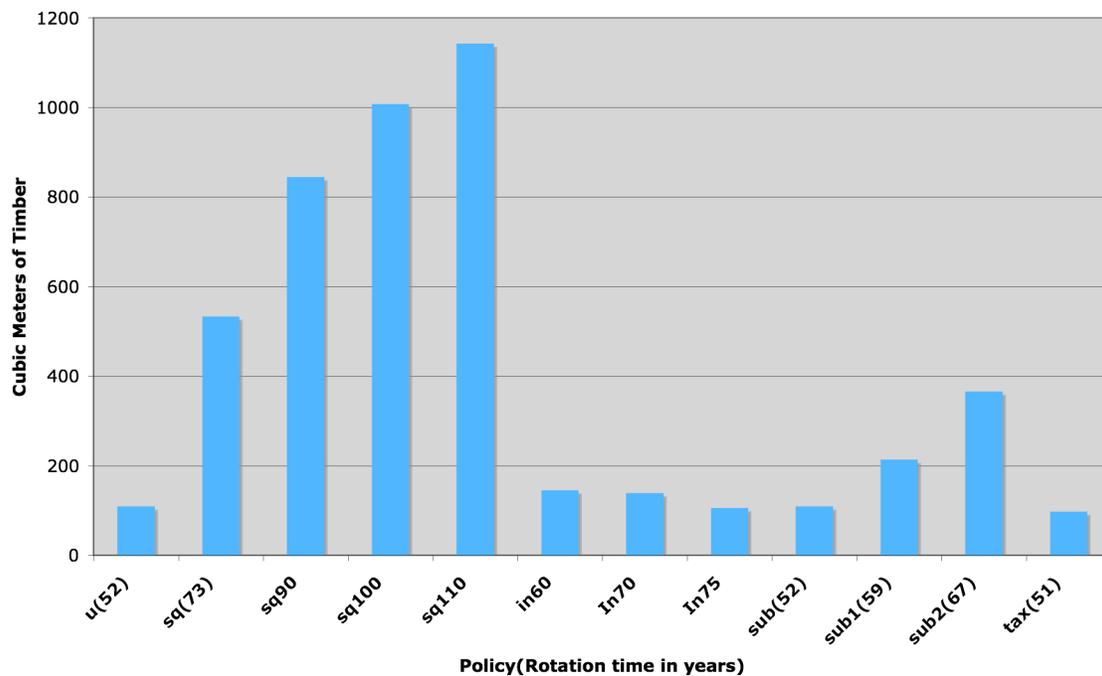
*Note: The amount of silvicultural investment is indicated at the top of each histogram column.  $S=29$  is the maximum amount of investment the firm can make into primarily volume-enhancing silviculture like fertilizer and moderate thinning without getting into environmental investment which sacrifices volume.*

The firm treats the two inputs as complements or neutrals when the government is subsidizing their investment. The firm chooses more investment and a longer rotation under the unconstrained status quo (sq) policy than under the purely unconstrained policy (u). For the rest of the sq policies, the firm chooses the same level of investment as under the unconstrained sq policy since it is not paying for this input. This  $s^*$  is the maximum level of investment the firm can make to enhance volume while also enhancing the environmental quality of the stand. Any more investment would be primarily focused on environmental stand management and volume would begin to fall. For the input policies, where the firm is paying for its own investment, it treats the two inputs as substitutes. The longer the imposed rotation time, the less investment the firm makes. When the firm is

subsidized for its environmental outputs, rotation time and investment are again treated like complements by the firm. Under the subsidy policies, the firm is choosing longer rotations and simultaneously more silvicultural investment.

The results from the base case simulation are shown in the figures 3.4-3.8 below. Timber volume is increasing in rotation time (Figure 3.4).

**Figure 3.4: Base case timber volume by policy**

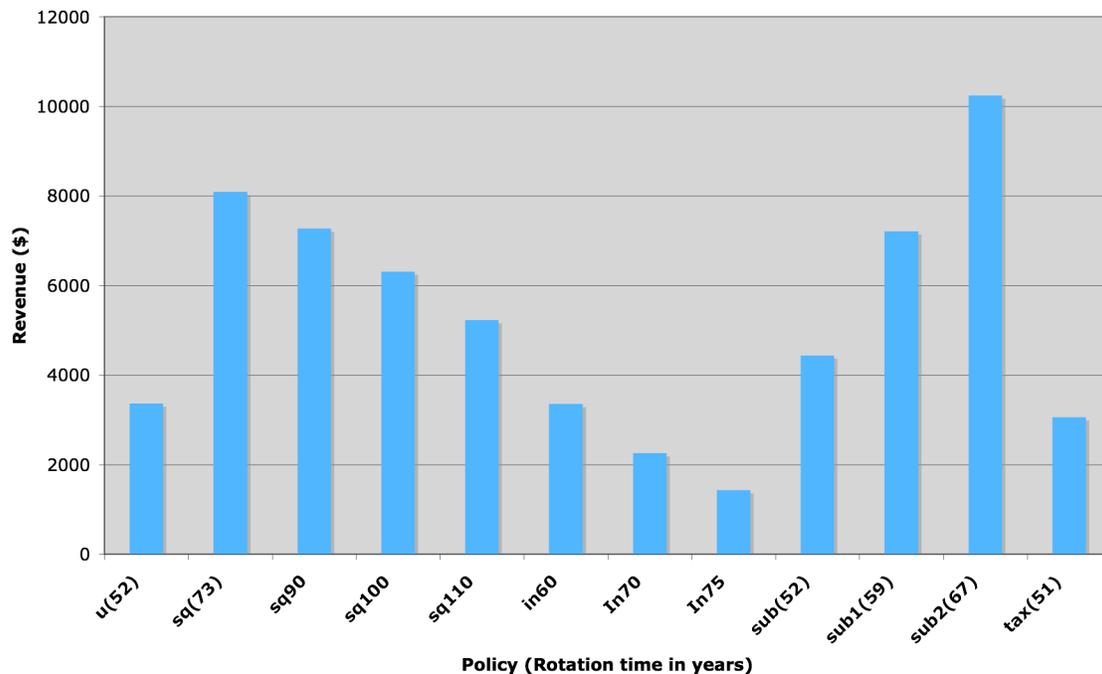


As a result, the highest timber volume is achieved under the policy that imposes a rotation time of 110 years on the firm. When the firm chooses the rotation time itself, it chooses between 51 and 73 years, which accumulates much less volume. Silvicultural investment also increases volume and the firm chooses the same level of investment (the maximum without sacrificing volume) for each of the status quo policies. This is intuitive since the firm is not paying for this investment, it chooses the level that maximizes profit

(volume). For the environmental subsidy policies, the firm chooses more investment and longer rotations the more they are compensated for their environmental output. It is a straightforward increasing relationship between volume and rotation time in this base case since the rotation times in this simulation never reach the maximum of the volume function (around 150 years).

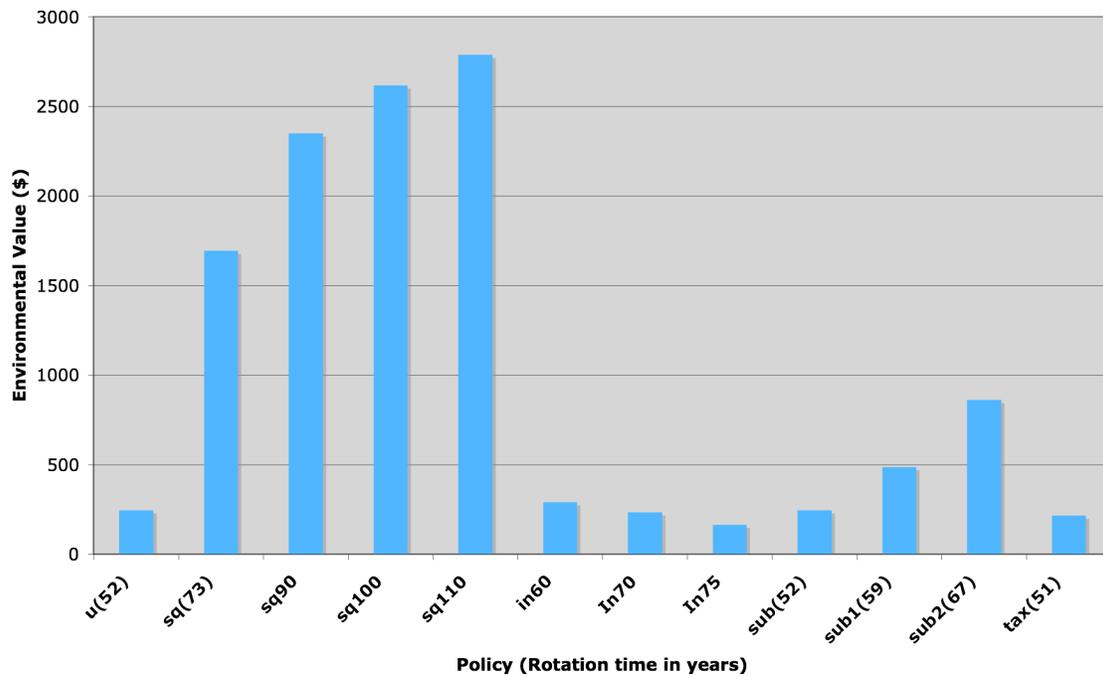
For the status quo policies, as rotation time increases past the optimal point of  $t^*$  (chosen by the firm), firm revenue starts to fall (Figure 3.5). For the input policies, revenue also falls as the rotation time lengthens beyond the unconstrained optimum of 52 years. When the firm is subsidized for its accumulation of environmental output (carbon and biodiversity), revenue rises.

**Figure 3.5: Base case firm revenue by policy**



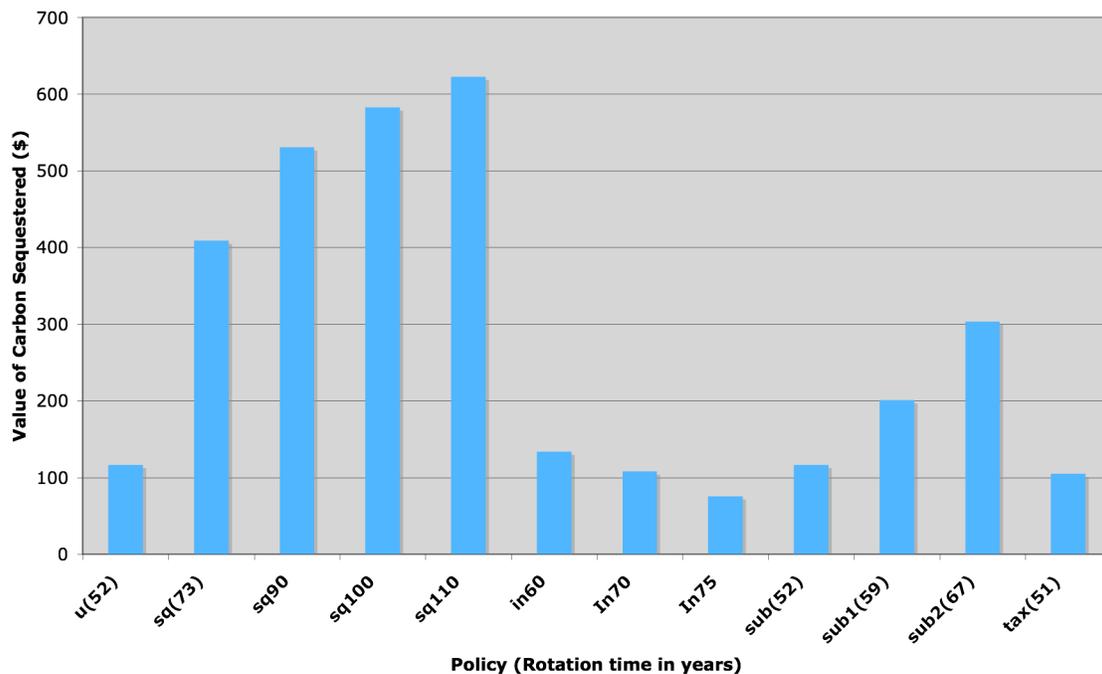
Although the subsidy is a cost to the government like the cost of the firm’s investment, unlike the status quo policies, the subsidy nets out overall and thus the status quo policies generate lower revenue since the expenditure is higher. Revenue falls when a tax is imposed on all carbon that is released at the time of harvest. For the subsidy policies, the firm chooses slightly longer rotation times the more environmental output is subsidized by the government. When the firm is subsidized for all of the value from the carbon sequestered and 10% of value from biodiversity-wildlife accumulated, it chooses a 59-year rotation and when the firm is subsidized for 20% of biodiversity-wildlife, it chooses a 67-year rotation. The amount of biodiversity-wildlife output accumulated and the corresponding value of this accumulation to society increases in rotation time (stand age) and is shown in Figure 3.6.

**Figure 3.6: Base case biodiversity-wildlife value by policy**



The longer the rotation, the more biodiversity-wildlife output is accumulated from the stand. Silviculture also comes into play for biodiversity, however, rotation time is a more important factor and thus drives the results. The value of carbon sequestered (Figure 3.7) matches the shape of timber volume (Figure 3.4). This is because carbon is a function of stand volume. When the firm is being subsidized for carbon and biodiversity-wildlife accumulation, they do take into account the fact that both of these outputs increase with stand age (up to a point) and as a result, slightly longer rotation times and more investment are chosen to maximize profit.

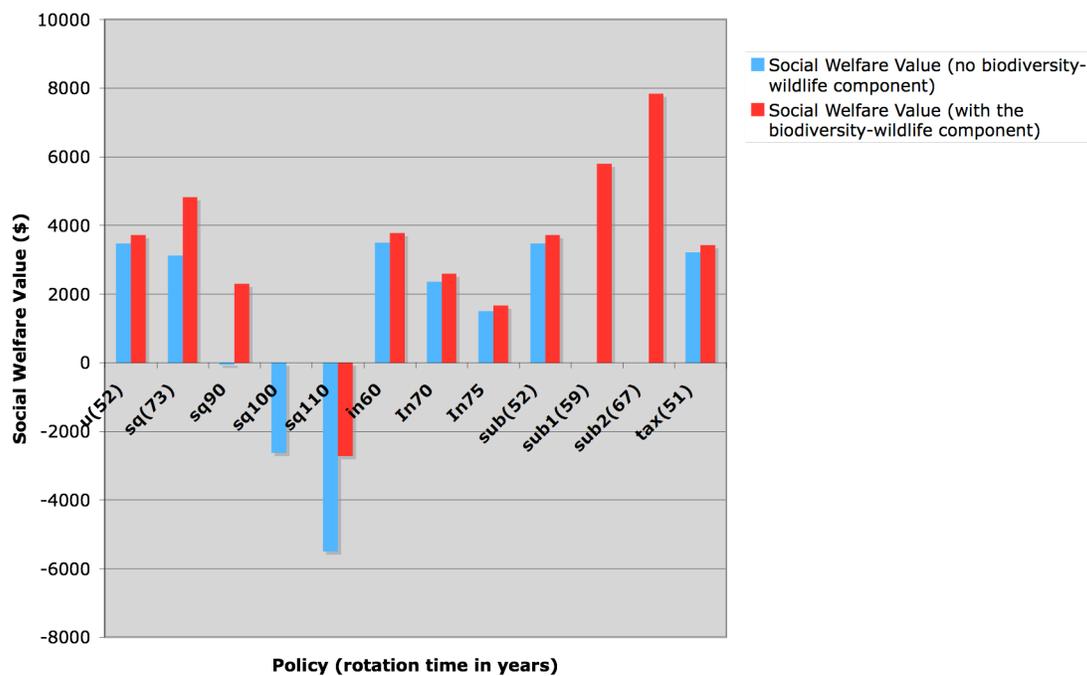
**Figure 3.7: Base case carbon sequestration value by policy**



The objective of this base case simulation is to observe the impact that different forestry policies have on the input decisions of a timber firm and ultimately what this impact

means for social welfare. Figure 3.8 shows the total value of social welfare accumulated from this one-hectare timber stand over the rotation, given different forestry policies. There are two social welfare values shown, one that includes firm revenue, net government expenditure, and carbon accumulation and one that includes the above as well as the value of the biodiversity-wildlife output from the stand. When the biodiversity-wildlife component is included, social welfare is maximized under the subsidy policy that compensates the firm for all its carbon and twenty percent of the value of the biodiversity-wildlife output. Under the subsidy policy (sub2), the firm chooses a rotation time of 67 years and 15 units of investment.

**Figure 3.8: Base case social welfare values by policy**



Even under the subsidy policies, the firm is choosing to only invest in silviculture that enhances volume as opposed to the environmental quality of the stand at the expense of volume. All silviculture that enhances volume is also assumed to enhance the

biodiversity-wildlife output simultaneously, however, the magnitudes are relatively small with short rotations and limited investment. The firm chooses increasing levels of  $s^*$  as the subsidy increases, and as rotation times increase. However, the low levels of  $s^*$  (Figure 3.3) indicate that the firm is only investing to enhance volume and profit. The environmental subsidy is not giving the firm enough incentive to invest further in the stand given the base case parameters. The subsidy policy generates more revenue and has no net social expenditure since the subsidy cancels out between the revenue and social welfare functions. The result is slightly lower volume and environmental output under the subsidy policy compared to the status quo policy (because of a shorter rotation and less investment) but more social welfare because of the netting out effect of the environmental subsidy. When the government compensates the firm for the value of its environmental output, the firm increases rotation time beyond what the unconstrained firm would do and as a result, generates enough revenue and environmental output to create more social welfare than the policies that require a large government expenditure to subsidize timber stand investment.

When the biodiversity-wildlife component is not included in the social welfare function, the environmental subsidy policies (sub1 and sub2) are not included in the analysis. In the case without environmental subsidy, the policy that generates the most social welfare is the input policy with an imposed 60-year rotation. This policy generates less volume, revenue and environmental output than the status quo policies but because there is no government expenditure, social welfare is higher. The lowest social welfare (for both measures) is achieved for the long rotation status quo policies (sq110 and sq120). These

policies have an imposed rotation time that is set at almost double the rotation chosen by the unconstrained firm. Although the environmental outputs and timber volume are substantially higher for these policies, the lower revenue and cost of the investment subsidy mean less social welfare.

### 3.3 Sensitivity analysis

The parameter values assigned in the initial set-up require some simplifying assumptions about the micro-economic and macro-economic conditions under which the firm and society are operating. To ensure that none of these parameters disproportionately influence the results, a sensitivity analysis was performed. Almost all of the sensitivity analyses showed no change in the overall ranking of the policies, however there were a few cases where the ranking did shift or interesting results were revealed. Refer to Appendix B for the sensitivity analysis results.

#### 3.3.1 Including the Biodiversity-Wildlife Component

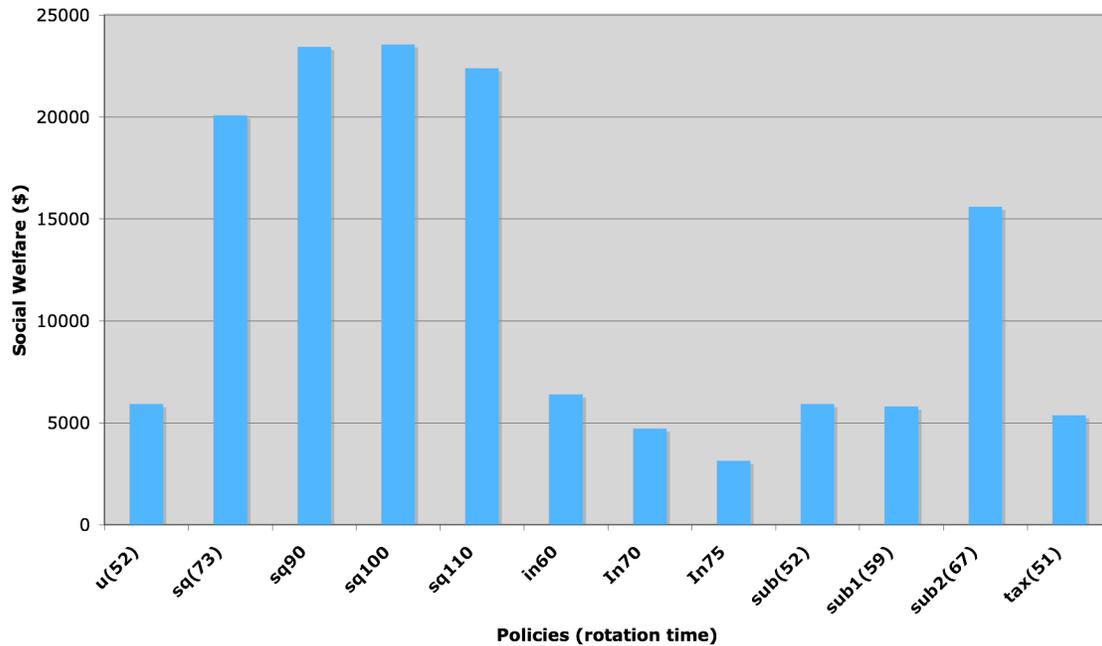
The following parameter modifications generated new results in the case where the biodiversity-wildlife component was included in the social welfare calculation.

##### *3.3.1.1 Carbon and Biodiversity-Wildlife Priority Weights*

Figure 3.9 shows the results from a change in the weighting of the social welfare components. When the biodiversity-wildlife value is weighted ten times more than revenue, carbon and government expenditure, the policy that generates the most social welfare is the status quo policy with a 100-year rotation compared to the environmental subsidy policy that had a rotation of 67 years. When a higher weight was also added to

the carbon component as well as biodiversity-wildlife, the preferred policy is again the long rotation status quo policy.

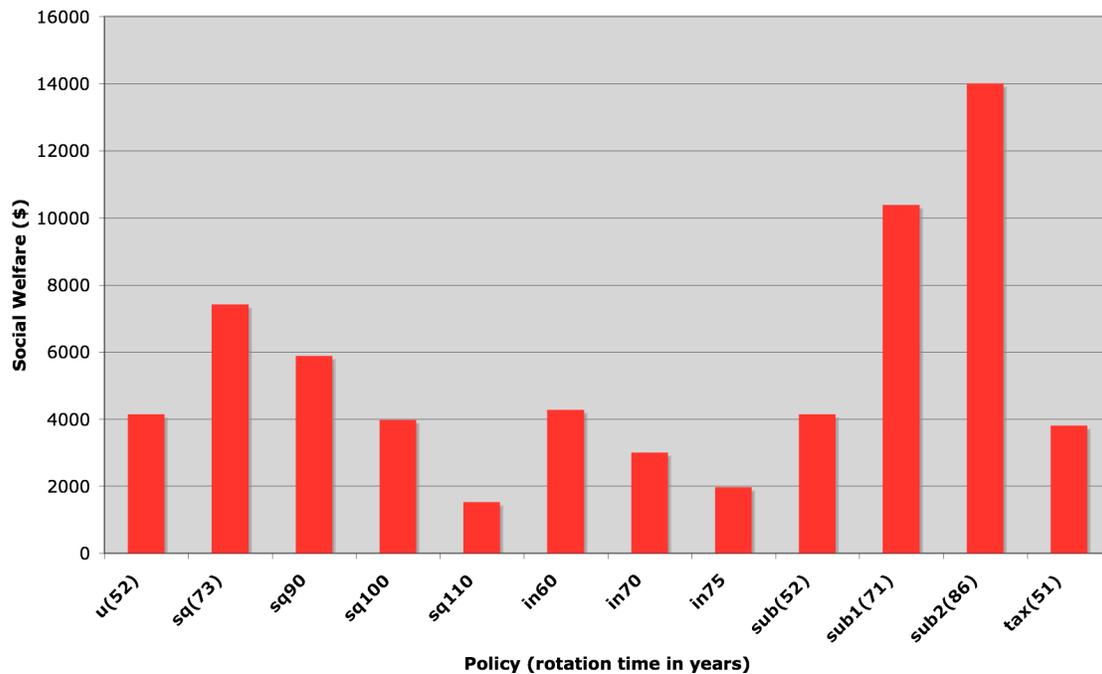
**Figure 3.9 Social welfare by policy when the biodiversity-wildlife weight is 10-times higher than the other components**



A higher price for a unit of biodiversity-wildlife output shows no change in the overall rankings, however, the higher price results in the preferred subsidy policies eliciting longer rotations and more investment from the profit-maximizing firm, which generates more biodiversity-wildlife output and social welfare (Figure 3.10). In this scenario, the firm's investment decision includes both volume-enhancing activities such as fertilizing and thinning and a very small amount of environmental stand management, e.g. preserving environmentally valuable trees and wildlife habitat, at the expense of volume. The more society values the environmental output from a forest, the more the firms

respond to incentives by making decisions that enhance the environmental quality of the forest stand and consequently improve social welfare. As carbon, biodiversity, and wildlife habitat become more highly valued in society, longer rotations yield more social welfare.

**Figure 3.10: Social welfare for price biodiversity-wildlife =50\$/unit**



### 3.3.1.2 Discount Rates

Discount rates play an important role in forestry models since harvests do not happen until at least half a century after the trees are planted. The sensitivity of a forestry model's results to the discount rate and the implications from these results has been explored and it has been shown that the discount rate used for socially desirable outputs from a forest should actually decline overtime (Hepburn et al. 2007).

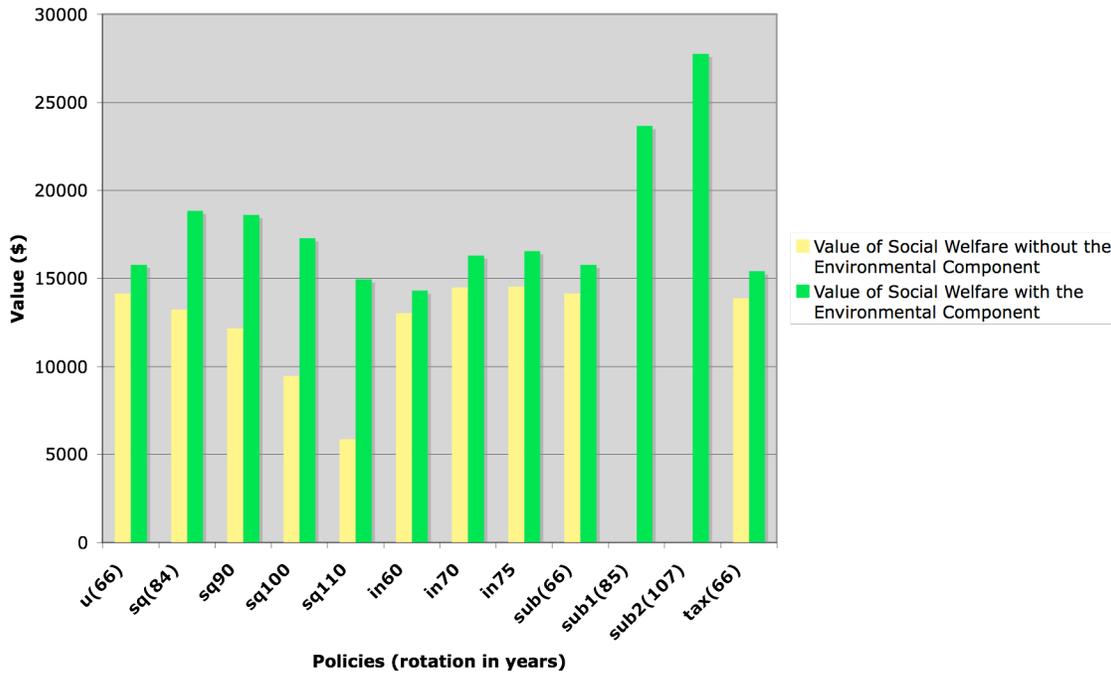
The initial simulation was run using a discount rate of 3%. To gauge the impact of this rate on the results, both a higher and lower rate were used in the simulation. A higher discount rate means that the firm's profits from timber at the end of the rotation are discounted by even more than in the base case. The highest discount rate that still supports positive profit for the timber firm in this model is 3.5%, the discount rate typically used by the British Columbia government for its timber industry analyses (personal communication with Glenn Farenholtz<sup>4</sup>). With a 3.5% discount rate, the firm chooses a rotation time of 46 years when it is responsible for paying for any investments (u policy) and 68 years when these inputs are subsidized (sq policy). For the most comprehensive subsidy policy (sub2) the rotation time is 57 years. This is several years shorter than under the same policies with the original discount rate of 3%. Also, the firm is choosing a lower level of investment when it is not subsidized. The social welfare ranking stays the same as under a 3% discount rate, with the subsidy policy (sub2) generating the highest social welfare, however, now this preferred policy has an even shorter rotation time.

As the discount rate falls to 2 percent, meaning that the government and the firm care more about the future (they are discounting future dollars by one percent less), rotation time increases and investment increases (Figure 3.11). Although the policy rankings stay the same, the preferred subsidy policies now have longer rotation times and more investment.

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<sup>4</sup> Glenn Farenholtz, RPF, Strategic Land and Policy Branch, Ministry of Forests and Range.

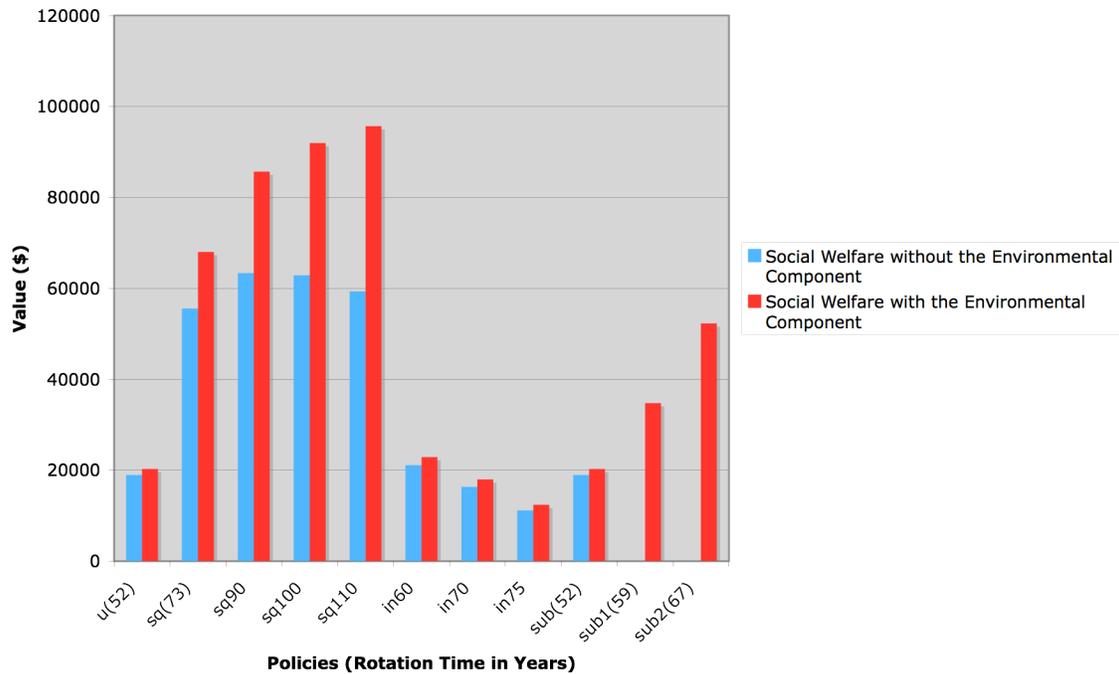
**Figure 3.11: Social welfare for a discount rate of 2%**



If the government cares more about the future than the firm does, a different discount rate can be used for the firm's profit maximization and for the government social welfare components and subsidies. Lowering discount rates on social amenities is a way for policy makers to recognize the significant social value of accumulating carbon as well as biodiversity-wildlife outputs over time. To explore the effect of two different discount rates on the outcome of the simulation, the standard financial discount rate of 3% was applied to the firm's profit function and the government's net expenditure. All other components of the social welfare function are discounted at a rate of 1%, these include the biodiversity-wildlife habitat function and carbon function and also the revenue function (since the government cares about social value of the industry's employment). With a 1% social discount rate, the firm chooses the same optimal values for  $t^*$  and  $s^*$  for

all policies since the social components being discounted at a lower rate are not found in the firm's profit function (Figure 3.12).

**Figure 3.12: Social welfare for social discount rate of 1%**



Under the lower social discount rate, social welfare is higher under the longer rotation time policies, such as the sq90, sq100, and sq110 year policies. This is an intuitive result since the values of the environmental outputs are discounted a lot less and thus the preferred policies are those that generate more environmental value over a longer rotation.

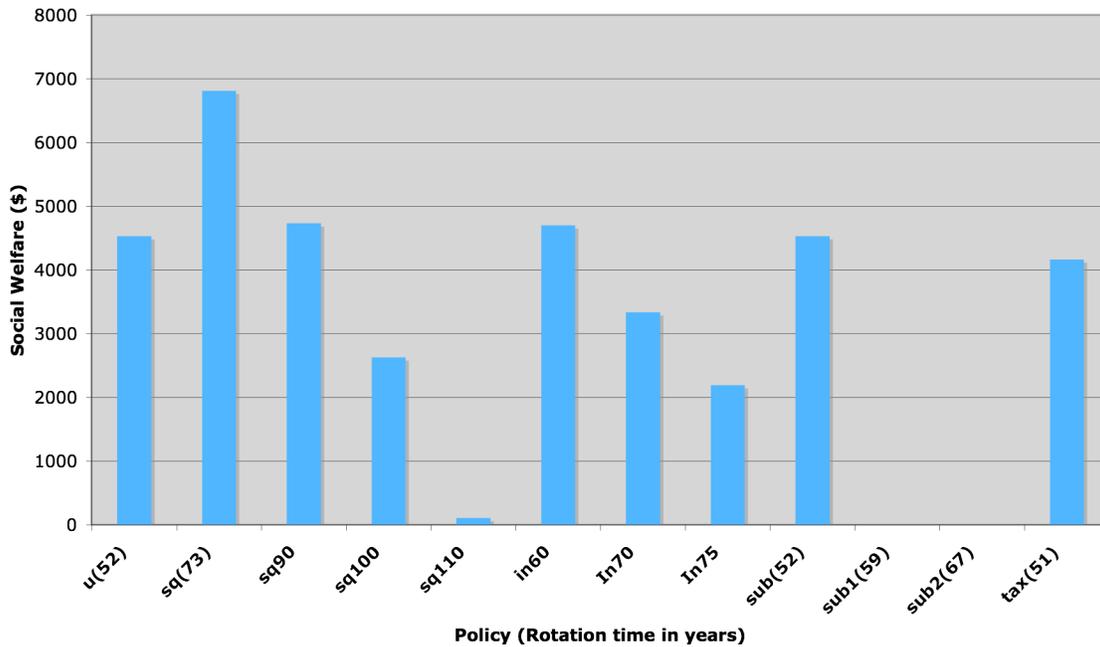
### 3.3.2 Without the Biodiversity-Wildlife Component

The following parameter modifications revealed new information in the case where the biodiversity-wildlife component was not included in the social welfare calculation.

#### 3.3.2.1 Carbon Priority Weighting and Price

When the priority weight given to carbon is ten times higher than the other components of the social welfare function, the status quo policy with a firm-chosen 73-year rotation generates the most social welfare (Figure 3.13).

**Figure 3.13: Social welfare (without biodiversity-wildlife value) and 10x the weight on the value of carbon sequestered**



A higher priority on carbon sequestration means a longer rotation creates more value. As the price of carbon increases, the unconstrained status quo policy with a 73-year rotation again generated slightly more social welfare compared to the input policy with a 60-year imposed rotation. When the value of carbon increases, a slightly longer rotation generates slightly more volume, more carbon and overall slightly more social welfare (even with the cost of the investment subsidy).

#### *3.3.2.2 Discount Rates*

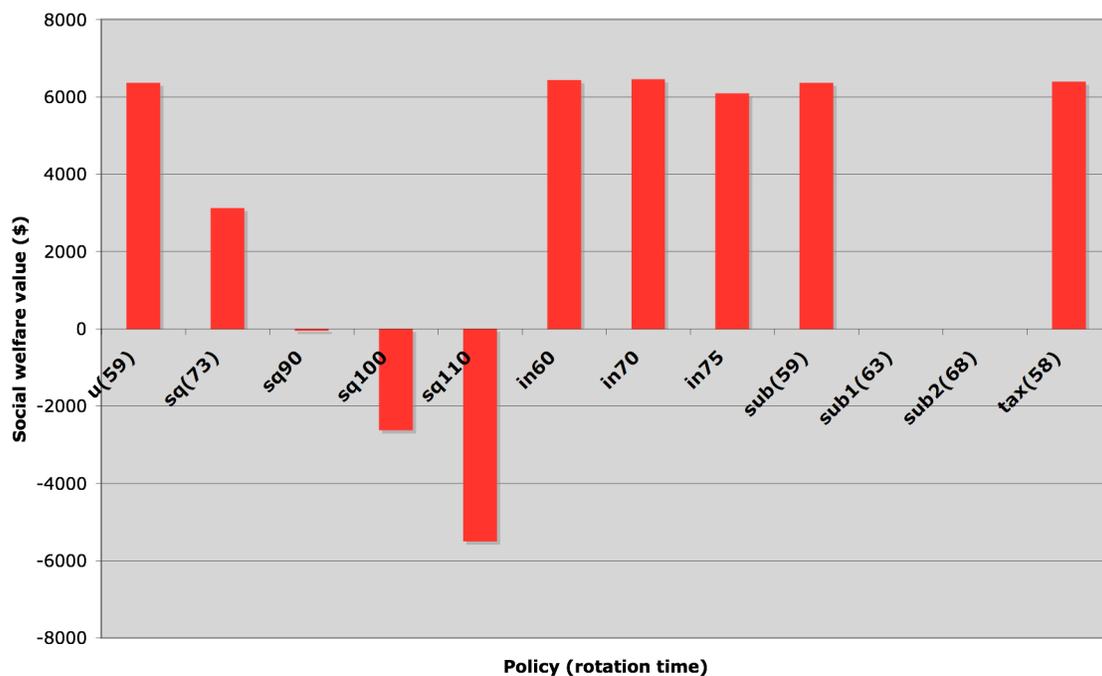
When discount rates are lower than the initial 3%, long rotation policies are preferred. Even though the biodiversity-wildlife component is not included, there is still more social value from carbon under longer rotations. With a 2% discount rate, the input policy with a 75 year rotation generates more social welfare than the 60-year input policy. As the discount rates continue to fall, firms choose longer and longer rotations and more investment and with a 1 % discount rate, the optimal policies are the unconstrained (u) policy and the carbon-only subsidy(sub) policy, with rotation times of 85 years.

#### *3.3.2.3 Timber Price and Harvest Cost*

When a lower timber price was used (or higher harvest cost), the firm chose shorter rotations and less investment to maximize profits. When timber prices were increased (or harvests decreased), the firm chose longer rotations and more investment. As the firm is

able to generate higher profit, they choose to extend the rotation and make more investment in the stand to maximize their profits. A lower harvest cost (40\$ compared to 80\$ in the base case) generated the most social welfare from the subsidy policies when the biodiversity-wildlife component was included but when it was not included, the input policy with an imposed 70-year rotation was preferred to the input 60-year policy as in the base case (Figure 3.14). Although these results are slightly different, when no biodiversity-wildlife component is included, a significantly lower harvest cost still generates the most social welfare from relatively short-rotation input policies.

**Figure 3.14: Social welfare by policy for a lower harvest cost (40\$)**



#### 3.3.2.4 *Other Results*

Other sensitivity analyses were done but yielded no change in the overall ranking of the policies by social welfare and only very small changes in rotation time and stand management investment. The security of the firm's property rights to the resource, the amount of timber that goes into long-term end uses (pickling rate), prices on timber, harvest costs and the cost of stand investment were all manipulated with no overall effect on the results. The model's results seem robust since most of the individual parameter values do not have a significant effect on the policy ranking.

### 3.4 Discussion

In the initial scenario, the subsidy policies where the government subsidizes all of the value from the carbon sequestered through a rotation and twenty percent of the biodiversity-wildlife value maximizes the province's social welfare. Changing the weight on biodiversity-wildlife changes the results and favours the 100-year rotation status quo policy where the firm's silvicultural activities are subsidized. When the price on the biodiversity-wildlife output increased, rotation times and investment increased for the preferred subsidy policy (sub2) to include some environmental investment at the expense of volume. When discount rates are increased, there is no change in the policy ranking, but rotation times decrease and when discount rates fall, the subsidy policies generate even more social welfare as rotation times and investment increase. When the government cares more about the future than the firm, a lower social discount rate results in longer rotations and more investment. When the biodiversity-wildlife value is not included in the social welfare function, the input policy with a 60-year rotation creates the most social welfare. When the price of a unit of carbon sequestered increases, slightly longer rotation policies generate more social welfare.

The sensitivity analysis shows some interesting results and highlights the importance of discount rates and other variables for rotation times and investment levels. When the government cares more about biodiversity, wildlife habitat and other outputs such as soil carbon (as seen in higher weights), the preferred policies switch from the comprehensive environmental subsidy policy to a status quo policy with a longer rotation. Even though

the firm is being compensated for its environmental contribution in the subsidy policies, the rotation is still not long enough to generate as much environmental value as the 100-year policy with more investment. As rotation times increase, the amount of biodiversity-wildlife value accumulated increases exponentially. This means that the gap between social welfare with and without this output widens as rotation time increases. For relatively short rotations, say between 50 and 75 years, there is very little difference between the two social welfare function values, which means that the government is likely to not consider the biodiversity-wildlife value as being very important. However, as the rotations lengthen, more and more of this environmental value is accumulated relatively and becomes more important to society. Policies that encourage longer rotation times, which are accompanied by either more investment or at the least no decrease in investment levels, accrue an exponential benefit in biodiversity-wildlife value.

Other variables that one would have initially expected to play an important role in the results, due to the formulation of the model, were fairly insignificant. These include property rights, pickling rate, timber price (and harvesting cost) and the cost of stand management investment. Although timber price and harvest cost revealed that the timber firm is treating timber price (harvest cost) and timber inputs as complements (substitutes). The higher the timber price (harvest cost) the firm generates, the longer (shorter) the rotation time and more (less) investment the firm makes to maximize profits. Despite this interesting outcome, the overall social welfare ranking did not change as a result of timber price or harvest cost. The simulation results for this forestry policy model suggest that there is a role for active management intervention when environmental

values matter. Moving away from status quo policies where the government is funding the firm's stand management investment (primarily silvicultural) to environmental subsidy policies may create more social welfare. The most comprehensive subsidy policy in this model only subsidizes the firm for 20% of its biodiversity-wildlife value over a rotation and generates the most social welfare consistently. The implication is that even though this environmental aggregated function is somewhat arbitrary and difficult to measure and price, if only a small amount of a timber firm's indirect contribution to environmental quality over a rotation is compensated, social welfare will increase.

## **4 Heterogeneity in the Forest Model**

### **4.1 Introduction**

The previous chapter outlined a forestry problem for a representative firm in an increasingly common growing second growth timber context where economic, social and environmental objectives matter to the policy makers. This firm could maximize timber profits by choosing rotation time and stand management investment levels under various policies implemented to capture more of the social value within the forests. The assumption motivating the last chapter was that investment and rotation time have ancillary benefits, beyond timber volume and profit, which, if managed properly, include carbon sequestration and biodiversity, soil carbon and wildlife value. The results showed that certain policies generated more social welfare than others and that there are a number of conditions that favour one policy over another, including changing discount rates, prices and priority weighting of social welfare components.

Harvesting cost/timber price was one variable that was explored in the sensitivity analysis and found to have a negligible effect on the policy ranking. As timber price increased or cost decreased, the firm marginally increased its rotation time and level of investment, however there was no significant change to the overall policy rankings in terms of social welfare. Although the harvest cost had little impact on the ranking, there are many other costs facing a timber firm that were not included in the previous analysis. One cost associated with operating on a timber stand is the fixed cost of securing, maintaining access to and managing this stand. This cost may be thought of as an infrastructure/access cost, including payment by the firm for roads to be built and maintained and other

services that are required for the harvest to take place each period. These activities require payment for the human as well as the machine hours involved. The requirements on each portion of land are variable from one stand and one region to another and present the timber license holder with a heterogeneous set of stand costs.

To explore the impact of heterogeneous infrastructure costs on the firm's profit maximizing decision-making, a modified version of the model described in the previous chapter is developed. The forest is assumed to be divided among a number of stands all owned by one firm. Each stand has a unique accessibility and associated access/infrastructure cost. The assumption is that the firm has to pay out this infrastructure maintenance cost at the beginning of each rotation to keep up the access to and quality of the stand. The fixed cost for the firm to maintain their timber stand may influence the ranking of policies. As a firm chooses not to harvest a particular stand in its inventory because the fixed cost is prohibitively high, the stand is then left unharvested and the in situ carbon and biodiversity-wildlife benefits are the only two components of the social welfare function. Thus, a particular stand will still generate positive social welfare even if the firm chooses not to harvest. The firm will choose not to invest in the unharvested stand and the stand's volume will be a function of time with only a nominal amount of silvicultural investment. The social welfare function for a given forest is then the aggregated social welfare accumulated by one firm with a number of harvested and unharvested stands. The same policies that were implemented in the previous chapter will be used in this analysis. Each policy will have a unique threshold level of the fixed cost where the firm will generate zero profit and thus will be indifferent between harvesting and not harvesting that stand. In the case where a firm is indifferent, no harvesting will

take place. The social welfare accumulated from each stand under a given policy will be aggregated as well as the social welfare accumulated from those stands that the firm chooses not to harvest. A discrete number of stands will be included in the aggregation to capture a range of low to high infrastructure costs.

## 4.2 Research Question and Objective

This chapter explores the impact of heterogeneous access costs on social welfare as modeled in the third chapter. The impact of pre- and post- harvest requirements and the associated costs on a firm's profitability, the ancillary environmental values and ultimately the social welfare function are explored from a multi-stand perspective. The research question being asked in this chapter is the following:

Are the policy rankings established in the first analysis consistent with a heterogeneous multi- stand timber industry and what is the impact on social welfare of firms 'exiting' the industry for certain stands and allowing these stands to mature (i.e. What is the trade-off between firm revenue/volume and environmental value of an unharvested timber stand?)

The research objective of this chapter is the following:

To ascertain whether or not more complexity and thus possibly more realistic scenarios can be built into the policy framework in the form of heterogeneity in stand access/infrastructure costs and whether these costs will shift the ranking of forestry policies from the initial economic analysis.

### 4.3 Literature Review

Many economists have looked at heterogeneity from the perspective of international trade and exporting (Das, Roberts and Tybout 2007, Yeaple 2004, Bernard, A., J. Eaton, J. Jensen and S. Kortum 2003). Heterogeneity is a natural fit for international trade as firms' relative competitiveness is very important. The issue of firm competitiveness in entering an industry is another area of heterogeneity that has been explored (Barbosa 2003). Other authors have explored the area of entry in industrial organization from a number of perspectives (Dixit 1980, Kadiyali 1996, and Tirole 1989). There has been some work done on firm heterogeneity in the forestry industry (Athey and Levin 2001, Baldwin 1995) mostly to do with timber auctions and risk aversion. Bolkesjo et al. (2005) found that a firm may be better off if they choose to conserve parts of their inventory subject to some financial compensation. Crepin (2003) evaluated the optimal harvesting decision for complex forests. Crepin's results showed that the optimal strategy is dependent on a number of factors, including the state of the forest, and that given the heterogeneous nature of a forest, more than one strategy may be optimal. Bolkesjo and Solberg (2007) also looked at a forests' heterogeneity and the impact of this complexity of policy making in forestry. The effect of stand diversity on timber prices has been analysed in the literature (Boltz and Jacobson 2002).

This type of firm heterogeneity surrounding investment can be thought of as a branch of the economic theory of technology adoption. Technology adoption refers to how new innovations are developed, how their benefit is communicated to potential adopters and then the process through which the innovation is adopted. In the case of silvicultural/

stand management adoption, policy makers along with other private forestry initiatives (ISSBC 1999, Sullivan et al. 2001), conduct research to determine the most appropriate and effective silvicultural methods to maintain timber volume and address some of the sustainability issues in forestry. These silvicultural practices will continually change as new technology and capabilities develop and a firm can make decisions based on the cost of the investment and its profitability. The final stage of technology adoption is to determine if, how, and when firms will decide to adopt any given practice.

Edwin Mansfield (1961) described a general firm adoption model in which he explored the factors that determine how quickly knowledge of a new technology diffuses between firms and is subsequently adopted (Mansfield 1961). His work explained earlier results (Bain 1963, Griliches 1957), who reported an S-shaped adoption curve that measures the percent of adopters of the total population. This curve explains that the rate of adoption is an increasing function of time. Mansfield's model assumes an increasing correlation between quantity of technological information and desire to adopt a given technology. He models the rate of adoption as a ratio of adopters at time  $t$  to non-adopters. This ratio is a function of adopters by time  $t$ , the profitability of adopting, the size of the investment required to adopt and other unspecified variables (Mansfield 1961). The rate of technology diffusion increases as its profitability rises and the cost of adoption decreases. Mansfield's model is limited by the assumption of homogeneous firms and the failure to address the dynamic aspects of adoption including decreasing costs through time (learning-by-doing) among others. A less restricted model was formulated by Just and Zilberman (1983), who model technology adoption in agriculture as a discrete choice. Net revenue per unit of input (per stand) is assumed to be greater under the new

technology and there is a fixed cost of adoption. With a given distribution over the particular input (land size or number of trees), there will be a critical point in that distribution above which adoption is universal. The adoption curve is shown again to be S-shaped and a function of the density function of the input and the dynamics of the fixed cost as well as profit. This model can be extended to include other sources of firm heterogeneity (besides land size or acreage) as well as partial adoption, which will be useful in the case of forestry.

The technology adoption framework is useful in the case of stand heterogeneity. The main difference in this case is that a firm will choose to either invest and harvest or make no investment and opt out as opposed to choosing not to adopt a given technology but still remaining in the industry. Thus a firm choosing to harvest a given stand will also choose to invest, and a firm choosing not to harvest a particular stand will not invest. The firm's choice depends on their own cost of adopting or investing with no reference to time as is the case with traditional technology adoption. Although a more complex model could explore the possibility that a firm is likely, over time, to be exposed to social/financial pressure in the case of its environmental impacts. The firm may be forced to amend their harvesting practices as a result of consumer pressure overtime. Thus, in this chapter, I assume cost of adoption are fixed over time. The adoption function will be a similar to shape to the S-shaped curve above, however in this case, the curve is a function of cost and policy instead of time and number of adopters.

In Canada, and especially in British Columbia, where most of the timber is publicly owned and economic activity is dictated by a few long-term license agreements and high entry costs, free entry into the market by new firms is uncommon. Heterogeneity enters Canadian forestry in the form of diverse forest stands in a given forest region resulting in a range of firm investment and harvest choices. A firm's decision to harvest a stand and stay in that particular market as opposed to leaving a stand unharvested as they choose to exit that market is a form of market entry and exit. Firm decisions to exit a market are also an important area in industrial organization and have been dealt with in general terms by several economists (Ghemawat and Nalebuff 1985, Whinston, M.1988, and Lieberman 1990). Gong and Lofgren (2007) looked at the heterogeneity problem from the perspective of timber reservation prices. The authors found that at certain prices, a particular stand will be harvested and at other prices, the stand may be left unharvested. Although the firm may remain in the industry to harvest other stands, the firm's decision to leave a stand unharvested is a function of various costs and policies associated with that stand. Some of the specific activities that must be undertaken before harvest takes place include: pre-harvest inventory and mapping of trees; pre-harvest planning and building of roads and skid trails; constructing landings of optimal size; and minimizing ground disturbance and slash management (personal communication with Thomas Sullivan)<sup>5</sup>. In British Columbia there are specific responsibilities and pre-harvest costs that are the responsibility of the licensee. The Ministry of Forests and Range outlined these requirements for licensees in British Columbia's Interior region for 2006. In each forest stand, the licensee is required to conduct and pay for road development and

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<sup>5</sup> Thomas Sullivan, Professor, Faculty of Land and Food Systems, The University of British Columbia.

management including erosion control, flood and storm damage and access maintenance (BC MFR (2006)). The implication of this is that each stand has unique pre and post harvest costs, making a timber firm's inventory of stands a heterogeneous set.

This chapter extends the current literature in the field by looking specifically at heterogeneous forest stands in terms of costs to the license holder and the effect of this stand diversity on firm decisions and the social welfare ranking of forestry policies. The previous chapter looked at the firm's investment decisions around silviculture and environmental management. This chapter explores the firm's decision to stay in or exit the industry of a particular timber stand which can be thought of as a discrete decision to invest or not. If the firm chooses to harvest then they must choose how much to invest and if it is not profitable for them to harvest, they choose not to invest and not to harvest. Timber stand heterogeneity produces an indifference curve where the firm is indifferent between operating on a given timber stand and choosing not to operate. The curve will be a function of an infrastructure/access cost, and the number of stands being invested in will depend on the policy. Each policy provides a firm with a unique indifference point where profit from harvesting a given stand is zero. For policies that generate more profit, the indifference point will be higher than for those policies that generate less profit.

## 4.4 Methods

### 4.4.1 Simulations and Parameterization

The simulations were conducted using Mathematica 6.1© with the same parameter values, assumptions and calibration as chapter 3. The heterogeneous access costs for this chapter include access, infrastructure and maintenance costs associated with operating a one-hectare timber stand. The magnitudes of the additional costs to the firm were chosen so that there were some stands that were too costly to harvest. The intention was to create a situation where different policies potentially meant a different number of harvested stands. The new access costs never enter the social welfare function since they are not a component in firm revenue, so the costs were never calibrated for the model's results. However, if the costs were calibrated in the same way as revenue, expenditure and volume, these costs would range from just over \$600 to over \$12,000 per stand. The requirements and costs to maintain a given timber stand overtime depend on many factors, including geography, previous maintenance and legislation. As a result, the actual cost range is difficult to estimate. In BC's southern interior forest region, the cost of building a new road was estimated to be round \$6,000 per kilometre, the cost of installing a culvert ranged from \$500 to \$30,000 depending on the size, and the cost of installing a cattle guard was estimated to be around \$3,000 (BCFS 2004). These costs give a general idea of some of the kinds of costs a firm may face on a timber stand.

#### 4.4.2 Firm's Profit Function

The profit function is essentially the same as that used in the third chapter. The profit maximizing timber company will be modeled using a traditional Faustmann formula extended to include an investment decision variable for the firm and in this case an access cost variable to account for different stands' accessibility or infrastructure cost. A modified Faustmann, which includes stand investment (s) as a lump sum one-time input (fixed cost per rotation) and access/infrastructure cost as a lump sum one-time investment ( $\beta$ ) (once per rotation) changes the profit function and the first order condition:

$$\pi = \frac{(p - c)v(t)e^{-rt} - sw - \beta}{1 - e^{-rt}}$$

$$\frac{d\pi}{dt} \rightarrow \frac{(p - c)v'_t}{(p - c)v(t) - sw - \beta} = \frac{r}{1 - e^{-rt}}$$

$$\pi(t, s) = \frac{\alpha(p - c - \lambda w_\lambda)v(t, s)e^{-rt} - sw - \beta}{1 - e^{-rt}}$$

Simplifies to:

$$\frac{d\pi(t, s)}{dt} = \frac{e^{-rt}}{(1 - e^{-rt})^2} \alpha(p - c - \lambda w_\lambda) \left( (1 - e^{-rt}) \frac{dv(t, s)}{dt} - r(v(t, s) - sw - \beta) \right)$$

$$\frac{d\pi(t, s)}{dt} = \frac{-e^{-rt} r (\alpha(p - c - \lambda w_\lambda) (v(t, s)) e^{-rt} - sw - \beta)}{(1 - e^{-rt})^2} + \frac{e^{-rt} \alpha(p - c - \lambda w_\lambda) \frac{dv(t, s)}{dt} - e^{-rt} r (\alpha(p - c - \lambda w_\lambda) (v(t, s)))}{1 - e^{-rt}}$$

So solving the above gives the optimal rotation time,  $t^*$ .

For s:

$$\pi(t,s) = \frac{\alpha(p - c - \lambda w_\lambda)v(t,s)e^{-rt} - sw - \beta}{1 - e^{-rt}}$$

$$\frac{d\pi(t,s)}{ds} = \frac{e^{-rt}\alpha(p - c - \lambda w_\lambda)\frac{dv(t,s)}{ds} - w}{1 - e^{-rt}}$$

Clearly, the additional one-time infrastructure cost ( $\beta$ ) is not a function of either rotation time or investment and thus does not enter into these derivatives. For unharvested stands, the firm profit drops to zero since there is no timber harvested.

Stand heterogeneity is based on the cost of accessing and maintaining a given site. Thus, there will be certain stands that under certain policies are not profitable to harvest. The result in these cases will be that the land is left unharvested and social welfare is a function of only the environmental values that accumulate in the unharvested stands. In these cases, there will be no investment by the firm and only an investment of one unit by the government to enable the volume function to maintain its properties. In the case of absolute zero investment ( $s=0$ ), the volume function is negative given the specific functional form. This result is counterintuitive and obviously incorrect since stands produce volume without silvicultural investment. This one unit of  $s$  can be thought of as a small cost to maintaining some sort of natural value in the stand, which may include fire suppression activities or preventing landslides.

#### 4.4.3 Social Welfare Function

The social welfare function is essentially the same as in the previous chapter. For the harvested stands, this means the four initial components are summed up in the function, these include revenue, government expenditure, carbon sequestered and biodiversity-wildlife habitat accumulated. The output from the firm's maximization of the harvestable (i.e. profitable) stands ( $t$ ,  $s$ , volume, revenue) is entered into the social welfare function components to determine the amount of social welfare created by each policy under the particular set of assumptions and parameter values.

For unprofitable stands, investment is set at one unit ( $s=1$ ), and the social welfare is calculated without revenue and is the same for each unharvested stand. To be able to calculate the accumulation of carbon and environmental value in the stand, the rotation time must be set at a given level for the unharvested stands. This level is set at 250 years to take into account the deterioration of tree volume through time but also the increasing soil carbon and other biodiversity-wildlife values through time. The unharvested stand's output is discounted at the same rate as the harvested stand. As well, an assumption is being made that the infrastructure cost is the same at the beginning of each rotation over infinite rotations. This means that if the firm chooses not to harvest a given stand today, it will not harvest this stand indefinitely. So the social welfare accumulated on this stand will be the same through time. The stands that are too costly for the firm to harvest will accumulate in situ carbon in the biomass and biodiversity-wildlife value, which includes soil carbon, biodiversity, habitat value and other intrinsic values of a natural stand.

In this heterogeneity analysis, only the social welfare with the environmental value is considered since the chapter deals with the unharvested stands, where the environmental value is recognized, and the harvested stands. The aggregated social welfare from all twenty stands is then compared across policies to determine the ranking of the policies.

#### 4.4.4 Policies

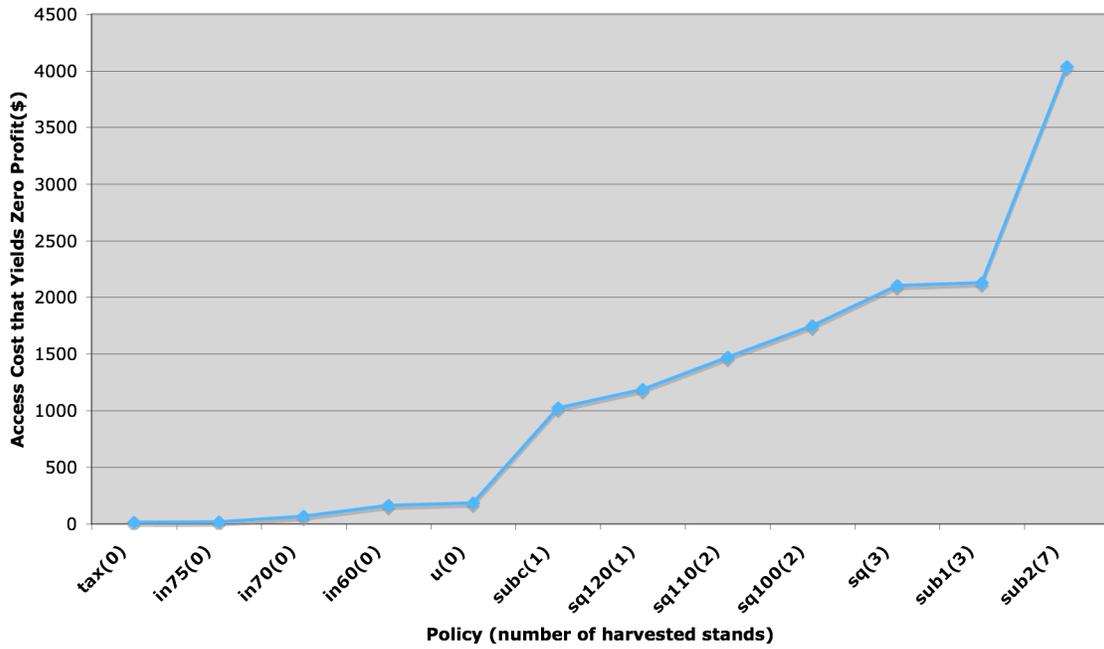
For the heterogeneity case, the initial simulations were run on essentially the same policies given in the initial model (see chapter 3). One difference here is that the firms are paying an infrastructure cost ( $\beta$ ). This cost is a lump-sum up-front cost that is discounted over infinite rotations.

## 4.5 Results

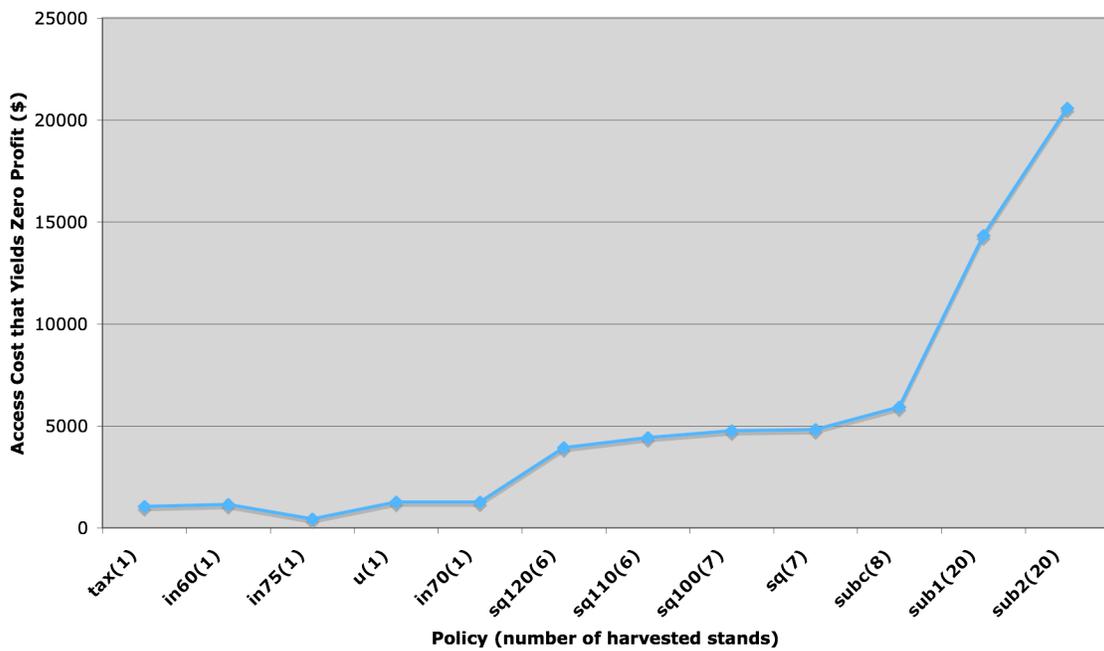
### 4.5.1 The Indifference Curve

The firm has tenure to twenty stands of trees each with a unique access/infrastructure cost. The firm is indifferent between staying in the market and not when their profits are zero and in this scenario, they opt out of the market at zero profit. The indifference function can be described in a graph with policies on the horizontal axis and access costs on the vertical axis. The curve describes each policy's indifference point where profits are zero under a 3% discount rate (Figure 4.1) and a 2% discount rate (Figure 4.2). As the discount rate falls, the indifference costs increase. These figures show that as the access cost rises, there are fewer policies with positive profits. With a 3% discount rate, there are several policies that do not allow any stands to be harvested. The policy that allows the firm to harvest the most stands is the comprehensive subsidy policy (sub2) with 7 of 20 stands harvested. The higher the indifference cost for each policy, the more stands become profitable to harvest. Under the 2% discount rate, more stands are harvested, up to twenty of twenty for the comprehensive subsidy policies (sub1 and sub2). The general trend for a 2% discount rate is the same, with the subsidy policies and the unconstrained status quo policy allowing the firm to harvest the most stands and having the highest indifference access cost. Although more stands are harvested, the policy ranking and outcome under a 2% discount rate is the same as under a 3% discount rate so the 2% results are not presented. Refer to Appendices C and D for indifference cost results.

**Figure 4.1: Access cost indifference curve by policy for a 3% discount rate**



**Figure 4.2 : Access cost indifference curve for a 2% discount rate**

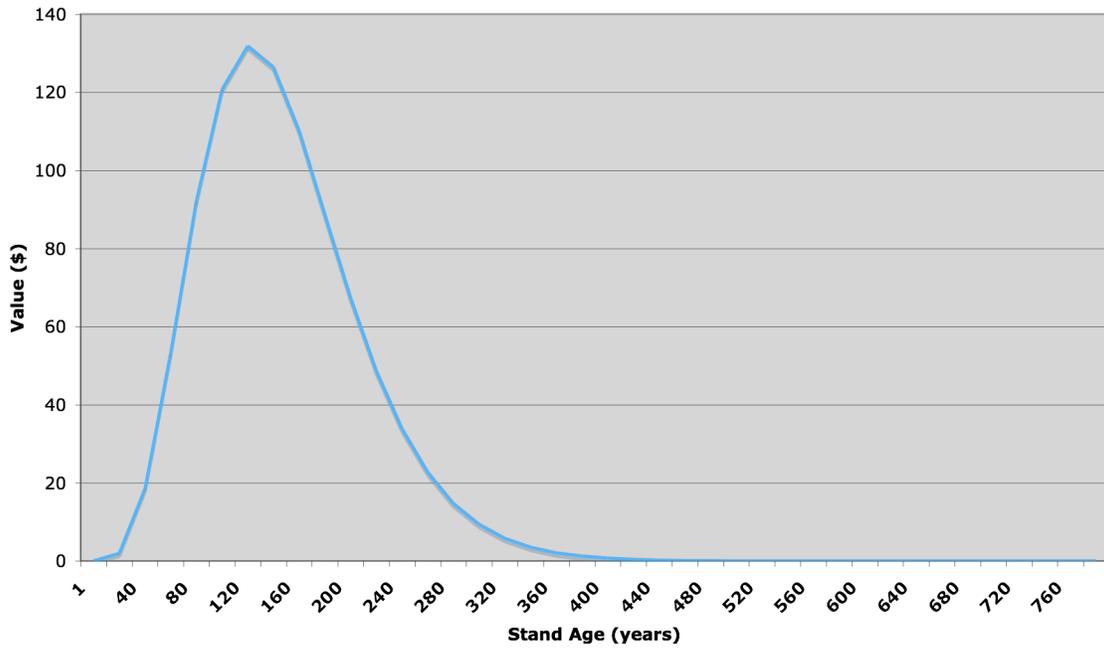


#### 4.5.2 The Unharvested Stand

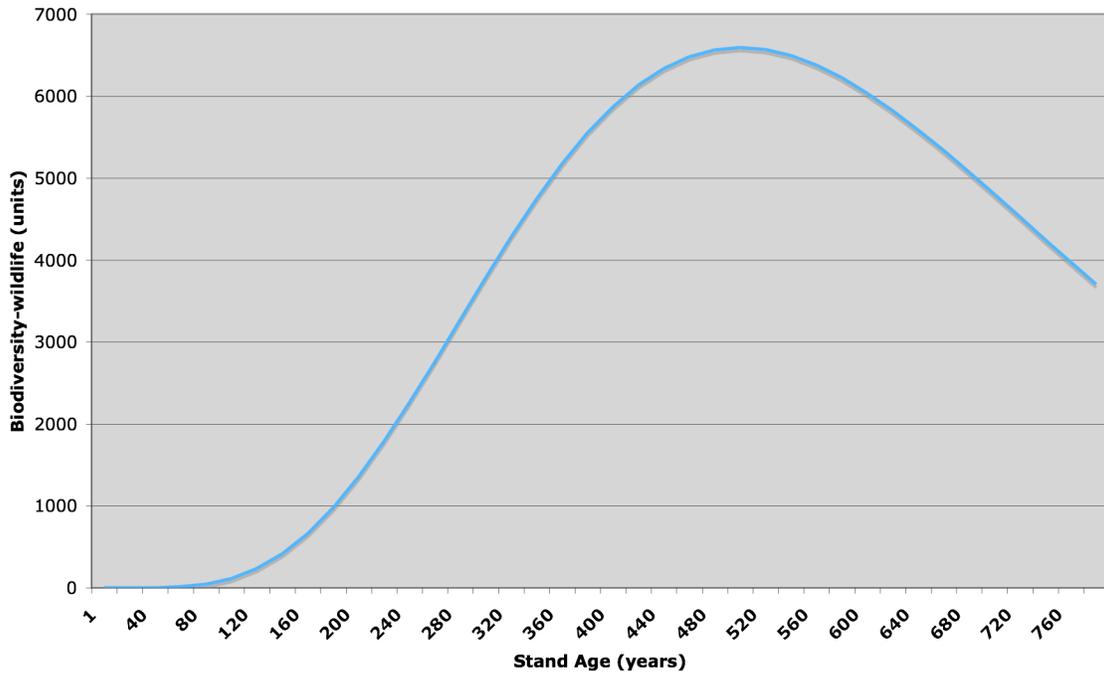
The unharvested stand generates social welfare through the carbon sequestered and biodiversity-wildlife values accumulated at a stand age of 250 years. These values are calculated using the same functions as in the harvested stand. However, there may be intrinsic natural value in a stand that is left unharvested, making this unharvested stand's carbon and biodiversity-wildlife outputs more valuable than the same stand at 250 years just before harvest. However, for a comparison of social welfare between policies, the harvested stand and the unharvested stand are assumed to produce comparable environmental outputs at the same stand age. The only difference between the two stands is the effect of investment on the forest outputs for the harvested stands. The policy implications of the disparity between the values of the harvested stands and the unharvested stands are explored later in the discussion.

The unharvested stand's carbon and biodiversity-wildlife output is also discounted at the same rate as the harvested stands' output. Discounting the environmental output from a forest stand that is not being harvested indefinitely means that there is less and less value, the older the stand. The value of the biodiversity-wildlife component at a 3% discount rate, peaks at 122 years (Figure 4.3) whereas the magnitude of biodiversity-wildlife output peaks at 500 years (Figure 4.4). Biodiversity-wildlife accumulation in a natural stand is significant and increases well past the point where its value peaks. Refer to Appendix E for unharvested stand results.

**Figure 4.3: Environmental value of the unharvested stand at a 3% discount rate**



**Figure 4.4: Total biodiversity-wildlife output**



Although there is a considerable amount of biodiversity-wildlife output accumulated over a 250-year period, the discounted value of this output is less than the biodiversity-wildlife value of a harvested stand after a 52-year rotation. Also, in situ carbon decreases through time following timber volume, which peaks at around 150 years. The implication of this is that biomass carbon is relatively low for a 250-year old stand. There is even more disparity between the harvested and unharvested stands' environmental values since the timber firms invest in harvested stands and as a result, both the biodiversity-wildlife and the carbon output is greater as investment increases. This is exemplified in the following result: At 250 years with one unit of investment and a discount rate of 3%, the unharvested stand accumulates only 45% of the total carbon and biodiversity-wildlife value accumulated in a harvested stand managed under an unconstrained (u) policy where the firm maximizes profit by setting  $t$  at 52 years and  $s$  at 7 units. This is a result of the model's parameters and functional forms.

There is relatively little environmental value after 250 years in a natural stand, which in the case of lodgepole pine may be somewhat accurate since volume peaks at around 140 years. For other forest species there would be more environmental value. However, regardless of the species, given current forestry discount rates, no investment and the economic parameters of a forestry model, the environmental value from a natural stand after 250 years will be significantly less than the absolute amount of environmental accumulation from that stand. Chapter 5 deals explicitly with the value of an old growth stand including a premium to capture the intrinsic value of a natural stand. The preceding analysis highlights the impact that the discount rate can have on the outcome of a time-

sensitive valuation. The disparity that the discount rate creates between the harvested and unharvested stands is explored later in the discussion.

### 4.5.3 Further Results

For the following analysis, a discount rate of 3% is used to compare policies to determine the policy ranking in a heterogeneous setting. As stated above, simulations were run using a 2% discount rate but the results did not reveal anything significantly different and are thus not presented here. The unharvested stand will yield the same social welfare for every rotation for infinite rotations. The social welfare from the harvested stand will not be impacted by the higher access cost explicitly since it is only firm revenue that is included in the social welfare, not firm profit. However the access cost will affect the firm's input decisions, and consequently output, and will also determine the number of harvested versus unharvested stands.

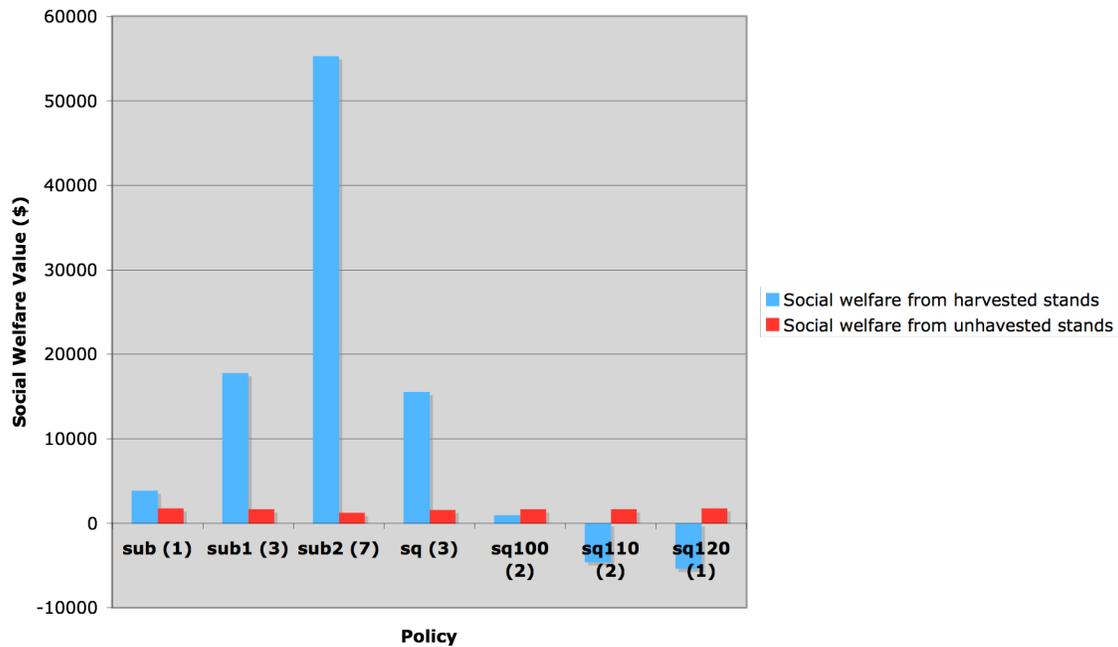
#### *4.5.3.1 Simulations*

Twenty simulations were run on each policy to ascertain the effect of twenty different access/infrastructure costs on the firm's behaviour and overall social welfare ranking. The twenty stands are the same for each policy, and each policy has a different break-even point given the access costs. Once the access costs are calibrated for a one-hectare,

one-stand model, the access costs range from just over \$600 to over \$12,000 dollars per stand. At a 3% discount rate, there are several policies that result in the firm leaving every stand unharvested. These policies include the unconstrained policy (u), the input policies (in60, in70, in75) and the taxation policy (tax). For these policies the firm cannot recover a profit under any of the twenty stands' access costs and thus the aggregate social welfare is just the sum of the value of the twenty unharvested stands' social welfare. The rest of the policies result in the firm harvesting some of the stands and not others. In some cases, social welfare is so small from the harvested stands that the preferred policy is to leave the stand unharvested.

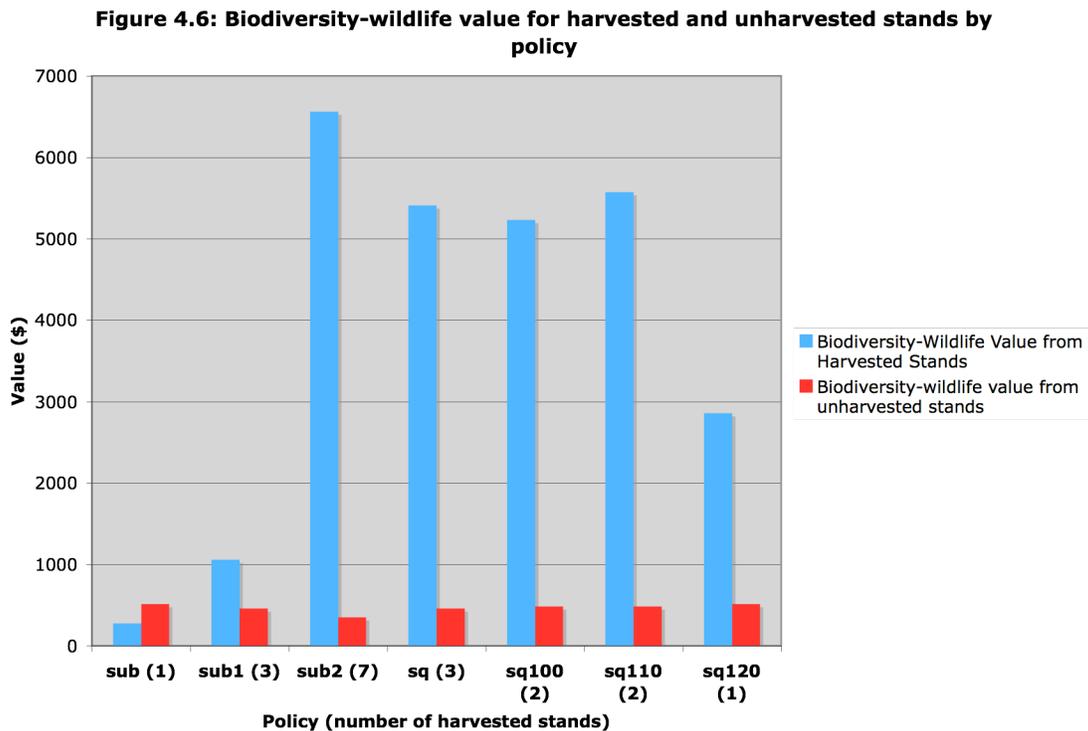
For the subsidy policies under a 3% discount rate, the maximum number of stands that were harvested was seven of twenty. The comprehensive environmental subsidy policy (sub2) policy resulted in seven stands being harvested, yielding over \$55,000 in social welfare, when full environmental values were included, compared to just over \$1,200 dollars in social welfare for the remaining thirteen unharvested stands together (Figure 4.5).

**Figure 4.5: Social welfare for harvested and unharvested stands by policy (with number of harvested stands in parentheses)**



The objective of these simulations, however, is not to compare the value of the harvested versus unharvested stands, but instead to compare the value (social welfare) of each policy. Under the sub2 policy the firm chooses a rotation time of 67 years for a lower cost stand and up to 70 years the higher cost stand. As the rotation lengthened in response to the higher cost, the silvicultural investment fell. The harvested stands generated more biodiversity-wildlife value compared to the unharvested stands, as a result of the time frame and limited investment. Under the preferred sub2 policy, as the access costs increase beyond the seven stands, the firm chooses not to operate and leaves the remaining thirteen stands unharvested. The policies that generated the least amount of social welfare were the long rotation status quo policies. These policies created a relatively high biodiversity-wildlife value (Figure 4.6), but this was outweighed by the large government expenditure for the silvicultural investments. These results reveal that

in a heterogeneous forest with different access costs for timber stands, the optimal policies are still the environmental subsidy policies for the stands that are harvested. For the prohibitively costly stands, more social welfare is generated by leaving the costly stands unharvested and accounting for the environmental value from these stands. The long rotation status quo policies actually generate less social welfare than the unharvested stands. In general, however, there is a significant differential between the two types of stands' aggregate social welfare.

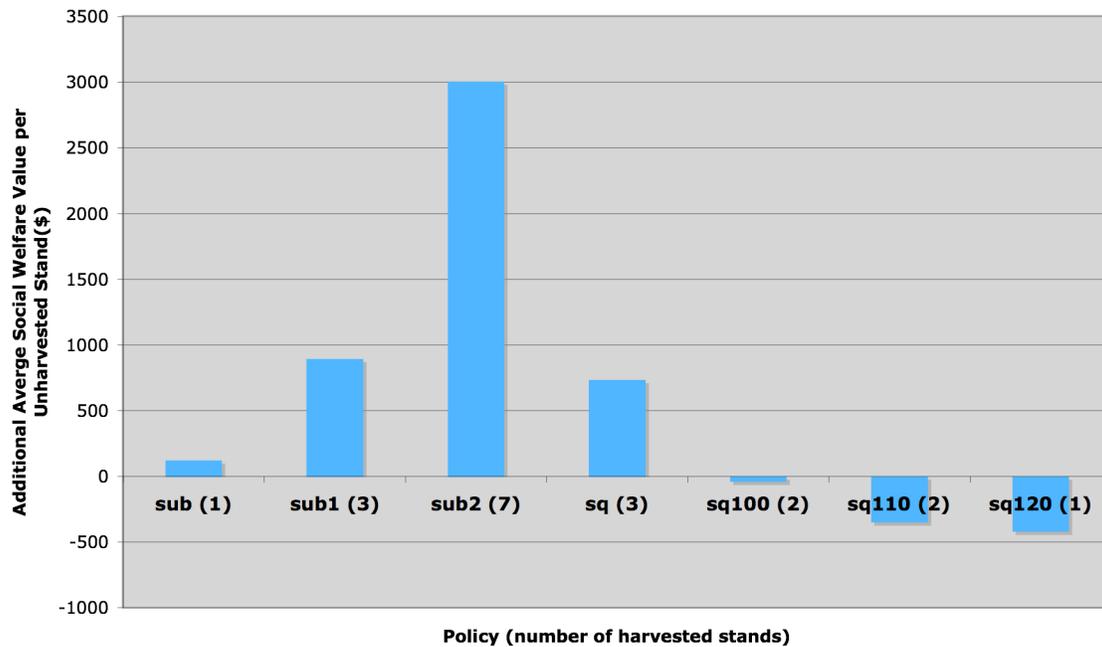


There are between one and seven stands harvested per policy and thus thirteen to nineteen stands are left unharvested each rotation. These multiple natural stands do not generate as much biodiversity-wildlife value as a few harvested stands for most policies particularly

for the subsidy policies (Figure 4.6). Although the natural stands are accumulating biodiversity-wildlife value and carbon value, the stands are not invested in and because of the discounting, the natural stands are not worth very much in this analysis. In this zoned landscape, there are on average more unharvested stands than harvested stands, yet at this discount rate, the social welfare from the very few harvested stands exceeds that of the unharvested stands.

If society inherently values an unharvested stand equally or more than a harvested stand, there must be an explicit value added to the unharvested stand that is not part of the harvested stand's social welfare function. On average, each unharvested stand would need to be valued by a specific dollar amount more than it is already in order for the unharvested stand to be of comparable value to the harvested stand (Figure 4.7). The long rotation policies (sq110, sq120) generate more value when no stand is harvested, meaning that this additional value is negative. For the other status quo policies, the unharvested stand does not have to be worth that much more to be comparable to the harvested stand.

**Figure 4.7: The average additional value for each unharvested stand to be worth the same as a harvested stand by policy**



However, for the subsidy policies, the more the government compensates the firm, the higher the social welfare from the harvested stands and the bigger the differential between harvested and unharvested stands. The more valuable a harvested stand is the more priority must be given to the natural stand to make the two comparable.

A lower discount rate means that more stands are harvested and thus the differential between the harvested and unharvested stands' social welfare is even greater. The result is that each unharvested stand needs to be valued that much more for the two types of stand to generate comparable social welfare. Even under a 3% discount rate, for the unharvested stand to be comparably valuable to the harvested stand, excluding the long rotation status quo policies, society would have to value the unharvested stand between 700% and 3100% more than the original unharvested stand, depending on the policy. As

a harvested stand generates more social welfare under preferred policies, the unharvested stand does not. The more social welfare a policy generates, the more costly it is for natural stands to be valued in the same way as harvested stands.

## 4.6 Discussion

Each policy in this model creates a simplified zoning-type landscape of stands. Some stands are harvested and some are not, in accordance with the firm's profit maximization problem. The heterogeneous forest generates similar results to the homogeneous single stand forest of the previous chapter. The policies that compensate the firms for their environmental contribution generate the most social welfare. The cost to society is lower under the subsidy policies since the subsidy nets out and the firm chooses longer rotation time and more silvicultural investment than if it was left unconstrained.

Depending on the social priorities of society, and given the economic factors outlined in a firm's profit maximizing problem and the government's social welfare function, a harvested stand of trees could be worth much more than an identical stand of trees left unharvested (or at least unharvested for a significant length of time). Given the model's functional forms and parameterization, the unharvested stands are generating less environmental value than the harvested stands. This result is consistent for a timber-focused society with a relatively low priority for carbon sequestration and biodiversity-wildlife accumulation. Although the social welfare weighting is the same for revenue, carbon, biodiversity and government expenditure, the environmental functions themselves yield relatively low levels of output once they are discounted over several hundred years. The definition of the unharvested stand in this model is a stand left untouched each rotation period for 250 years. As mentioned previously, the model does not account for any inherent value that an unharvested stand may generate. Since the

unharvested stand generates relatively little social welfare under the initial parameterization, only stands that generate very little or negative profit if harvested will generate more social welfare if left unharvested. Most other stands that generate positive profits when harvested will be preferred to an unharvested stand. The implication of this is that a timber stand that is prohibitively costly to harvest will not contribute very much to society (relatively). However, if society values the environmental output from unharvested stands as much or more than from harvested stands, there may be intangible value in a natural stand of trees that is not captured in this model. If this is the case, there is an opportunity for policy makers to assess this intangible value and determine when a stand ought to be left unharvested. By adding a 'natural premium' to unharvested stands, social welfare may more accurately reflect the value in unharvested natural stands.

The caveat is that, as the previous results show, if society wanted to account for some intangible value inherent in an unharvested stand of trees, the cost to society of leaving a previously profitable stand unharvested is significant. The cost of this natural premium is higher as more socially valuable policies are implemented and even more as the discount rate falls. Stands previously harvested under the socially preferred subsidy policy (sub2) would be very costly to replace with unharvested stands. In our current economic paradigm, there is a high opportunity cost of leaving economically valuable stands to naturally develop and decay if the socially desirable policies are adopted.

## 5 A British Columbia Case Study

### 5.1 Introduction

British Columbia forestry is in a transition from mostly old growth harvesting to a second growth industry at a time when there are environmental and economic challenges facing the Province. In the southern interior, the current mountain pine beetle epidemic will result in timber volume insecurity over the coming decades. The projection for beetle-infested trees is that 57 million cubic meters will be killed by 2015. The harvest levels will increase over the next several decades to capture the mountain pine beetle wood, but will be followed by a ten percent decrease after forty years, with the lowest timber supply in decades to come in seventy to eighty years (BC MFR 2006b). British Columbia is also home to diverse and important forest ecosystems. A successfully managed forest in southern British Columbia would mean adequate timber supply and a healthy timber industry in the long run, as well as a thriving natural forest ecosystem. The theoretical model developed in the previous chapters is used to explore some of the competing objectives within the southern interior forest region of British Columbia. British Columbia's forestry policy makers, The Ministry of Forests and Range (MFR), manage the public forest resource for economic, social and environmental value. The tenure holders in the province are for the most part large timber companies who are managing the resource to maximize their profit. The level of investment in silviculture and stand management is the responsibility of these two primary stakeholders/actors. As a result, the amount and subsequent impact of this investment on timber volume and other externalities (environmental and social) is a direct result of the government and timber

firms combined decision-making. A basic level of silvicultural investment, consisting of planting and a limited amount of stand management, is required of the tenure holders by law and is thus undertaken consistently by the firms. Additional silviculture and stand management (shown in chapter 2 to create positive environmental externalities) is very limited in the province. The MFR invests only minimally as do the timber companies who do not have enough incentive to invest significantly in their tenured holdings. Thus, the productivity of the Province's forests is a function of the decision-making of a profit-maximizing firm who is given little economic incentive to invest and the MFR who often operates within a volatile political climate with a fickle budget.

#### 5.1.1 Research Questions

What are the public and private timber and environmental objectives that have been set out by policy makers and timber companies in British Columbia, and are these objectives being satisfied?

If not, given the general and specific objectives for a timber supply area (TSA) in the southern interior of British Columbia, are there policies that could increase social welfare by meeting these objectives more successfully?

Given that there are some competing objectives in this timber supply area, is there a scenario that creates more value by pursuing different objectives on different forest stands?

This chapter will outline the economic and environmental objectives of the MFR over a specific TSA in the province, as well as the objectives of a large timber company operating in that TSA. The actual investments and economic and environmental outputs from that TSA will be presented to determine the reality of implementing subsidy and rotation-time policies in a specific forest case study. The mountain pine beetle infestation in the region means that over the next few decades there is an accelerated need for effective policy to achieve constant timber supply among other objectives. Since second growth forestry (and specifically post-beetle forestry) is taking on greater importance in the province, the Okanagan TSA will act as a test case to determine the potential for second growth subsidy and rotation-time policies to play a role in achieving the region's desired objectives. The Okanagan TSA was selected since it represents an important economic region of the province, is susceptible to future pine beetle attack and there is recent and reliable data available on effects of silviculture on lodgepole pine forests.

## 5.2 B.C. Forestry

### 5.2.1 General Government Objectives and Action

*The State of British Columbia's Forests* was published in 2006 by the MFR to provide the province's stakeholders with an assessment of the government's progress in achieving the primary objective of sustainable forest management.<sup>6</sup> The State of the Forests report outlines the specific indicators, and their effectiveness, that are used to determine the Province's success in realizing this lofty goal. The indicators fall into three categories: environmental; economic and social; and governance and support. The indicators that will be used in the following analysis include: timber volume/timber harvest and silviculture (economic indicators); and species diversity and air quality/greenhouse gases (environmental indicators). Governance and support are not explored in this analysis. The report outlines the current condition and trend for each indicator.

The state of the timber harvest, as we are just on the cusp of the beetle impacts, was deemed to be in good condition, with levels within sustainable limits. The trend is decreasing due to the post-beetle harvests. As the mountain pine beetle trees are killed and/or harvested, the temporary increase in timber volume will be followed by up to a 12% decrease in allowable annual cut (AAC) levels in some areas. Current levels of silvicultural investment in the province were considered more than adequate with high

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<sup>6</sup> According to this report, the promise of sustainable forest management means that "the long-term health of Canada's forest will be maintained and enhanced, for the benefit of all living things, and for the social, cultural, environmental and economic well-being of all Canadians now and in the future" (BC MFR 2006a, p. 16)

levels of reforestation and moderate investment into certain silvicultural practices such as choosing genetically superior seeds for planting (called select seed). However, funding for silvicultural investments in general has fallen over the past few decades, which, combined with certain regional challenges, such as the mountain pine beetle epidemic, is forecasted to result in some significant difficulties in the future. British Columbia has a naturally diverse forest ecosystem, however the current state for species diversity in the province was deemed by the report to be mixed as forestry practices continue to impact habitat. The future trend for species diversity was assessed to be deteriorating. Only very limited information on both air quality and greenhouse gases was presented with no assessment of the current state or trend for the future (BC MFR 2006a).

#### *5.2.1.1 Timber Harvest/Volume*

Over the last ten years the average yearly timber harvest in British Columbia was over 75 million cubic meters, eighty-eight percent of which was regulated by the government's annual allowable cut (AAC), as set by the chief forester of the province. In 2005, over ninety million cubic meters were harvested in total, eighty million under the AAC, and the remaining ten million cubic meters were unregulated and mostly from private lands. These harvest rates are still below the sustainable level (BC MFR 2006a). Over the next five years, it is forecast that as a result of the mountain pine beetle epidemic, particularly in the southern interior lodgepole pine stands, there will be a significant increase in the AAC to capture as much commercial value from the beetle-infested trees as possible before they lose their merchantability. Following this increase in harvesting, there will be

a natural decrease as the next rotation matures to harvestable age. The gap in timber over this period may result in economic and social challenges in the province. Properly managed second growth timber stands may provide a bridge to this gap if the funding and political issues in the province can be overcome to adequately invest in these stands.

#### *5.2.1.2 Silviculture*

There are two primary avenues for silvicultural investment in the province. Reforestation of harvested or otherwise degraded land is the first and most basic form of silvicultural management. Reforestation is the legal obligation of the tenure holder on any given timber area and reforestation levels over the past decade have been well within the legal time limit for reforestation following a disturbance (BC MFR 2006a). Once the trees have been planted, the management of those trees is the second type of silviculture that takes place. Certain second growth stands respond well to fertilizing, thinning, and pruning among other possible inputs to enhance volume and other environmental outputs from the stand (see Chapter 3). The only type of silviculture legally required is the use of select seed planting, which consists of using genetically superior seeds to enhance the timber outcome.

Silvicultural inputs, including fertilizing, thinning, and pruning, which have been shown to increase volume and/or environmental quality, are modestly invested in by licensees and have been largely abandoned by the government over the past few years. From 1976 to 2006, silvicultural activities on timber stands in British Columbia included fertilizing

0.2 million hectares, pruning 0.06 million hectares and thinning 0.7 million hectares. (BC MFR 2006a). Of the over 6 million hectares of second growth forest in the province, these investment levels are relatively small. The benefit of these investments has been determined by policy makers to be relatively insignificant compared to other practices such as select seed. However, it has been shown that there are significant economic and environmental benefits from properly managing a stand of second growth trees using fertilizing and thinning among other inputs (see chapter 3). As expressed by Ralph Winter<sup>7</sup>, from the Forest Practices Branch of the Ministry of Forests and Range, forests can be compared to milk or wheat: cows don't make milk without being properly cared for, and farmers can't make wheat without carefully managing and investing in their crops. BC's policy makers and timber companies have historically relied on forests to produce timber output with little or no management effort. This regime has been successful when old growth timber stands were harvested, however, with second growth stands, particularly in the wake of the beetle epidemic, management investment is likely to add significant value.

Tight budgets have resulted in the MFR decreasing their incremental silviculture treatments (besides select seed), at the expense of enhanced timber volume and the positive environmental and economic externalities associated with these inputs. In 2006, there were a total of over 169,000 hectares of trees planted in British Columbia. Of these planted areas, just over 21,000 were fertilized (12%), 526 hectares were thinned (0.003%)

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<sup>7</sup> **Ralph Winter, RFP**, is a stand management officer with the Forest Practices Branch of the Ministry of Forests & Range. He is responsible for the Stand Management Unit which helps develop legislation, policy and guidelines related to silviculture. Ralph is also responsible for the implementation of the Incremental Silviculture Strategy for BC.

and 210 hectares were pruned (0.001%) (BC MFR 2007). The most striking result from these figures is that there are a significant number of second growth stands that are not receiving any incremental silviculture investment at all. Of these silvicultural accomplishments, the majority were funded by the province. Twenty four percent of the total thinning and 23 percent of the total pruning was privately funded and less than 5 percent of the total fertilizing was privately funded (BC MFR 2007). There is some contribution being made by the private sector, which indicates that licensees do see a benefit from some investment, however, a lack of incentives for the forest firms means that British Columbians are paying for the majority of the silvicultural investment. The issue is two-fold: first, given the empirical evidence that certain silvicultural activities enhance growth and can also increase positive environmental externalities from a forest stand, more silvicultural investment could potentially yield higher social welfare; second, adequate incentives for the licensees may result in more of the cost of the investment being born by the timber firms.

#### *5.2.1.3 Species Diversity*

British Columbia's forests are home to a diverse set of plant and animal communities. Among B.C.'s 3,201 vascular plant and terrestrial vertebrate species, almost half are forest-associated, including 721 vascular plants, 303 birds, 189 mammals, 81 freshwater fish, 20 amphibians and 10 reptiles (BC MFR 2006a). Appropriate forestry management is a critical component in maintaining the health of this ecologically rich forested landscape. Historical forest management and other disturbances have resulted in 106

forest-dependent plant and animal species in the province being on the red list, meaning these species are either extirpated, endangered or threatened.<sup>8</sup> According to the State of the Forests report (BCMFR 2006a), there is a downward trend in British Columbia for the biological diversity of the plant and animal species in forested regions. Habitat quality and quantity is deteriorating due to clear cutting and other practices. There have been several attempts made to improve this situation, including increasing the amount of protected forests in the province and focusing on species-specific breeding and recovery programs. However, since the amount of forest-related biological diversity continues to deteriorate in British Columbia, there is room for more investment in environmental stand management and/or more protected areas. Another simultaneous mitigation strategy that could be implemented in the province is to increase silvicultural investment such as fertilizing and thinning to create old growth characteristics, which would provide more wildlife habitat and diversity (Sullivan et al. 2006a & 2006b).

#### *5.2.1.4 Air/Greenhouse Gases*

In the State of the Forests report, there is a very brief section included on greenhouse gases and air quality (indicator 10 in BC MFR 2006a). In the International Panel on Climate Change (IPCC) Fourth Assessment Report 2007 there is an extensive section on forestry. According to the IPCC report, the degradation of primary forests (old-growth forests) has resulted in a considerable release of stored carbon. Protecting old-growth

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<sup>8</sup> The red list in British Columbia “[i]ncludes any ecological community, and indigenous species and subspecies that is extirpated, endangered, or threatened in British Columbia. Extirpated elements no longer exist in the wild in British Columbia, but do occur elsewhere. Endangered elements are facing imminent extirpation or extinction. Threatened elements are likely to become endangered if limiting factors are not reversed” (BC Ministry of the Environment, n.d.-a).

forests while simultaneously pursuing reforestation and proper forest management can help to increase carbon sequestration. In the IPCC report, some work is reportedly being done looking at the potential for Canada's forests to be part of the solution. Several scenarios were examined as potential forest-based carbon accumulation strategies. "Of the four scenarios examined, [t]he second largest estimate was obtained with annual, large-scale (125 million ha) low-intensity (5 kg N/ha/yr) nitrogen fertilization programmes" (IPCC 2001, pp. 553-554). The report goes on to suggest that these large-scale projects are likely not realistic, however, the finding highlights the role for terrestrial carbon sequestration. Protecting old growth stands that store relatively more carbon than younger stands will undoubtedly improve the carbon outcome. Second growth stands can be managed to produce old-growth characteristics (Sullivan et al 2006b) and more timber, while also providing some wildlife habitat and diversity value. If trees are managed to provide construction lumber (to be used in longer lasting end uses such as housing), the carbon will be stored for even longer. As well, stand management focusing on longer rotations and habitat quality will increase other longer lasting sinks of carbon, such as soil carbon (Schultze et al. 2000).

### 5.2.2 Southern Interior: Objectives and Strategies

British Columbia's policy-makers want to realize the potential that BC forests have to achieve economic, social and environmental objectives in the province. Each forest region in the province has unique geographical, political and economic features that

require careful and specific management. The following is a case study of one of the province's forested regions. Policies and actions that aim to realize the government's general objectives (outlined in the last section), any regional objectives and one timber company's objectives will be explored to determine whether there is a further role for forestry policy.

British Columbia's forest regions are divided into Coastal, Southern Interior, and Northern Interior. Each region is unique in its tree species and climate and as a result requires specific management to maximize the given region's output. For this case study, the Southern Interior is examined. The Southern Interior is a large forested area, comprising 25 million hectares, 60% of which is considered productive forestland. The AAC for the region is approximately 32 million cubic meters that generates over \$400 million in forestry revenue (almost 40 percent of British Columbia's total). There are fifteen timber supply areas, as well as woodlot licenses, tree farm licenses and community forest agreements. In the Southern Interior, there are generally over 90 million seedlings planted annually. The region has a number of tree species, the most common being lodgepole pine, which is the primary target for the mountain pine beetle, with over 4.7 million hectares of forestland having been infested by mountain pine beetle so far (BC MFR n.d.a). One of the fifteen TSA's in the Southern Interior is the Okanagan TSA, which covers 2.2 million hectares and includes the communities of Penticton, Vernon, Kelowna and Salmon Arm. The AAC for the Okanagan TSA is approximately 3 million cubic meters (in 2006 it was 3,375,000 cubic meters), nearly 10 percent of the entire Southern Interior's AAC. The Okanagan TSA is an important economic,

environmental and social part of the Southern Interior's forestry sector. The following analysis will focus on the Okanagan TSA where information is available and otherwise will use data from the Southern Interior as a whole (BC MFR n.d.a).

The silviculture strategy for the Okanagan TSA was updated for 2006 and outlines specific goals for the timber area in terms of silvicultural investment types and cost (BC MFR 2006b). The strategy outlines three major objectives for the area, namely, timber supply, timber quality, and habitat supply. One of the region's main objectives over the next half-decade is to address the current mountain pine beetle epidemic which has profoundly affected the region's lodgepole pine forests. To mitigate the negative effects of the epidemic, the strategy focuses on increasing timber volume from other tree species. As well, the region needs to increase harvest levels of the beetle-wood to maximize the merchantability of these dying stands before they are projected to lose their value (in around 2013). Finally, the region wants to continue with environmentally sensitive programs to preserve habitat quality in the area. Timber supply and habitat supply are considered in this report to be of greater priority than timber quality (BC MFR 2006b).

In the Okanagan TSA, the incremental silviculture history indicates that since 1995, the most frequently used silvicultural treatment was juvenile spacing (thinning), with a small amount of pruning and virtually no fertilizing. Since 1997, the use of all of these treatments have tapered off and in 2004 (the most recent data reported), 344 hectares of timber land received juvenile spacing treatments (compared to 2879 hectares in 1997)

with zero fertilizing and zero pruning. Select seed is legally required in the Okanagan TSA and as a result is now the dominant form of silvicultural treatment applied.

*The following information on the Okanagan TSA, unless otherwise stated, comes from the incremental silviculture strategies report (BC MFR 2006b).*

#### *5.2.2.1 Timber Supply*

The Okanagan TSA covers a total of 2 million hectares with just less than 1 and a half million hectares (sixty-five percent) considered productive forest and just over 1 million hectares (forty-six percent) of it characterized as the timber harvesting land base (THLB). The THLB of the Okanagan TSA is crown land that is considered harvestable forest area. In 2006, this harvestable land translated into an AAC of almost 3 and a half million cubic meters of timber. The most common tree species in this productive crown forestland is lodgepole pine (29% of all trees). There is also a significant amount of Douglas fir in the Okanagan TSA. Of this productive forest, the most abundant age class is between 141 and 250 years old, which is considered old growth for lodgepole pine and puts these stands at higher risk for mountain pine beetle infestations (BC MFR 2006b). The silvicultural strategies designed to address the region's objectives are planting, fertilizing, spacing (thinning), and stand rehabilitation where necessary. To address the timber supply issues raised in the previous discussion, the Silviculture Strategy report for the Okanagan TSA outlines several high priority management strategies. Fertilizing both young and mature stands to enhance timber volume was considered a high priority

strategy. Fertilizing young stands has been proven to increase timber volume. Fertilizing stands later in their rotation may have reduced risks and added investment potential, however, it is a less trusted method (BC MFR 2006b). Both types of fertilizing provide an opportunity to increase second growth volume to mitigate the economic effects of the dip in the timber supply over the next several decades. Thinning stands in conjunction with fertilizing can create more timber volume over time and is a high priority strategy in the TSA. Other high priority strategies include planting, addressing backlog areas and rehabilitation programs. Despite the high priority of these strategies, the province has consistently reduced its silvicultural budgets over the past few decades.

#### *5.2.2.2 Timber Quality*

The current objective for all of British Columbia is to produce 10% of a timber supply area's AAC as premium logs. Premium quality logs are generally larger, older logs that required longer rotations and specific silvicultural investment (for example, pruning creates clear wood without knots which is of higher market value). This goal will be increasingly difficult to attain once second growth stands become more important in the Southern Interior. Second growth is taking the place of much of the region's older stands that are being harvested and/or killed by mountain pine beetle infestations. The region's objectives in terms of timber quality are to "...identify incremental silviculture activities that could increase timber quality during this deficit period. These activities could include a range of incremental silviculture activities aimed at increased average piece size at harvest and/or creating clear logs" (BC MFR 2006b, p. 14). Timber quality was

considered less important in the Okanagan TSA report than timber supply and habitat supply. As a result, there were fewer strategies outlined to address the quality issue. Pruning to create clear wood was considered prohibitively costly and managing for long rotations to enhance timber quality was considered impractical given the urgency created by the mountain pine beetle epidemic. Managing stands for higher densities was the only high priority strategy. More trees per stand results in higher quality (mechanical stress rated) lumber because the rings are more closely spaced and produce denser wood, which garners a higher price on the market (personal communication with Thomas Sullivan<sup>9</sup>).

#### *5.2.2.3 Habitat Supply*

The Okanagan TSA is home to many wildlife species and offers long-term habitat supply with close to 8 percent of the productive land base reserved as protected areas. The mountain pine beetle epidemic not only threatens the timber land base, but also the biodiversity, habitat supply and other environmental values in the region. As the pine stands are killed and/or harvested, wildlife habitat is compromised. Improving habitat supply is considered a very important component of the Okanagan TSA's set of objectives. There are several high priority strategies aimed at realizing this objective. The strategies include: planting non-timber harvesting land base areas that have been impacted by the mountain pine beetle; thinning stands to create more old growth characteristics and to reduce encroachment and overstocking of certain areas; treating for invasive species to provide more room for desirable species; and road management to protect wildlife from unnecessary human and predator disturbance (BC MFR 2006b).

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<sup>9</sup> Thomas Sullivan, Professor, Faculty of Land and Food Systems, The University of British Columbia.

#### *5.2.2.4 Funding for Silviculture Strategies*

To achieve the goals outlined for the Okanagan TSA, substantial funding is required. In the Silviculture Strategy Report of 2006, there are two possible funding scenarios that could occur over the next five years (three years as of 2008). The ideal funding level to achieve the TSA's objectives would be almost 79 million dollars. If the historical funding level in the TSA were maintained until 2011, a budget of 25 million dollars would be available to implement all of the strategies outlined above. The result would be that with less than a third of the ideal funding amount, significantly fewer hectares would be managed to improve and maintain timber supply, timber quality and habitat supply (Table 5.1). With historical funding levels as opposed to ideal funding levels, there would be less timber supply to mitigate the trough that is going to be experienced following the increased mountain pine beetle harvests. As well, there would be fewer hectares managed to improve habitat quality on timber and non-timber lands following the mountain pine beetle epidemic. In second growth stands of both lodgepole pine and other species, there would be less silvicultural investment, which would result in less old growth-type habitat for wildlife and less timber.

Table 5.1: Silviculture Strategies and outcomes by funding level

<b>Strategies</b>	<b>Historical Funding Outcomes: (\$25 million available from 2006-2011)</b>	<b>Idealized Funding Outcomes: (\$79.8 million available from 2006-2011)</b>
<b>Timber Supply</b>	Additional 167,000 $m^3$ of timber available in short term of timber shortage	Additional 181,400 $m^3$ of timber available in short term of timber shortage
	Additional 370,000 $m^3$ of timber available in mid-term of timber shortage	Additional 2,974,700 $m^3$ of timber available in mid-term of timber shortage
	Additional 983,800 $m^3$ of timber available in end of timber shortage	Additional 765,000 $m^3$ of timber available in end of timber shortage
<b>Habitat Supply</b>	Enhance old growth structure on 5250 hectares from thinning	Enhance old growth structure on 12,550 hectares from thinning
	Maintain wildlife and recreation values by removal of 300 hectares of roads	Maintain wildlife and recreation values by removal of 1200 hectares of roads
	Protect plant species on 8,000 hectares by removal of invasive species	Protect plant species on 10,000 hectares by removal of invasive species
	Regenerate 3150 hectares of impacted stands with a habitat focus	Regenerate 4100 hectares of impacted stands with a habitat focus
	Regenerate 4892 hectares of impacted stands with a habitat focus	Regenerate 4892 hectares of impacted stands with a habitat focus
<b>Timber Quality</b>	Potentially improve log quality through increasing densities, pruning and thinning	Potentially improve log quality through increasing densities, pruning and thinning

Data Source: BC MFR 2006b.

### 5.2.3 Gorman Brothers Lumber – A Case Study

To complete the discussion of the Southern Interior’s current forestry situation, one of the timber companies operating in the region is presented, as a representative case study.

Gorman Brothers Lumber operates in the Southern Okanagan, and produces timber products using pine, fir and spruce trees. Ninety five percent of their total production comes from crown land in the southern interior. In 2006, Gorman Brothers Lumber had an AAC of over 246 thousand cubic meters (over 13% of the AAC for the entire TSA). Gorman Brothers makes one-inch spruce and lodgepole pine boards as well as many other products (Gorman Brothers, 2005b).

Gorman Brothers Lumber, as a license holder in the Okanagan TSA, is required to comply with all environmental legislation set out by the Ministry of Forests and Range (MFR). Gorman Brothers has committed to meeting the government's environmental objectives. The company has outlined specific strategies for meeting the MFR's environmental legislation.<sup>10</sup> Despite Gorman Brothers' apparent commitment to the government's legislation, the language used by the MFR regarding some of the environmental protection requirements has a profound timber supply bias. For example, "...the objective set by government for wildlife and biodiversity at the stand level is, without unduly reducing the supply of timber from British Columbia's forests, to retain wildlife trees" (Gorman Brothers 2006, p. 19). This same language is used to describe almost every environmental objective in the report. This type of legislation allows the timber company the freedom to operate first and foremost to meet their AAC, and then turn their attention to the stewardship of environmental values. This is not necessarily a

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<sup>10</sup> These strategies include: protecting old growth through sustainable road management; protecting wildlife species through partial cutting, select harvesting of non-habitat trees and timed harvests to protect species during vulnerable times; protecting wildlife and biodiversity in general through managed harvests and retention of key habitat areas; protecting riparian wildlife and water quality through careful management and retention in and around key stream habitats/water sources including frequent hydrologic assessments of the areas; and finally, practicing management that protects culturally significant heritage resources by harvesting where no area of significance will be affected (Gorman Brothers 2006).

problem, since timber supply is certainly a very important objective for all participants in the forestry community. However, if the other objectives are always subjugated in the name of timber supply, there will be trade-offs on the part of the environment since all forestry objectives are not perfect complements. In the theoretical model, firms maximize profit by choosing rotation time and investment levels. If these decisions are being made unconstrained, then more profit is generated in part at the expense of environmental outputs including wildlife habitat, soil carbon and biodiversity (chapter 3).

#### 5.2.4 Overview: Public and Private Objectives

One of the main objectives in the southern interior region of British Columbia is to maintain timber supply in a future characterized by uneven AAC's reflecting the effect of the mountain pine beetle epidemic on the area's lodgepole pine forests. This objective may be realized by increasing the amount of silvicultural investment in second growth stands in the region, an investment that as of 2007 had not yet been made. One of the other key objectives mentioned was to improve and maintain habitat supply and species diversity. To realize this environmental goal, more silvicultural investment of second growth stands is required, along with protection of old growth stands and more environmentally focused stand management, possibly at the expense of some timber supply. Greenhouse gases were mentioned briefly, and a possible mitigation strategy to address carbon issues through our forests would be to increase carbon sequestration in both biomass, by increasing volume, and in soil carbon, by leaving old growth trees standing. Finally, timber quality was addressed, with one of the silvicultural strategies

being to lengthen rotation times to develop higher quality wood, along with pruning to produce clear wood (BC MFR 2006a, 2006b).

### 5.2.5 The Southern Interior Today

Since the 2006 silviculture strategy report was published, there has been some investment in the southern interior region of British Columbia. In the Southern Interior in 2006/2007, there were a significant number of seedlings planted on crown land with 74 percent of the planting done by the MFR and 26 percent done by license holders (Table 5.2). Less than 0.01% of total planted area was pruned, less than 1% of the total planted area was thinned, and just over 11% of the total planted area was fertilized. The province paid for the majority of the investment, with some moderate investment by license holders. In addition, over 11 million hectares were managed for forest health.

Table 5.2: Silvicultural activities by hectare and private funding

	Total hectares	Proportion of total planted area treated	Proportion of total treated area privately funded
Seedlings Planted	84,278	100%	26%
Fertilized	9,565	11%	8.9%
Thinned	313	<1%	37%
Pruned	64	<0.01%	0%

Data Source: BC MFR (2006-2007).

If we consider that of the 25 million hectares in the Southern Interior, 60 percent is productive forest land and if 46 percent is the timber harvesting land base (the same percentage as the Okanagan TSA), then the amount of silvicultural investment over the last year covers less than 1 % of the timber harvesting land base. Even if the silvicultural investments had been made only in the Okanagan TSA, they would have covered just 1.5% of the timber harvesting land base. If the Southern Interior's silvicultural investments were made only on Gorman Brothers land, it would still have covered less than 12 percent of their portion of the timber harvesting land base. These results are indicative of the lack of incentive for private investment as well as a lack of funding and political will for public investment. There is no information regarding the success of the silviculture strategy in realizing the short-term objectives in the southern interior and middle and long-term outcomes are not available yet. However, given the amount of investment made in the second year following the silviculture strategies report, it is possible that even the short-term goals have not been met. The MFR has a Policy Manual for 2007, describing all forestry-related policies that have been implemented, however, there is virtually no information about silviculture in the report but instead an indication that the information will be provided at a later date (BC MFR IMG, 2007).

To ascertain the potential for forest policy to address some of the investment shortages in the province, the profit-maximizing forestry model used in the previous analysis is presented and modified to better reflect British Columbia's unique Southern Interior region. The model will be parameterized according to the available information from this region.

### **5.3 The Southern Interior Modeled**

The previous discussion highlighted certain key forestry and related objectives of British Columbia's Southern Interior region. Mitigating the anticipated timber supply shortage, improving timber quality, and enhancing habitat supply are three of these goals. To realize these goals, specific forestry policy aimed at modifying timber companies' behaviour can be implemented. However, because of the competitive nature of some of these objectives, more than a single-policy tool may be required. When objectives are complements, it is possible to apply one policy tool and achieve two or more outcomes. In the case of timber supply and carbon sequestration, implementing a policy that increases timber volume will work towards meeting these objectives. This is also the situation for product quality and habitat supply, both objectives can be at least partially realized through longer rotations and more stand management. As well, it may be possible to protect old growth forests for biodiversity-wildlife value, long-term carbon value and spiritual values simultaneously. There are also contexts where it is possible to implement one policy to partially achieve two objectives that may be somewhat conflicting. For example, timber supply is enhanced with more silvicultural investment and habitat supply is also improved as a stand takes on more volume and more old growth characteristics (Sullivan et al. 2006b). However, once that stand is harvested, the habitat value is less but the length of the rotation may have allowed a species time to rehabilitate or recover and then move to a contiguous stand that will not be harvested.

In the case of the Southern Interior, the primary objectives are somewhat complementary. Short-term timber supply and carbon sequestration can be achieved simultaneously on the same stand through volume-enhancing policies. Timber quality requires longer rotations, which directly conflicts with producing more timber volume in the short-term, however, there is biodiversity-wildlife value on a high quality timber stand that is managed with longer rotations. Habitat supply, long-term carbon sinks, recreational and spiritual values can all be achieved if old growth forests are left unharvested, obviously at the direct expense of timber volume. The three main competing forest objectives for the region are timber supply, timber quality and long-term wildlife habitat and environmental quality. As a result, the following analysis will assume that there are three types of forest stands in the Southern Interior: old growth stands that are never harvested; second growth stands that provide habitat value over a relatively long period and enhanced timber product quality once the stand is harvested following a longer rotation; and a timber stand that produces timber volume after a relatively short rotation. A timber company will operate on each type of stand to maximize profits. The government will implement policy to maximize the region's social welfare. The policies used in the earlier chapters will be used again and each policy will be implemented on each stand to determine the combination of policies that achieves the highest social welfare for a region like the Southern Interior.

### 5.3.1 The Model

#### *5.3.1.1 Old Growth Stand*

The unharvested old growth stand will have no investment, no harvesting and no explicit management. This stand will be allowed to mature naturally. The value from the stand is purely environmental (carbon, biodiversity-wildlife habitat), spiritual (predominantly to first nations communities) and recreational (tourism) (BC MFR 2006a). These last two values are important to the BC MFR and as a result would ideally be incorporated into the old growth forest stand. However, both spiritual and recreational values are difficult to quantify. There is information about tourism in British Columbia and specific outdoor recreation in the province, however, there is no readily available data describing the revenue accumulated from recreational activities taking place in forested regions like the Southern Interior. Spiritual value is inherently illusive. In the Okanagan TSA, there are over 11 thousand hectares of productive forest land base that are deemed to have spiritual values as well as 900 archaeological sites identified, few of which are found within the timber harvesting land base (BC MFR 2005). These values are not quantified or included in this thesis and as a result the value for the old growth stand is conservative.

In British Columbia, there are 25 million hectares of old growth forests (BC MON, 2007). Protected forests account for over 10 percent of all forests, which amounts to just under 6 million hectares. Older forests are well represented in the province's protected areas: the proportion of protected (and total) forest area over 100 years old is 78% (62%);

over 140 years old is 63% (41%); and over 250 years old is 27% (14%) (BC MFR 2006a). In the Southern Interior, protected areas account for 7.9% of the productive forest land base. There are also other areas that are managed for environmental value.<sup>11</sup> The majority of the trees in the Okanagan region are lodgepole pine or Douglas fir. There is a significant portion of the lodgepole pine in this region of the Interior that is considered mature, and is more susceptible to mountain pine beetle attacks. The result is that a significant number of the old growth trees in the region will either be harvested or killed in the next decade or earlier. As a result, the old growth stand used in the model for this analysis will be a mixed-species stand with old growth Douglas Fir, as well as lodgepole pine. This is to ensure some biodiversity within this stand. Assuming a mix will also ensure some consistency overtime, as well to provide a buffer against future beetle infestations. A similar volume curve was estimated by Liang et al. (2005) to describe a mixed-species forest stand.

The social welfare function for the old growth will look very much like the function used in the previous chapters for the unharvested stand. However, it will be assumed that the stand will begin as an uneven aged stand and thus will have volume from time zero. The stand will plateau at around 400 years and will eventually drop off because of natural disturbances. This stand's value is derived from biodiversity, soil carbon, habitat values and other less tangible environmental values, and the old growth stand is being managed to maximize these values. The social welfare function for this unharvested stand will

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<sup>11</sup> There are 10,000 ha allocated to Enhanced Riparian Protection, 9500 ha to Caribou Reserves, 10,000 ha deferred harvesting in Caribou habitat and approximately 62,000 ha of draft Old Growth Management Areas in the Timber Harvest Land Base (BC MFR 2006b).

have a premium for old growth-environmental value in order to capture the difference between a natural stand at a given stand age a stand about to be harvested at the same age

#### *5.3.1.2 Timber Quality/Wildlife Habitat Stand*

The second type of stand in the model will be a harvestable stand with the objective of creating higher product quality and short-term wildlife habitat through longer rotations and properly managed stands. Enhancing product quality is a goal in British Columbia, as is providing more habitat supply. This stand will ideally create habitat for wildlife during the stand's rotation. To maximize the benefit of this stand to wildlife habitat, the stand will be assumed to be contiguous to the old growth/natural stand, to provide a short to medium term haven for wildlife that can transition to the old growth stand near the harvest time. The habitat premium supplied by this stand will be captured in the social welfare function by its contribution to the aggregate biodiversity-wildlife component. At the end of the rotation, the stand will produce higher quality timber, which garners a market premium. There will be a modification to the timber price to account for the relationship between time and quality. To capture the concept of a timber quality premium, the timber price will be a function of time. The longer the rotation, the more likely the trees will generate high quality products and higher prices. Each policy will be implemented on this stand in a simulation and the results will reveal the policy that generates the most social welfare.

### *5.3.1.3 Timber Supply Stand*

The third type of stand will be a second growth timber stand that responds well to silvicultural investment and produces timber volume with old growth attributes more quickly because of the investment. This stand will maximize profit and will also provide some environmental value. The profit and social welfare function will be the same as in the initial analysis in chapter 3.

### *5.3.1.4 Simulations and Parameterization*

The simulations are run using Mathematica 6.1©. The methods for the firm's profit function on the timber stand and habitat/quality stand are identical to chapter 2. The old growth stand premium was chosen to acknowledge the added value of a mixed aged, natural stand. Essentially the same functional form from chapter 2 was used to describe the old growth stands' accumulation of the biodiversity-wildlife value overtime, except to account for the mixed-aged stand and a the 'natural' premium, the equation begins at time zero with \$500 worth of calibrated value instead of zero. This means that compared to the timber stand, the old growth stand generates more social welfare than most of the policies, except the subsidy policy, and compared to the timber supply-habitat quality stand, it generates less than the average amount.

The timber premium for the high-quality products is a function of time:

$$P_{iq} = P_t + 0.6t - (1/t).$$

Where  $P_{iq}$  and  $P_i$  are the timber quality price and initial timber price respectively. The new quality price was calculated so that the timber premium is at the high end of the range indicated by the MFR (BC MFR 2001 & 2002). The timber price in the initial simulations, and used for the timber stand is \$120/cubic meter and the quality-premium price for the unconstrained firm was just under \$150/cubic meter. The percentage of timber that is used for long-term end products such as housing, in the region also varies by manufacturer, species and region (BC FR 2001). Gorman Brothers Lumber produces only construction-quality lumber and thus the model will assume a 90% pickling rate to account for any lost or damaged timber that may be discarded and release its carbon sooner.

The Southern Interior provides a few unique qualities, which will enhance the model's results. The property rights in the region, as in most of British Columbia, are a function of the license agreement between the license holder and the crown. The license holder is given the right to harvest a given AAC from a specific TSA and in return, must pay the crown a percentage of the value, called stumpage. In the Southern Interior, a stumpage rate of between twelve and twenty dollars per cubic meter was used in 2004, depending on the species and the region. Timber price per cubic meter was between 30 and 80 dollars per cubic meter in 2007, depending on the product and region (BC MFR, 2004). Using the percentage of total price that is paid out in stumpage as a proxy for security of tenure, if 100% is ownership with full return on investment, then the Southern Interior would be somewhere between 60% and 85%.

## 5.4 Results

The three forest stands generated social welfare given their objectives. The unharvested stand was a mixed-species and mixed-aged stand and generated social welfare based on the environmental values it accumulated over a 400-year period. The natural premium placed on the stand differentiated the natural stand at age 400 years from a stand about to be harvested at the same age. Since there are no policies applied to this stand, other than legislating its preservation, the total social welfare from this stand was aggregated with the social welfare from the other two stands to determine the policy mix that creates the most value to society. The product quality/habitat supply stand generated the most social welfare under the subsidy policy that compensated the firm for 20% of its environmental accumulation. The firm chose a rotation time of 74 years with a moderate amount of silvicultural investment (no environmental investment) on this quality stand. The timber supply stand generated the most social welfare under the same subsidy policy and the firm chose a rotation time of 67 years with fourteen units of silvicultural investment. Since there was no explicit subsidy for any silvicultural or stand management investment, very little of the former and none of the latter was made. The quality/habitat stand policy generated slightly higher levels of environmental output than the purely timber stand since the rotation time was longer and the investment was higher. Refer to Appendix F for simulation results by stand type.

This quality-habitat stand also generated higher levels of every social welfare component than the timber stand, which is an intuitive result, since the only difference between the two stands is the quality premium reflected in the timber price being an increasing

function of rotation time. Under the subsidy policy, and several other policies, the quality/habitat stand generated more social welfare than the old growth stand as well. As a result, the optimal policy for the government, given these parameters and in this context, would be to have only high quality timber-habitat stands operating under a subsidy policy (sub2) that allows the firm to choose its own levels of investment and rotation time.

The caveat to this finding is that there is an assumption that this quality premium is available in the province and that it is available to everyone. As well, this result assumes that the demand for high quality products is endless. In other words, that the market for high quality timber will not get saturated even if all timber from the region is identical. This is clearly not the case. The market will get saturated if this premium is available and the reality is that this premium may not even be available. In this latter case, we have two types of stand left in our model: the timber stand and the old growth stand. The optimal policy for the timber stand (subsidy policy (sub2) with a 67-year rotation) generates more social welfare overall than the old growth stand, which generates more environmental value but no revenue. In this case, given the parameters and context, the results imply that all stands should be timber stands, in the absence of the quality premium.

The timber stand generates more social welfare than the old growth stand given the most comprehensive environmental subsidy policy (sub2). Assuming only timber and old growth stands are available, the complementarities in production of carbon and profit result in a single forest type generating the most social welfare on all land. Since more

volume generates more profit and more carbon up to a point, the policy that is generating the most social welfare on the timber stand is one that maximizes volume. Although volume and carbon are maximized under a much longer rotation than profit. The profit maximizing and social welfare maximizing result for the timber stand occurs under the environmental government subsidized policy (sub2) where the firm chooses a longer rotation and more investment than it would if left unconstrained. Since the old growth stand generates less social welfare than the timber stand under this policy, the results imply that there would be only one type of forest stand in the province and it would be focused on timber production. However, a zoning-type landscape, where there are different types of stands on different pieces of land is justified if the government cares specifically about components that are substitutes in production, such as profit (revenue) and biodiversity. As the firm generates more timber profit, biodiversity is accumulated very slowly since the rotation times (stand ages) are relatively short. However, as stand ages increase well beyond the profit maximizing timber age, exponentially more biodiversity is accumulated. Since profit and biodiversity are substitutes, the only way to generate a significant amount of both is to pursue zoning.

To take the extreme case, where the government only cares about biodiversity and profit, it is possible to show that a combination of old growth stands and unconstrained firm profit maximization can produce more profit and biodiversity-wildlife output than the 'optimal' subsidy policy. In this example, we are looking at the total magnitude of biodiversity accumulated (not value) under each scenario and the total value of firm profit with the cost of the silvicultural investments netted out. In the case of the

unconstrained policy, firm profit already accounts for the cost of the investment, and in the subsidy case, the subsidy cost to the government is subtracted from the firm's profit. For a preliminary analysis, if there are ten stands in a given forest region, such as the Okanagan TSA, total unconstrained firm profit from those ten stands is positive but biodiversity is low since the firm is choosing shorter rotation times and less investment. The firm operating under the subsidy policy (sub2) generates higher profit but once the cost of the subsidies are netted out, the profit is smaller than the unconstrained profit. This is an intuitive result, since the firm always chooses to make whatever investment decision maximizes its profit. Biodiversity for the subsidy policy, however, is higher than under the unconstrained scenario since rotation times are longer and there is more investment. A zoning policy would be preferred if social welfare is higher when the ten stands are managed under some combination of unconstrained (u) timber stands and old growth stands than all ten stands under the subsidy policy.

If the government cares only about profit, net of the cost of any subsidy, and the amount of biodiversity-wildlife output accumulated, society is better off with at least one old growth stand and not more than nine timber stands (where the firm is unconstrained) than ten stands under the previously optimal subsidy policy. If the firm was unconstrained (u) and operated all ten timber stands, they would have more profit but less biodiversity than if the ten stands were operated under the previously optimal subsidy policy (sub2). However, as old growth stands replace unconstrained timber stands, profit falls but biodiversity increases. Since this is comparing biodiversity units with dollars for profit, it is only possible to say that once one old growth stand is added to nine unconstrained

timber stands, there is both more profit in dollars and more biodiversity in units than under the subsidy policy alone (Table 5.3). The first two columns show the profit and biodiversity for nine timber stands (u) and one old growth (og) and the last two show the results for ten stands under sub2. This result shows that as weights on social welfare components are shifted around to emphasize profit and biodiversity, it is quite possible to see how a zoning policy could be optimal for a region like the southern interior.

Table 5.3 Trade-offs between biodiversity and profit by policy and stand

<b>Unconstrained Timber (u) + Old Growth (og)</b>		<b>Timber Stand Subsidy Policy (sub2)</b>	
Profit (\$)	Biodiversity (units)	Profit (\$)	Biodiversity (units)
Stand 1:158 (u)	200 (u)	Stand 1: -565	826
Stand 2:158 (u)	200 (u)	Stand 1: -565	826
Stand 3:158 (u)	200 (u)	Stand 1: -565	826
Stand 4:158 (u)	200 (u)	Stand 1: -565	826
Stand 5:158 (u)	200 (u)	Stand 1: -565	826
Stand 6:158 (u)	200 (u)	Stand 1: -565	826
Stand 7:158 (u)	200 (u)	Stand 1: -565	826
Stand 8:158 (u)	200 (u)	Stand 1: -565	826
Stand 9:158 (u)	200 (u)	Stand 1: -565	826
Stand 10: 0(og)	7216 (og)	Stand 1: -565	826
Total: 1106	Total: 9016	Total: -5650	Total: 8260

Another way to explore the possibility that different types of stands may be preferred to one type of stand is to look at the demand (or price) for the environmental value. The amount of biodiversity-wildlife output has been priced at a constant rate no matter how much of this value is preserved in the province. To capture the trade-offs that exist between the timber supply objective and the biodiversity-wildlife objective, the price for the biodiversity-wildlife component must reflect the scarcity of this component.

The less biodiversity-wildlife output from a forest, the more valuable this output is to society. This implies that the biodiversity-wildlife component has a downward-sloping demand curve (or a downward sloping price function). If there are ten forest stands in the region, and each stand was managed under the optimal subsidy policy, there would be a given amount of the biodiversity-wildlife output as well as revenue from the stand. If the price of that environmental output was a function of the amount of the output itself, timber stands producing little environmental output would mean a high social value for this biodiversity quantity produced. For simplicity, if social welfare was a function of only timber revenue, government expenditure and biodiversity, too little of this valuable output would motivate the government to shift forestry management towards more old growth stands to provide more environmental value. As there are more old growth stands protected, the value of this environmental component decreases.

There is an optimal combination of revenue (timber stands) and biodiversity-wildlife value (old growth) given this downward sloping demand curve and the specific parameterization in the model. This optimal combination turns out to be four old growth stand which yields a lot of biodiversity output at a relatively low price and no revenue combined with six timber stands under the subsidy policy (sub2) with more revenue but less biodiversity value at a relatively high price. The trade-offs between biodiversity output, biodiversity price and revenue are shown in the table below (Table 5.4). With 10 identical timber stands under the subsidy policy, the biodiversity output is 826 units for each stand. For the first stand, the price is \$242 per unit. As more timber stands produce more biodiversity, but still relatively little compared to an old growth stand, the price

slowly falls until for all ten stands' biodiversity, the price is \$30 per unit. If one old growth stand is added in to replace the last timber stand, there are over 7000 units of additional biodiversity accumulated but the price for this biodiversity, taking into account the other nine stands with biodiversity already accumulated, is \$13 per unit.

Table 5.4 Environmental and economic trade-offs with timber and old growth stands

<b>Stand</b>	<b>Biodiversity (units)</b>	<b>Biodiversity unit * price (\$)</b>	<b>Revenue (\$)</b>	<b>Social welfare (bio + rev-subsidies)</b>
Timber 1	826	$826 * 242 = 199892$	8096	206421
Timber 2	826	$826 * 121 = 99946$	8096	106475
Timber 3	826	$826 * 81 = 66906$	8096	73435
Timber 4	826	$826 * 61 = 50386$	8096	56915
Timber 5	826	$826 * 48 = 39648$	8096	46177
Timber 6	826	$826 * 40 = 33040$	8096	39569
OG 1	7216	$7216 * 13 = 93808$	0	43296
OG 2	7216	$7216 * 10 = 72160$	0	50512
OG 3	7216	$7216 * 7 = 50512$	0	72160
OG 4	7216	$7216 * 6 = 43296$	0	93808
			Total social welfare (1-10):	788768

Once four old growth stands are added, given the increased biodiversity and lower price, and reduced revenue, there is more aggregate environmental value plus revenue

generated than from the ten timber stands under the subsidy policy. Adding more than four old growth stands is not optimal as the social welfare falls.

## 5.5 Discussion

Given the parameters and weights on variables within this forest model, social welfare is maximized with only one type of policy on one type of stand. The optimal policy subsidizes the firm's environmental output and allows the firm to choose freely both rotation time and silvicultural investment. The high product quality-wildlife habitat stand generates more social welfare under this policy and all policies than the timber stand. However, in the case where this high quality timber premium is either not available or not available to everyone and/or the high quality market becomes saturated, the timber stand under the subsidy (sub2) policy generates the next highest amount of social welfare.

One type of stand may be optimal given the formulation of the social welfare function where the government is concerned about timber volume, revenue, environmental value and expenditure equally and where prices are fixed. However, in the case where the government cares about certain elements more than others, there is a case to be made for zoning. In the extreme example where the government only cares about profit and biodiversity output, the optimal strategy switches from ten timber stands under the subsidy policy to not more than nine unconstrained timber stands and at least one old growth stand. This highlights the potential for a government to achieve more social welfare depending on their social priorities by zoning a forested region into different stand types operating under different policies.

A similar result was found when the price for biodiversity was modified to incorporate diminishing returns to biodiversity. As the amount of biodiversity increases, the value associated with each unit of biodiversity falls. In this case, given the specific functional form of the biodiversity price function, the optimal mix is four old growth stands and six subsidized timber stands. Depending on a given society's objectives and priorities, a different optimal combination of stand types and policies can create more social value. Different regions have unique geographical, economic and social objectives and challenges. To properly manage a landscape of timber stands to meet competing objective, a zoning strategy is one opportunity to enhance social welfare.

## **6 Summary and Policy Recommendations**

### **6.1 Initial Model: Summary**

Given the influence of rotation time and firm investments on the economic and environmental outputs of a forest, there is a role for forestry policy to enhance social welfare. If BC's timber firms were left unconstrained, they would choose a 52-year rotation and very little incremental silvicultural investment, and no environmental investment. If the government was operating in a command and control framework, social welfare would be maximized under a 120-year rotation with 300% more incremental silvicultural investment than the unconstrained firm scenario and a considerable amount of environmental stand management investment. When the firm maximizes profit and the government's social welfare function takes the firm's optimal inputs choices as given, the policy that generates the most social welfare is an environmental subsidy policy. This policy (sub2) compensates the firm for the value of all of the biomass carbon that is sequestered through a rotation and 20% of the value of the biodiversity-wildlife output accumulated. Under this sub2 policy, the firm chooses a rotation time of 67 years, a moderate amount of incremental silvicultural investment and no explicit environmental investment. The environmental subsidy policy is a price policy. Determining the amount of carbon in biomass is relatively simple, however, determining the accumulation of various environmental outputs would be considerably more difficult. As a result, there are additional costs associated with this subsidy policy that should be considered.

When the biodiversity-wildlife output is not included in the social welfare function, the best policy is the input 60-year policy (in60), where the firm chooses very little silvicultural investment and is required to harvest after 60 years. Although the biodiversity-wildlife component is difficult to measure or price, the sub2 policy generates the most social welfare with only 20% of this environmental component being subsidized. The implication of this is that if the biodiversity-wildlife component overestimates the biodiversity, soil carbon and wildlife habitat values accumulated in a forest stand by as much as 80%, then the sub2 policy would still be preferred and all of the biodiversity-wildlife value would be subsidized.

The parameters that affect the initial results are discount rates, changing the priority weighting on the environmental outputs, and certain prices and costs. As discount rates increase, the firm chooses shorter rotations and less investment. As discount rates fall, longer rotation policies generate more social welfare. If the social discount rate is less than the firm's discount rate, longer rotations are desirable. When the biodiversity and carbon outputs are given a higher priority weighting, longer rotations and more investment generate more social welfare. When the harvest cost falls, a slightly longer rotation is preferred. In most parameterizations when the biodiversity-wildlife value is included, the subsidy policies that compensate the firm for their carbon sequestered and biodiversity-wildlife value accumulated generate the most social welfare. The lower the discount rate, or the higher the biodiversity-wildlife price, or the higher the biodiversity-wildlife priority weighting, the longer the rotations chosen by the firm for the subsidy policy and the more social welfare is generated.

## 6.2 Heterogeneity: Summary

The policy rankings established in the first analysis are consistent with a heterogeneous multi-stand timber industry. When there are multiple timber stands with different access costs, the policies that generate the highest profit will enable the firm to harvest the most stands. As the discount rate falls, the number of harvested stands increases since profit increases. Given the initial parameterization, when firms 'exit' the industry for certain stands and allow these stands to mature, there is no overall change on the policy ranking. The comprehensive environmental subsidy policy (sub2) allows the firm to harvest the most stands and generates the most social welfare. The trade-off between the value from a harvested stand and an unharvested stand is significant. The environmental values alone are greater in the harvested stand because of the impact of discount rates and investment. To account for some inherent value in the natural stand would be costly to society. This is particularly the case as the harvested stand becomes more valuable under the subsidy policies. The more social welfare that a forest stand generates when harvested, the larger the opportunity cost if the stand is left unharvested.

### 6.3 B.C. Case Study: Summary

BC's southern interior forest region is economically and environmentally valuable. There are challenges that face the region, such as the mountain pine beetle crisis and limited public and private funding for incremental silvicultural investment in timber stands. The region's main objectives include maintaining timber supply in the short and long term, managing stands for timber quality and improving the diversity and general environmental health of the area. To account for these objectives, the region was modeled as having three distinct forest stands: unharvested old growth stands; high timber quality and short-term wildlife habitat stands; and timber supply stands. The comprehensive environmental subsidy policy (sub2) generated the most social welfare on both types of harvested stands. Since the value of the old growth stand included a 'natural' premium, the social welfare from this stand was comparable to the other two stands. However, the timber quality stand, managed under the sub2 policy, generated the most social welfare of the three stand types. The implication is that, given the parameterization of the model, the southern interior region should be managed only for timber quality and short-term wildlife habitat, under an environmental subsidy policy, with no other types of forest stand. If the market for timber quality saturates, or the quality premium is not available, the next highest social welfare is generated from the timber supply stand. In this case, the results suggest that the region be managed only for timber supply, under an environmental subsidy policy, with no other types of stands.

A homogeneous forest focused only on timber supply does not meet all of the region's objectives. A heterogeneous forest with different objectives met on different timber

stands is justified when there are strictly competing objectives, such as maximizing timber profit and preserving old growth forests. In this context, more social welfare is generated on a ten-stand forested area, when there is at least one old growth stand preserved and no more than nine timber stands managed by an unconstrained firm, than if all ten stands were managed under the sub2 policy. Managing a forest for different stand types is also desirable if the price for the environmental output within a stand reflects the scarcity of that environmental output. If the price for the biodiversity-wildlife component is a decreasing function of the amount of biodiversity-wildlife output accumulated, social welfare is greatest in a ten-stand scenario when six stands are managed under the sub2 policy and the remaining four are preserved as old growth.

## 6.4 Policy Recommendations

The results from the previous analyses offer several policy recommendations regarding forestry management in British Columbia.

*1. Subsidize biodiversity and carbon, not silviculture.*

Assuming there is some biodiversity-wildlife value in a BC forest stand, more social welfare can be generated if the government moves away from subsidizing incremental silviculture and instead, subsidizes environmental output.

*2. If environmental output from the forest has social value, allow the market to optimally manage the forests.*

If biodiversity, wildlife habitat and carbon accumulation are valuable to society, firms will respond by setting their stand investment levels and rotation times to maximize profit which will generate the most social welfare.

*3. In B.C.'s southern interior, manage as many stands as possible for timber quality and short-term wildlife habitat under an environmental subsidy policy.*

Where a premium for high quality timber products exists, social welfare is greatest if firms are allowed to manage timber stands to produce high quality

timber and simultaneously generate positive environmental externalities from longer rotations and more investment. This is the case under the environmental subsidy policy where firms are compensated for their environmental accumulation.

*4. In the absence of a quality premium, manage all stands for timber supply under an environmental subsidy policy.*

Where no such premium exists, social welfare is greatest under an environmental subsidy policy on timber supply stands.

*5. Manage for timber supply and old growth if the scarcity of old growth is recognized or if a forest region has strictly competing objectives.*

If the price for a unit of old growth forest reflected the number of units preserved in BC, policy makers would maximize social welfare by legislating that some old growth stands be preserved and other timber stands be harvested. This is also the case if the region's objectives are substitutes, such as profit and old growth.

## **6.5 Further Research Needs**

Future research could explore the impact of additional features such as monitoring and enforcement costs built into each forestry policy. As well, it would be interesting to further evaluate the effect of non-fixed prices and discount rates overtime on the model's results.

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## Appendix A: Initial Model Simulations and Results by Policy

### Unconstrained (u)

A=100

$\alpha=1$

P=120

H=80

$\lambda=0.5$

W=10

$r=0.03$

a=1

b=1

c=1

d=1

Pb=20

Pc=20

Pj=20

$\gamma=0.2$

$v[s,t]=((s*t^5) (\text{Exp}[-0.035*(t+s)]));$

$\pi u[s,t] = ((\alpha (P-H-\lambda*W) (v[s,t]) (\text{Exp}[-r*t])-(s*t*t*10^5)))/(1-\text{Exp}[-r*t]);$

soln=Maximize[ $\pi u[s,t], s \geq 2 \& \& 250 \geq t \geq 0, \{s,t\}][[2]]$

s1=soln[[1,2]]

t1=soln[[2,2]]

GE=0

$v[s,t]/\text{soln}$

$v[s1,t1]$

$\pi u[s1,t1]$

$v0[s1,t1]=(v[s1,t1])/10^{6.5}$

v0=%

$v1[s1,t1]=(P*(a*(v[s1,t1])) (\text{Exp}[-r*t1])/(1-\text{Exp}[-r*t1])/10^{6.5}$

v1=%

$pr[s1,t1]=((d/10^{6.5}*\alpha (P-H-\lambda*W) (v[s1,t1]) (\text{Exp}[-r*t1])-(s1*(t1*t1*10^5)/10^{6.5}))/ (1-\text{Exp}[-r*t1])$

pr=%

bd[t1\_,s1\_]=(1/10<sup>7.5</sup> Pb\*b\*s1\*t1<sup>5</sup>\*Exp[-0.010\*(t1+s1)] Exp[-r\*t1]/(1-Exp[-r\*t1]))

bd=%

cs[s1\_,t1\_]=1/10<sup>6.5</sup> (Pc\*γ\*c\*(s1\*t1<sup>5</sup>) (Exp[-0.035\*(t1+s1)])\*λ (Exp[-r\*t1]/(1-Exp[-r\*t1])))+Pc\*γ\*c\*r (NIntegrate[1/10<sup>6.5</sup> (s1\*t1<sup>5</sup>) Exp[-0.035\*(t+s1)] (Exp[-r\*t1]/(1-Exp[-r\*t1]),{t,10,t1}])

cs=%

swf1=cs+v1-GE

swf2=cs+v1-GE+bd

### Results:

{s\*=6.87624, t\*=52.023}

Volume (m3)	105.449
Revenue (\$)	3363.5
Profit (\$)	236.101
Bio-Wild (\$)	244.417
Carbon (\$)	116.552
SWF1	3480.06
SWF2	3724.47

## Status Quo (sq)

$$A=100$$

$$\alpha=1$$

$$P=120$$

$$H=80$$

$$\lambda=0.5$$

$$W=10$$

$$r=0.03$$

$$a=1$$

$$b=1$$

$$c=1$$

$$d=1$$

$$Pb=20$$

$$Pc=20$$

$$Pj=20$$

$$\gamma=0.2$$

$$v[s,t]=((s*t^5) (\text{Exp}[-0.035*(t+s)]));$$

$$\pi u[s,t] = ((\alpha (P-H-\lambda*W) (v[s,t]) (\text{Exp}[-r*t])))/(1-\text{Exp}[-r*t]);$$

$$\text{soln}=\text{Maximize}[\pi u[s,t],s>=2\&\&250>=t>=0,\{s,t\}][[2]]$$

$$s1=\text{soln}[[1,2]]$$

$$t1=\text{soln}[[2,2]]$$

$$GE=((s1*t1*t1*10^5)/10^{6.5})/(1-\text{Exp}[-r*t1])$$

$$v[s,t]/.\text{soln}$$

$$v[s1,t1]$$

$$\pi u[s1,t1]$$

$$v0[s1,t1]=(v[s1,t1])/10^{6.5}$$

$$v0=0\%$$

$$v1[s1,t1]=(P*(a*(v[s1,t1])) (\text{Exp}[-r*t1]))/(1-\text{Exp}[-r*t1])/10^{6.5}$$

$$v1=0\%$$

$$\text{pr}[s1,t1]=(d/10^{6.5}*\alpha (P-H-\lambda*W) (v[s1,t1]) (\text{Exp}[-r*t1]))/(1-\text{Exp}[-r*t1])$$

$$\text{pr}=0\%$$

$$\text{bd}[t1,s1]=(1/10^{7.5} Pb*b*s1*t1^5*\text{Exp}[-0.010*(t1+s1)] \text{Exp}[-r*t1]/(1-\text{Exp}[-r*t1]))$$

bd=%

cs[s1\_,t1\_]=1/10<sup>6.5</sup> (Pc\*γ\*c\*(s1\*t1<sup>5</sup>) (Exp[-0.035\*(t1+s1)])\*λ (Exp[-r\*t1])/(1-Exp[-r\*t1]))+Pc\*γ\*c\*r (NIntegrate[1/10<sup>6.5</sup> (s1\*t<sup>5</sup>) Exp[-0.035\*(t+s1)] (Exp[-r\*t])/(1-Exp[-r\*t]),{t,10,t1}])  
cs=%

swf1=cs+v1-GE

swf2=cs+v1-GE+bd

### Results:

{s\*=28.5714, t\*=72.6469}

Volume(m3)	529.016
Revenue (\$)	8096.07
Profit (\$)	2361.35
Bio-Wild (\$)	1694.68
Carbon (\$)	408.963
SWF1	3128.57
SWF2	4823.25

### Status Quo 90 (sq90)

$$A=100$$

$$\alpha=1$$

$$P=120$$

$$H=80$$

$$\lambda=0.5$$

$$W=10$$

$$r=0.03$$

$$a=1$$

$$b=1$$

$$c=1$$

$$d=1$$

$$Pb=20$$

$$Pc=20$$

$$Pj=20$$

$$\gamma=0.2$$

$$t1=90$$

$$v[s_]=((s*t1^5)) (\text{Exp}[-0.035*(t1+s)]);$$

$$\pi u[s_] = ((\alpha (P-H-\lambda*W) (v[s]) (\text{Exp}[-r*t1])))/(1-\text{Exp}[-r*t1]);$$

$$\text{soln}=\text{Maximize}[\pi u[s],s>=2,\{s\}][[2]]$$

$$s1=\text{soln}[[1,2]]$$

$$GE=((s1*t1*t1*10^5)/10^{6.5})/(1-\text{Exp}[-r*t1])$$

$$v[s]/.\text{soln}$$

$$v[s1]$$

$$\pi u[s1]$$

$$v0[s1_]=(v[s1])/10^{6.5}$$

$$v0=\%$$

$$v1[s1_]=(P*(a*(v[s1])) (\text{Exp}[-r*t1]))/(1-\text{Exp}[-r*t1])/10^{6.5}$$

$$v1=\%$$

$$pr[s1_]=(d*(1/10^{6.5} \pi u[s1]))$$

$$pr=\%$$

$$bd[s1\_]=\frac{1}{10^{7.5}} Pb*b*s1*t1^5*Exp[-0.010*(t1+s1)] Exp[-r*t1]/(1-Exp[-r*t1])$$

bd=0%

$$cs[s1\_]=\frac{1}{10^{6.5}} (Pc*\gamma*c*(s1*t1^5) (Exp[-0.035*(t1+s1)])*\lambda (Exp[-r*t1]/(1-Exp[-r*t1]))+Pc*\gamma*c*r (NIntegrate[(1/10^{6.5} s1*t^5) Exp[-0.035*(t+s1)] (Exp[-r*t])/(1-Exp[-r*t]),\{t,10,t1\}])$$

cs=0%

$$swf1=cs+v1-GE$$

$$swf2=cs+v1-GE+bd$$

**Results:**

$$\{s^*=28.5714\}$$

Volume(m3)	841.051
Revenue (\$)	7271.48
Profit (\$)	2120.85
Bio-Wild (\$)	2348.79
Carbon (\$)	530.679
SWF1	-43.5326
SWF2	2305.26

## Status Quo 100 (sq 100)

A=100  
 $\alpha=1$   
P=120  
H=80  
 $\lambda=0.5$   
W=10  
r=0.03  
a=1  
b=1  
c=1  
d=1  
Pb=20  
Pc=20  
Pj=20  
 $\gamma=0.2$   
t1=100

$$v[s_] = ((s*t1^5) (\text{Exp}[-0.035*(t1+s)]));$$

$$\pi u[s_] = ((\alpha (P-H-\lambda*W) (v[s]) (\text{Exp}[-r*t1])))/(1-\text{Exp}[-r*t1]);$$

$$\text{soln} = \text{Maximize}[\pi u[s], s \geq 2, \{s\}][[2]]$$

$$s1 = \text{soln}[[1,2]]$$

$$GE = ((s1*t1*t1*10^5)/10^{6.5})/(1-\text{Exp}[-r*t1])$$

$$v[s]/.\text{soln}$$

$$v[s1]$$

$$\pi u[s1]$$

$$v0[s1_] = (v[s1])/10^{6.5}$$

$$v0 = \%$$

$$v1[s1_] = (P*(a*(v[s1])) (\text{Exp}[-r*t1]))/(1-\text{Exp}[-r*t1])/10^{6.5}$$

$$v1 = \%$$

$$pr[s1_] = (d*(1/10^{6.5} \pi u[s1]))$$

$$pr = \%$$

$$bd[s1_] = (1/10^{7.5} Pb*b*s1*t1^5*\text{Exp}[-0.010*(t1+s1)] \text{Exp}[-r*t1]/(1-\text{Exp}[-r*t1]))$$

bd=%

$$cs[s1\_]=1/10^{6.5} (Pc*\gamma*c*(s1*t1^5) (Exp[-0.035*(t1+s1)])*\lambda (Exp[-r*t1])/(1-Exp[-r*t1]))+Pc*\gamma*c*r (NIntegrate[(1/10^{6.5} s1*t^5) Exp[-0.035*(t+s1)] (Exp[-r*t])/(1-Exp[-r*t]),\{t,10,t1\}])$$
  
cs=%

swf1=cs+v1-GE

swf2=cs+v1-GE+bd

### Results:

{s\*=28.5714}

Volume(m3)	1003.71
Revenue (\$)	6310.79
Profit (\$)	1840.65
Bio-Wild (\$)	2617.45
Carbon (\$)	582.746
SWF1	-2614.94
SWF2	2.51034

### Status Quo 110 (sq 110)

A=100  
 $\alpha=1$   
P=120  
H=80  
 $\lambda=0.5$   
W=10  
r=0.03  
a=1  
b=1  
c=1  
d=1  
Pb=20  
Pc=20  
Pj=20  
 $\gamma=0.2$   
t1=110

$$v[s_] = ((s*t1^5) (\text{Exp}[-0.035*(t1+s)]));$$

$$\pi u[s_] = ((\alpha (P-H-\lambda*W) (v[s]) (\text{Exp}[-r*t1])))/(1-\text{Exp}[-r*t1]);$$

$$\text{soln} = \text{Maximize}[\pi u[s], s \geq 2, \{s\}][[2]]$$

$$s1 = \text{soln}[[1,2]]$$

$$GE = ((s1*t1*t1*10^5)/10^{6.5})/(1-\text{Exp}[-r*t1])$$

$$v[s]/.\text{soln}$$

$$v[s1]$$

$$\pi u[s1]$$

$$v0[s1_] = (v[s1])/10^{6.5}$$

$$v0 = \%$$

$$v1[s1_] = (P*(a*(v[s1])) (\text{Exp}[-r*t1]))/(1-\text{Exp}[-r*t1])/10^{6.5}$$

$$v1 = \%$$

$$pr[s1_] = (d*(1/10^{6.5} \pi u[s1]))$$

$$pr = \%$$

$$bd[s1\_]=\frac{1}{10^{7.5}} Pb*b*s1*t1^5*Exp[-0.010*(t1+s1)] Exp[-r*t1]/(1-Exp[-r*t1])$$

bd=0%

$$cs[s1\_]=\frac{1}{10^{6.5}} (Pc*\gamma*c*(s1*t1^5) (Exp[-0.035*(t1+s1)])*\lambda (Exp[-r*t1]/(1-Exp[-r*t1]))+Pc*\gamma*c*r (NIntegrate[(1/10^{6.5} s1*t^5) Exp[-0.035*(t+s1)] (Exp[-r*t])/(1-Exp[-r*t]),\{t,10,t1\}])$$

cs=0%

$$swf1=cs+v1-GE$$

$$swf2=cs+v1-GE+bd$$

**Results:**

$$\{s^*=28.5714\}$$

Volume(m3)	1139.11
Revenue (\$)	5234.77
Profit (\$)	1526.81
Bio-Wild (\$)	2787.83
Carbon (\$)	622.571
SWF1	-5493.77
SWF2	-2705.94

### Input 60 (in60)

A=100

$\alpha=1$

P=120

H=80

$\lambda=0.5$

W=10

r=0.03

a=1

b=1

c=1

d=1

Pb=20

Pc=20

Pj=20

$\gamma=0.2$

t1=60

$v[s_] = (s*t1^5) (\text{Exp}[-0.035*(t1+s)]);$

$\pi u[s_] = ((\alpha (P-H-\lambda*W) (v[s]) (\text{Exp}[-r*t1])-(s*t1^2*10^5)))/(1-\text{Exp}[-r*t1]));$

soln=Maximize[ $\pi u[s]$ , s>=2, {s}][[2]]

s1=soln[[1,2]]

GE=0

$v[s]/.$ soln

$v[s1]$

$\pi u[s1]$

$v0[s1_] = (v[s1])/10^{6.5}$

v0=%

$v1[s1_] = (P*(a*(v[s1])) (\text{Exp}[-r*t1])/(1-\text{Exp}[-r*t1])/10^{6.5}$

v1=%

$pr[s1_] = (d*(1/10^{6.5} \pi u[s1]) - ((GE) 1/10^{6.5}/(1-\text{Exp}[-r*t1])))$

pr=%

$bd[s1_] = (1/10^{7.5} Pb*b*s1*t1^5*\text{Exp}[-0.010*(t1+s1)] \text{Exp}[-r*t1]/(1-\text{Exp}[-r*t1]))$

bd=%

$$cs[s1\_]=1/10^{6.5} (Pc*\gamma*c*(s1*t^{1.5}) (Exp[-0.035*(t1+s1)])*\lambda (Exp[-r*t1])/(1-Exp[-r*t1]))+Pc*\gamma*c*r (NIntegrate[(1/10^{6.5} s1*t^{1.5}) Exp[-0.035*(t+s1)] (Exp[-r*t])/(1-Exp[-r*t]),\{t,10,t1\}])$$

$$cs=0\%$$

$$swf1=cs+v1-GE$$

$$swf2=cs+v1-GE+bd$$

**Results:**

{s\*= 5.74364}

Volume(m3)	141.456
Revenue (\$)	3361.56
Profit (\$)	197.098
Bio-Wild (\$)	289.862
Carbon (\$)	133.803
SWF1	3495.36
SWF2	3785.22

### Input 70 (in70)

A=100

$\alpha=1$

P=120

H=80

$\lambda=0.5$

W=10

r=0.03

a=1

b=1

c=1

d=1

Pb=20

Pc=20

Pj=20

$\gamma=0.2$

t1=70

$v[s_] = ((s*t1^5)) (\text{Exp}[-0.035*(t1+s)]);$

$\pi u[s_] = ((\alpha (P-H-\lambda*W) (v[s]) (\text{Exp}[-r*t1])-(s*t1^2*10^5)))/(1-\text{Exp}[-r*t1]);$

soln=Maximize[ $\pi u[s]$ , s>=2, {s}][[2]]

s1=soln[[1,2]]

GE=0

$v[s]/.$ soln

$v[s1]$

$\pi u[s1]$

$v0[s1_] = (v[s1])/10^{6.5}$

v0=%

$v1[s1_] = (P*(a*(v[s1])) (\text{Exp}[-r*t1])/(1-\text{Exp}[-r*t1])/10^{6.5}$

v1=%

$pr[s1_] = (d*(1/10^{6.5} \pi u[s1]-((GE) 1/10^{6.5}/(1-\text{Exp}[-r*t1])))$

pr=%

$bd[s1_] = (1/10^{7.5} Pb*b*s1*t1^5*\text{Exp}[-0.010*(t1+s1)] \text{Exp}[-r*t1]/(1-\text{Exp}[-r*t1]))$

bd=%

$$cs[s1\_]=1/10^{6.5} (Pc*\gamma*c*(s1*t1^5) (Exp[-0.035*(t1+s1)])*\lambda (Exp[-r*t1])/(1-Exp[-r*t1]))+Pc*\gamma*c*r (NIntegrate[(1/10^{6.5} s1*t1^5) Exp[-0.035*(t+s1)] (Exp[-r*t])/(1-Exp[-r*t]),\{t,10,t1\}])$$

$$cs=\%$$

$$swf1=cs+v1-GE$$

$$swf2=cs+v1-GE+bd$$

Results:

{s\*= 3.29565}

Volume(m3)	134.684
Revenue (\$)	2255.32
Profit (\$)	75.8761
Bio-Wild (\$)	234.885
Carbon (\$)	108.168
SWF1	2363.49
SWF2	2598.38

### Input 75 (in75)

A=100

$\alpha=1$

P=120

H=80

$\lambda=0.5$

W=10

r=0.03

a=1

b=1

c=1

d=1

Pb=20

Pc=20

Pj=20

$\gamma=0.2$

t1=75

$v[s_] = (s*t1^5) (\text{Exp}[-0.035*(t1+s)]);$

$\pi u[s_] = ((\alpha (P-H-\lambda*W) (v[s]) (\text{Exp}[-r*t1]) - (s*t1^2*10^5)))/(1-\text{Exp}[-r*t1]);$

soln=Maximize[ $\pi u[s]$ , s>=2, {s}][[2]]

s1=soln[[1,2]]

GE=0

$v[s]/\text{soln}$

$v[s1]$

$\pi u[s1]$

$v0[s1_] = (v[s1])/10^{6.5}$

v0=%

$v1[s1_] = (P*(a*(v[s1])) (\text{Exp}[-r*t1])/(1-\text{Exp}[-r*t1])/10^{6.5}$

v1=%

$pr[s1_] = (d*(1/10^{6.5} \pi u[s1]) - ((GE) 1/10^9 (\text{Exp}[-r*t1])/(1-\text{Exp}[-r*t1])))$

pr=%

$bd[s1_] = (1/10^{7.5} Pb*b*s1*t1^5*\text{Exp}[-0.010*(t1+s1)] \text{Exp}[-r*t1]/(1-\text{Exp}[-r*t1]))$

bd=%

$$cs[s1\_]=1/10^{6.5} (Pc*\gamma*c*(s1*t1^5) (Exp[-0.035*(t1+s1)])*\lambda (Exp[-r*t1])/(1-Exp[-r*t1]))+Pc*\gamma*c*r (NIntegrate[(1/10^{6.5} s1*t^5) Exp[-0.035*(t+s1)] (Exp[-r*t])/(1-Exp[-r*t]),\{t,10,t1\}])$$

$$cs=0\%$$

$$swf1=cs+v1-GE$$

$$swf2=cs+v1-GE+bd$$

**Results:**

{s\*= 2(minimum)}

Volume(m3)	101.371
Revenue (\$)	1433.18
Profit (\$)	20.3417
Bio-Wild (\$)	163.745
Carbon (\$)	75.8807
SWF1	1509.07
SWF2	1672.81

## Subsidy (sub)

A=100  
 $\alpha=1$   
P=120  
H=80  
 $\lambda=0.5$   
W=10  
r=0.03  
a=1  
b=1  
c=1  
d=1  
Pb=20  
Pc=20  
Pj=20  
 $\gamma=0.2$   
t2=52  
s2=7

$$v[s_,t_]=((s*t^5) (\text{Exp}[-0.035*(t+s)]));$$

$$\pi u[s_,t_] = ((\alpha (P-H-\lambda*W) (v[s,t] (\text{Exp}[-r*t])-(s*t*t*10^5)))/(1-\text{Exp}[-r*t]) + N\text{Integrate}(((Pc)*(\gamma)*(r)*(s2*t^5) (\text{Exp}[-0.035*(t+s2)])*(\text{Exp}[-r*t])/(1-\text{Exp}[-r*t])) + \lambda*Pc*\gamma*(s2*t^5) (\text{Exp}[-0.035*(t+s2)]) (\text{Exp}[-r*t])/(1-\text{Exp}[-r*t])), \{t,0,t2\}$$

$$\text{soln}=\text{Maximize}[\pi u[s,t],s>=2\&\&250>=t>=0, \{s,t\}][[2]]$$

$$s1=\text{soln}[[1,2]]$$

$$t1=\text{soln}[[2,2]]$$

$$GE=0$$

$$\text{subc}=\text{NIntegrate}(((1/10^{6.5}) (Pc)*(\gamma)*(r)*(s1*t^5) (\text{Exp}[-0.035*(t+s1)])*(\text{Exp}[-r*t])/(1-\text{Exp}[-r*t])) + (1/10^{6.5}) \lambda*Pc*\gamma*(s1*t^5) (\text{Exp}[-0.035*(t+s1)]) (\text{Exp}[-r*t])/(1-\text{Exp}[-r*t])), \{t,0,t1\}$$

$$v[s1,t1]$$

$$\pi u[s1,t1]$$

$$v0[s1_,t1_]=(v[s1,t1])/10^{6.5}$$
$$v0=0\%$$

$$v1[s1_,t1_]=(P*(a*(v[s1,t1]))) (\text{Exp}[-r*t1])/(1-\text{Exp}[-r*t1])/10^{6.5}+\text{subc}$$

v1=%

pr[s1\_,t1\_]=(((d 1/10<sup>6.5</sup>\*α (P-H-λ\*W) (v[s1,t1]) (Exp[-r\*t1])-(s1\*(t1\*t1\*10<sup>5</sup>)/10<sup>6.5</sup>))/(1-Exp[-r\*t1]))+subc)

pr=%

bd[t1\_,s1\_]=1/10<sup>7.5</sup> (Pb\*b\*s1\*t1<sup>5</sup>\*Exp[-0.010\*(t1+s1)] Exp[-r\*t1]/(1-Exp[-r\*t1]))

bd=%

cs[s1\_,t1\_]=1/10<sup>6.5</sup> (Pc\*γ\*c\*(s1\*t1<sup>5</sup>) (Exp[-0.035\*(t1+s1)])\*λ (Exp[-r\*t1])/(1-Exp[-r\*t1]))+Pc\*γ\*c\*r (NIntegrate[1/10<sup>6.5</sup> (s1\*t1<sup>5</sup>) Exp[-0.035\*(t+s1)] (Exp[-r\*t])/(1-Exp[-r\*t]),{t,10,t1}])

cs=%

swf1=cs+v1-GE-subc

swf2=cs+v1-GE+bd-subc

### Results:

{s\*= 6.87624, t\*=52.023}

Volume(m3)	105.449
Revenue (\$)	4433.81
Profit (\$)	1306.41
Bio-Wild (\$)	244.417
Carbon (\$)	116.552
SWF1	3480.06
SWF2	3724.47

### Subsidy 10% (sub1)

A=100  
 $\alpha=1$   
P=120  
H=80  
 $\lambda=0.5$   
W=10  
r=0.03  
a=1  
b=1  
c=1  
d=1  
Pb=20  
Pc=20  
Pj=20  
 $\gamma=0.2$   
t2=59  
s2=10

$$v[s_,t_]=((s*t^5) (Exp[-0.035*(t+s)]);$$

$$\pi u[s_,t_] = ((\alpha (P-H-\lambda*W) (v[s,t] (Exp[-r*t])-(s*t*t*10^5)))/(1-Exp[-r*t])+NIntegrate[(((Pc)*(gamma)*(r)*((s2*t^5) (Exp[-0.035*(t+s2)])*(Exp[-r*t])/(1-Exp[-r*t])))+\lambda*Pc*gamma*((s2*t^5) (Exp[-0.035*(t+s2)] (Exp[-r*t])/(1-Exp[-r*t])), {t,0,t2}]+0.1 (Pb*s*t^5*Exp[-0.010*(t+s)] Exp[-r*t]/(1-Exp[-r*t]))$$

$$\text{soln}=\text{Maximize}[\pi u[s,t],s>=2\&\&250>=t>=0, \{s,t\}][[2]]$$

$$s1=\text{soln}[[1,2]]$$

$$t1=\text{soln}[[2,2]]$$

$$GE=0$$

$$\text{subc}=\text{NIntegrate}[(((1/10^{6.5}) (Pc)*(gamma)*(r)*((s1*t^5) (Exp[-0.035*(t+s1)])*(Exp[-r*t])/(1-Exp[-r*t])))+(1/10^{6.5}) \lambda*Pc*gamma*((s1*t^5) (Exp[-0.035*(t+s1)] (Exp[-r*t])/(1-Exp[-r*t])), {t,0,t1}]$$

$$v[s,t]/.\text{soln}$$

$$v[s1,t1]$$

$$\pi u[s1,t1]$$

subb[s1,t1]

subb[s1\_,t1\_]=(1/10<sup>7.5</sup>) 0.1 (Pb\*s1\*t1<sup>5</sup>\*Exp[-0.010\*(t1+s1)] Exp[-r\*t1]/(1-Exp[-r\*t1]))  
subb=%

v0[s1\_,t1\_]=(v[s1,t1])/10<sup>6.5</sup>  
v0=%

v1[s1\_,t1\_]=(P\*(a\*(v[s1,t1]))) (Exp[-r\*t1])/(1-Exp[-r\*t1])/10<sup>6.5</sup>+subc +subb  
v1=%

pr[s1\_,t1\_]=(((d 1/10<sup>6.5</sup>\*α (P-H-λ\*W) (v[s1,t1]) (Exp[-r\*t1])-(s1\*(t1\*t1\*10<sup>5</sup>)/10<sup>6.5</sup>))/(1-  
Exp[-r\*t1]))+subc+subb  
pr=%

bd[t1\_,s1\_]=1/10<sup>7.5</sup> (Pb\*b\*s1\*t1<sup>5</sup>\*Exp[-0.010\*(t1+s1)] Exp[-r\*t1]/(1-Exp[-r\*t1]))  
bd=%

cs[s1\_,t1\_]=1/10<sup>6.5</sup> (Pc\*γ\*c\*(s1\*t1<sup>5</sup>) (Exp[-0.035\*(t1+s1)])\*λ (Exp[-r\*t1])/(1-Exp[-  
r\*t1]))+Pc\*γ\*c\*r (NIntegrate[1/10<sup>6.5</sup> (s1\*t1<sup>5</sup>) Exp[-0.035\*(t+s1)] (Exp[-r\*t])/(1-Exp[-  
r\*t]),{t,10,t1}])  
cs=%

swf1=cs+v1-GE-subc  
swf1=%

swf2=cs+v1-GE+bd-subc-subb  
swf2=%

## Results:

{s\*=10.3633,t \*=59.3005}

Volume(m3)	209.835
Revenue (\$)	7210.12
Profit (\$)	2201.41
Bio-Wild (\$)	486.355
Carbon (\$)	201.019
SWF1	n/a
SWF2	5801.13

## Subsidy 20% (sub2)

A=100  
 $\alpha=1$   
 P=120  
 H=80  
 $\lambda=0.5$   
 W=10  
 $r=0.03$   
 $a=1$   
 $b=1$   
 $c=1$   
 $d=1$   
 $P_b=20$   
 $P_c=20$   
 $P_j=20$   
 $t_2=67$   
 $s_2=15$

$$v[s_,t_]=((s*t^5) (Exp[-0.035*(t+s)]);$$

$$\pi u[s_,t_] = ((\alpha (P-H-\lambda*W) (v[s,t] (Exp[-r*t])-(s*t*t*10^5)))/(1-Exp[-r*t])+NIntegrate[((Pc)*(gamma)*(r)*((s2*t^5) (Exp[-0.035*(t+s2)])*(Exp[-r*t])/(1-Exp[-r*t]))+\lambda*Pc*\gamma*((s2*t^5) (Exp[-0.035*(t+s2)]) (Exp[-r*t])/(1-Exp[-r*t])),\{t,0,t2\}]+0.2 (Pb*s*t^5*Exp[-0.010*(t+s)] Exp[-r*t]/(1-Exp[-r*t]))$$

$$\text{soln}=\text{Maximize}[\pi u[s,t],s>=2\&\&250>=t>=0,\{s,t\}][[2]]$$

$$s1=\text{soln}[[1,2]]$$

$$t1=\text{soln}[[2,2]]$$

GE=0

$$\text{subc}=\text{NIntegrate}[((1/10^{6.5}) (Pc)*(gamma)*(r)*((s1*t^5) (Exp[-0.035*(t+s1)])*(Exp[-r*t])/(1-Exp[-r*t]))+(1/10^{6.5}) \lambda*Pc*\gamma*((s1*t^5) (Exp[-0.035*(t+s1)]) (Exp[-r*t])/(1-Exp[-r*t])),\{t,0,t1\}]$$

$$v[s,t]/.\text{soln}$$

$$v[s1,t1]$$

$$\pi u[s1,t1]$$

$$\text{subb}[s1,t1]$$

$$\text{subb}[s1_,t1_]=(1/10^{7.5}) 0.2 (Pb*s1*t1^5*Exp[-0.010*(t1+s1)] Exp[-r*t1]/(1-Exp[-r*t1]))$$

subb=%

v0[s1\_,t1\_]=(v[s1,t1])/10<sup>6.5</sup>  
v0=%

v1[s1\_,t1\_]=(P\*(a\*(v[s1,t1]))) (Exp[-r\*t1])/(1-Exp[-r\*t1])/10<sup>6.5</sup>+subb +subc  
v1=%

pr[s1\_,t1\_]=(((d 1/10<sup>6.5</sup>\*α (P-H-λ\*W) (v[s1,t1]) (Exp[-r\*t1])-(s1\*(t1\*t1\*10<sup>5</sup>)/10<sup>6.5</sup>))/(1-Exp[-r\*t1]))+subc+subb  
pr=%

bd[t1\_,s1\_]=1/10<sup>7.5</sup> (Pb\*b\*s1\*t1<sup>5</sup>\*Exp[-0.010\*(t1+s1)] Exp[-r\*t1]/(1-Exp[-r\*t1]))  
bd=%

cs[s1\_,t1\_]=1/10<sup>6.5</sup> (Pc\*γ\*c\*(s1\*t1<sup>5</sup>) (Exp[-0.035\*(t1+s1)])\*λ (Exp[-r\*t1])/(1-Exp[-r\*t1]))+Pc\*γ\*c\*r (NIntegrate[1/10<sup>6.5</sup> (s1\*t<sup>5</sup>) Exp[-0.035\*(t+s1)] (Exp[-r\*t])/(1-Exp[-r\*t]),{t,10,t1}])  
cs=%

swf1=cs+v1-GE-subc  
swf1=%

swf2=cs+v1-GE+bd-subc-subb  
swf2=%

## Results:

{s\*=14.6815, t\*=67.1564}

Volume(m3)	361.615
Revenue (\$)	10244
Profit (\$)	3098
Bio-Wild (\$)	861.017
Carbon (\$)	303.273
SWF1	n/a
SWF2	7841.87

## Tax (tax)

A=100

$\alpha=1$

P=120

H=80

$\lambda=0.5$

W=10

$r=0.03$

a=1

b=1

c=1

d=1

Pb=20

Pc=20

Pj=20

$\gamma=0.2$

$v[s,t]=((s*t^5) (\text{Exp}[-0.035*(t+s)]));$

$\pi u[s,t] = ((\alpha (P-H-\lambda*W) (v[s,t]) (\text{Exp}[-r*t])-(s*t*t*10^5)))/(1-\text{Exp}[-r*t])-(Pc*(\gamma) (1-\lambda))*(v[s,t])*(\text{Exp}[-r*t])-s*w)/(1-\text{Exp}[-r*t]);$

soln=Maximize[ $\pi u[s,t], s \geq 2 \& \& 250 \geq t \geq 0, \{s,t\}][[2]]$

s1=soln[[1,2]]

t1=soln[[2,2]]

GE=0

$v[s,t]/\text{soln}$

$v[s1,t1]$

$\pi u[s1,t1]$

$v0[s1,t1]=(v[s1,t1])/10^{6.5}$

v0=%

$v1[s1,t1]=(P*(a*(v[s1,t1]))) (\text{Exp}[-r*t1])/(1-\text{Exp}[-r*t1])/10^{6.5}$

v1=%

$pr[s1,t1]=(1/10^{6.5} (\alpha (P-H-\lambda*W) (v[s1,t1]) (\text{Exp}[-r*t1])-(s1*t1*t1*10^5)/10^{6.5}))/((1-\text{Exp}[-r*t1])-(1/10^{6.5} (Pc*(\gamma) (1-\lambda))*(v[s1,t1])*(\text{Exp}[-r*t1])-s1*w)/(1-\text{Exp}[-r*t1]))$

pr=%

$$bd[t1\_ ,s1\_]=1/10^{7.5} (Pb*b*s1*t1^5*Exp[-0.010*(t1+s1)] Exp[-r*t1]/(1-Exp[-r*t1]))$$

bd=%

$$cs[s1\_ ,t1\_]=1/10^{6.5} (Pc*\gamma*c*(s1*t1^5) (Exp[-0.035*(t1+s1)])*\lambda (Exp[-r*t1]/(1-Exp[-r*t1]))+Pc*\gamma*c*r (NIntegrate[1/10^{6.5} (s1*t1^5) Exp[-0.035*(t+s1)] (Exp[-r*t])/(1-Exp[-r*t]),\{t,10,t1\}])$$

cs=%

$$Tax[s1\_ ,t1\_]=1/10^{6.5} (Pc*(\gamma) (1-\lambda) ((s1*t1^5)) (Exp[-0.035*(t1+s1)]) (Exp[-r*t1]/(1-Exp[-r*t1])))$$

Tax=%

$$swf1=cs+v1-GE+Tax$$

$$swf2=cs+v1-GE+bd+Tax$$

**Results:**

$$\{s^*= 6.19617, t^*=51.427\}$$

Volume(m3)	93.7971
Revenue (\$)	3060.5
Profit (\$)	849.518
Bio-Wild (\$)	215.415
Carbon (\$)	104.995
SWF1	3216.5
SWF2	3431.92

## Appendix B: Initial Model Sensitivity Analysis Results by Policy

### Base Case

	u(52)	sq(73)	sq90	sq100	sq110	in60	in70	in75	sub(52)	sub1(59)	sub2(67)	tax(5)
Volume (m3)	105.449	529.016	841.051	1003.71	1139.11	141.456	134.684	101.371	105.449	209.835	361.615	93.7
Revenue (\$)	3363.5	8096.07	7271.48	6310.79	5234.77	3361.56	2255.32	1433.18	4433.81	7210.12	10244	306
Profit (\$)	236.101	2361.35	2120.85	1840.65	1526.81	197.098	75.8761	20.3417	1306.41	2201.41	3098	849.
Bio-wildlife (\$)	244.417	1694.68	2348.79	2617.45	2787.83	289.862	234.885	163.745	244.417	486.355	861.017	215.
Carbon (\$)	116.552	408.963	530.679	582.746	622.571	133.803	108.168	75.8807	116.552	201.019	303.273	104.
SWF1(no bio)	3480.06	3128.57	-43.5326	-2614.94	-5493.77	3495.36	2363.49	1509.07	3480.06	n/a	n/a	32
SWF2(with bio)	3724.47	4823.25	2305.26	2.51034	-2705.94	3785.22	2598.38	1672.81	3724.47	5801.13	7841.87	343
Investment (units)	7	29	29	29	29	6	3	2	7	10	15	6

### Price Carbon \$50

	u(52)	sq(73)	sq90	sq100	sq110	in60	in70	in75	sub(52)	sub1(59)	sub2(67)	tax(5)
Volume (m3)	105.449	529.016	841.051	1003.71	1139.11	141.456	134.684	101.371	105.449	209.835	361.615	74.8
Revenue (\$)	3363.5	8096.07	7271.48	6310.79	5234.77	3361.56	2255.32	1433.18	6039.27	10281.7	15335.3	253'
Profit (\$)	236.101	2361.35	2120.85	1840.65	1526.81	197.098	75.8761	20.3417	3654.43	5273.01	8189.34	640.
Bio-wildlife (\$)	244.417	1694.68	2348.79	2617.45	2787.83	289.862	234.885	163.745	244.417	486.355	861.017	169.
Carbon (\$)	291.379	1022.41	1326.7	1456.87	1556.43	334.507	270.419	189.702	291.379	502.546	758.181	21.
SWF1(no bio)	3654.88	3742.02	752.486	-1740.82	-4559.91	3696.06	2525.74	1622.89	3654.88	n/a	n/a	285'
SWF2(with bio)	3899.3	5436.7	3101.28	876.63	-1772.08	3985.93	2760.63	1786.63	3899.3	6102.66	8296.78	3026
Investment (units)	7	29	29	29	29	6	3	2	7	10	15	5

### Price Carbon \$100

	u(52)	sq(73)	sq90	sq100	sq110	in60	in70	in75	sub(52)	sub1(59)	sub2(67)	tax(4)
Volume (m3)	105.449	529.016	841.051	1003.71	1139.11	141.456	134.684	101.371	105.449	209.835	361.615	38.
Revenue (\$)	3363.5	8096.07	7271.48	6310.79	5234.77	3361.56	2255.32	1433.18	8715.03	15401.1	23820.9	142
Profit (\$)	236.101	2361.35	2120.85	1840.65	1526.81	197.098	75.8761	20.3417	5587.62	10392.4	16674.9	299.
Bio-wildlife (\$)	244.417	1694.68	2348.79	2617.45	2787.83	289.862	234.885	163.745	244.417	486.355	861.017	85.
Carbon (\$)	582.758	2044.82	2653.39	2913.73	3112.85	669.015	540.839	379.404	582.758	1005.09	1516.36	232.
SWF1(no bio)	3946.26	4764.43	2079.18	-283.958	-3003.49	4030.57	2796.16	1812.59	3946.26	n/a	n/a	177.
SWF2(with bio)	4190.68	6459.1	4427.97	2333.5	-215.654	4320.43	3031.05	1976.33	4190.68	6605.2	9054.96	185'
Investment (units)	7	29	29	29	29	6	3	2	7	10	15	3

## Discount 0.1%

	u(106)	sq(113)	sq90	sq100	sq110	in60	in70	in75	sub(106)	sub1(365)	sub2(372)	tax(104)
Volume (m3)	1050.28	1169.4	841.051	1003.71	1139.11	305.375	467.9	555.363	1050.28	24.5185	18.2224	104.7
Revenue (\$)	1130250	1176890	1071700	1145230	1175580	592611	774368	855675	2016600	2013180	2754370	1125
Profit (\$)	252546	343261	312578	334025	342876	130632	175091	194700	1138900	818950	1447470	309
Bio-wildlife (\$)	457612	669635	346173	474993	626065	75947	129210	162355	457612	8802440	8887440	448
Carbon (\$)	20606.5	21713.5	19097.7	20694	21587.7	10232.3	13492.7	14984.7	20606.5	2359.37	2021.08	2050
SWF1(no bio)	1150860	1090990	1005760	1070980	1092210	602844	787861	870660	1150860	n/a	n/a	1164
SWF2(with bio)	1608470	1760630	1351940	1545970	1718280	678791	917071	1033020	1608470	8811490	8894320	1613
Investment (units)	22	29	29	29	29	22	22	22	22	86	93	22

## Discount 1%

	u(85)	sq(98)	sq90	sq100	sq110	in60	in70	in75	sub(85)	sub1(181)	sub2(204)	tax(85)
Volume (m3)	679.307	973.513	841.051	1003.71	1139.11	288.727	440.621	520.773	679.307	999.833	588.875	664
Revenue (\$)	60722.6	70153.1	69146.3	70096.1	68204.8	42143.9	52157.3	55947	96788.4	146257	126316	599
Profit (\$)	10766.7	20461.3	20167.7	20444.7	19893.1	7747.93	9639.8	10261	46832.5	72371.9	20131.6	1650
Bio-wildlife (\$)	13120.7	27697.8	22335.2	29072.9	36323.2	4938.08	7865.95	9527.83	13120.7	114455	147560	126
Carbon (\$)	1719.04	2253.11	2049.46	2298.23	2497.91	972.188	1297.58	1449.6	1719.04	2573.89	1866.97	168
SWF1(no bio)	62441.6	58509.7	58863.4	58101	54315.4	43116.1	53454.9	57396.6	62441.6	n/a	n/a	625
SWF2(with bio)	75562.3	86207.6	81198.6	87173.9	90638.5	48054.1	61320.8	66924.4	75562.3	140595	159981	752
Investment (units)	17	29	29	29	29	18	18	18	17	46	65	17

## Discount 2%

	u(66)	sq(84)	sq90	sq100	sq110	in60	in70	in75	sub(66)	sub1(85)	sub2(107)	tax(66)
Volume (m3)	315.868	733.129	841.051	1003.71	1139.11	244.425	356.605	406.577	315.868	689.713	1100.47	300
Revenue (\$)	13705.1	20200	19986.8	18851.7	17033.4	12642	14006.5	14013.1	19619.5	32112.5	40896.5	132
Profit (\$)	1699.06	5891.66	5829.47	5498.42	4968.09	1629.85	1675.36	1571.61	7613.45	13636.7	16066	365
Bio-wildlife (\$)	1623.28	5602.5	6456.01	7818.92	9071.34	1294.87	1800.58	2004.33	1623.28	4132.74	9043.73	152
Carbon (\$)	455.756	866.843	945.095	1056.11	1145.71	387.05	489.976	526.199	455.756	811.032	1119.53	436
SWF1(no bio)	14160.8	13245.9	12164.2	9458.62	5884.42	13029.1	14496.5	14539.3	14160.8	n/a	n/a	138
SWF2(with bio)	15784.1	18848.4	18620.2	17277.5	14955.8	14324	16297	16543.6	15784.1	23663.7	27766.6	154
Investment (units)	12	29	29	29	29	13	12	11	12	19	30	12

Discount 3.5%

	u(46)	sq(68)	sq90	sq100	sq110	in60	in70	in75	sub(46)	sub1(51)	sub2(57)	tax(4)
Volume (m3)	48.1626	446.527	841.051	1003.71	1139.11	56.1523	85.526	101.371	48.1626	103.46	183.77	38.9
Revenue (\$)	1429.45	5473.93	4518.53	3750.37	2972.05	940.289	969.284	950.011	1822.37	3282.97	4931.7	1180
Profit (\$)	61.5211	1596.56	1317.9	1093.86	866.848	14.7949	-56.4636	-106.453	454.436	838.494	1245.19	330.
Bio-wildlife (\$)	84.086	1019.05	1459.55	1555.5	1582.8	73.8357	97.7305	108.541	84.086	176.623	311.496	67.5
Carbon (\$)	49.4696	292.812	408.792	444.29	470.493	42.5133	54.231	59.5173	49.4696	93.7672	148.17	40.6
SWF1(no bio)	1478.92	1167.9	-2718.74	-5121.75	-7727.6	982.802	1023.52	1009.53	1478.92	n/a	n/a	124'
SWF2(with bio)	1563.01	2186.95	-1259.19	-3566.25	-6144.8	1056.64	1121.25	1118.07	1563.01	2726.83	3952.16	131.
Investment (units)	4	29	29	29	29	2	2	2	4	7	10	3

Bio Price \$50

	u(52)	sq(73)	sq90	sq100	sq110	in60	in70	in75	sub(52)	sub1(71)	sub2(86)	tax(5)
Volume (m3)	105.449	529.016	841.051	1003.71	1139.11	141.456	134.684	101.371	105.449	448.259	767.682	93.7
Revenue (\$)	3363.5	8096.07	7271.48	6310.79	5234.77	3361.56	2255.32	1433.18	4433.81	11653.4	15416.6	300
Profit (\$)	236.101	2361.35	2120.85	1840.65	1526.81	197.098	75.8761	20.3417	1306.41	3409.78	2160.98	849.
Bio-wildlife (\$)	611.043	4236.7	5871.98	6543.63	6969.58	724.656	587.212	409.362	611.043	2739.63	5899.32	538.
Carbon (\$)	116.552	408.963	530.679	582.746	622.571	133.803	108.168	75.8807	116.552	354.589	504.104	104.
SWF1(no bio)	3480.06	3128.57	-43.5326	-2614.94	-5493.77	3495.36	2363.49	1509.07	3480.06	n/a	n/a	32
SWF2(with bio)	4091.1	7365.27	5828.44	3928.69	1475.81	4220.01	2950.7	1918.43	4091.1	10339.9	13954.6	375.
Investment (units)	7	29	29	29	29	6	3	2	7	17	31	6

Bio Price \$100

	u(52)	sq(72)	sq90	sq100	sq110	in60	in70	in75	sub(52)	sub1(86)	sub2(99)	tax(5)
Volume (m3)	105.449	529.016	841.051	1003.71	1139.11	141.456	134.684	101.371	105.449	767.682	792.701	93.7
Revenue (\$)	3363.5	8096.07	7271.48	6310.79	5234.77	3361.56	2255.32	1433.18	4433.81	15416.6	15599.7	300
Profit (\$)	236.101	2361.35	2120.85	1840.65	1526.81	197.098	75.8761	20.3417	1306.41	2160.98	-4821.66	849.
Bio-wildlife (\$)	1222.09	8473.4	11744	13087.3	13939.2	1449.31	1174.42	818.724	1222.09	11798.6	18545.6	107'
Carbon (\$)	116.552	408.963	530.679	582.746	622.571	133.803	108.168	75.8807	116.552	504.104	464.936	104.
SWF1(no bio)	3480.06	3128.57	-43.5326	-2614.94	-5493.77	3495.36	2363.49	1509.07	3480.06	n/a	n/a	32
SWF2(with bio)	4702.14	11602	11700.4	10472.3	8445.39	4944.67	3537.92	2327.79	4702.14	19853.9	24218	429.
Investment (units)	7	29	29	29	29	6	3	2	7	31	52	6

Carbon & Bio weights x10

	u(52)	sq(73)	sq90	sq100	sq110	in60	in70	in75	sub(52)	sub1(59)	sub2(67)	tax(5)
Volume (m3)	105.449	529.016	841.051	1003.71	1139.11	141.456	134.684	101.371	105.449	209.835	361.615	93.7
Revenue (\$)	3363.5	8096.07	7271.48	6310.79	5234.77	3361.56	2255.32	1433.18	4433.81	7210.12	10244	306
Profit (\$)	236.101	2361.35	2120.85	1840.65	1526.81	197.098	75.8761	20.3417	1306.41	2201.41	3098	849.
Bio-wildlife (\$)	2444.17	16946.8	23487.9	26174.5	27878.3	2898.62	2348.85	1637.45	2444.17	4863.55	8610.17	215.
Carbon (\$)	1165.52	4089.63	5306.79	5827.46	6225.71	1338.03	1081.68	758.807	1165.52	2010.19	3032.73	104.
SWF1(no bio)	4529.02	6809.24	4732.58	2629.77	109.369	4699.59	3337	2191.99	4529.02	n/a	n/a	416
SWF2(with bio)	6973.19	23756	28220.5	28804.3	27987.7	7598.21	5685.85	3829.44	6973.19	11987.5	18320.5	631.
Investment (units)	7	29	29	29	29	6	3	2	7	10	15	6

Bio weight x10

	u(52)	sq(73)	sq90	sq100	sq110	in60	In70	In75	sub(52)	sub1(59)	sub2(67)	tax(5)
Volume (m3)	105.449	529.016	841.051	1003.71	1139.11	141.456	134.684	101.371	105.449	209.835	361.615	93.7
Revenue (\$)	3363.5	8096.07	7271.48	6310.79	5234.77	3361.56	2255.32	1433.18	4433.81	7210.12	10244	306
Profit (\$)	236.101	2361.35	2120.85	1840.65	1526.81	197.098	75.8761	20.3417	1306.41	2201.41	3098	849.
Bio-wildlife (\$)	2444.17	16946.8	23487.9	26174.5	27878.3	2898.62	2348.85	1637.45	2444.17	486.355	8610.17	215.
Carbon (\$)	116.552	408.963	530.679	582.746	622.571	133.803	108.168	75.8807	116.552	201.019	303.273	104.
SWF1(no bio)	3480.06	3128.57	-43.5326	-2614.94	-5493.77	3495.36	2363.49	1509.07	3480.06	n/a	n/a	32
SWF2(with bio)	5924.23	20075.4	23444.4	23559.6	22384.5	6393.98	4712.34	3146.51	5924.23	5801.13	15591	5370
Investment (units)	7	29	29	29	29	6	3	2	7	10	15	6

Carbon weight x10

	u(52)	sq(73)	sq90	sq100	sq110	in60	In70	In75	sub(52)	sub1(59)	sub2(67)	tax(5)
Volume (m3)	105.449	529.016	841.051	1003.71	1139.11	141.456	134.684	101.371	105.449	209.835	361.615	93.7
Revenue (\$)	3363.5	8096.07	7271.48	6310.79	5234.77	3361.56	2255.32	1433.18	4433.81	7210.12	10244	306
Profit (\$)	236.101	2361.35	2120.85	1840.65	1526.81	197.098	75.8761	20.3417	1306.41	2201.41	3098	849.
Bio-wildlife (\$)	244.417	1694.68	2348.79	2617.45	2787.83	289.862	234.885	163.745	244.417	486.355	861.017	215.
Carbon (\$)	1165.52	4089.63	5306.79	5827.46	6225.71	1338.03	1081.68	758.807	1165.52	2010.19	3032.73	104.
SWF1(no bio)	4529.02	6809.24	4732.58	2629.77	109.369	4699.59	3337	2191.99	4529.02	n/a	n/a	416
SWF2(with bio)	4773.44	8503.92	7081.37	5247.23	2897.2	4989.45	3571.89	2355.74	4773.44	7610.29	10571.3	4370
Investment (units)	7	29	29	29	29	6	3	2	7	10	15	6

Pickling 0%

	u(53)	sq(73)	sq90	sq100	sq110	In60	In70	In75	sub(53)	sub1(60)	sub2(67)	tax(5)
Volume (m3)	131.708	529.016	841.051	1003.71	1139.11	172.032	194.167	168.461	131.708	233.487	374.767	111.
Revenue (\$)	3997.65	8096.07	7271.48	6310.79	5234.77	4088.19	3251.4	2381.71	4072.77	5719.89	7258.36	350.
Profit (\$)	390.005	2698.69	2423.83	2103.6	1744.92	353.082	191.657	97.3421	465.124	443.927	94.4113	10.
Bio-wildlife (\$)	311.561	1694.68	2348.79	2617.45	2787.83	367.448	353.827	282.537	311.561	553.548	911.505	25.
Carbon (\$)	75.015	274.029	409.488	477.567	535.325	94.5892	101.751	86.4057	75.015	128.338	198.793	63.5
SWF1(no bio)	4072.67	2993.64	-164.724	-2720.12	-5581.02	4182.78	3353.15	2468.11	4072.67	n/a	n/a	368.
SWF2(with bio)	4384.23	4688.32	2184.07	-102.669	-2793.18	4550.22	3706.98	2750.65	4384.23	6217.96	7987.42	394.
Investment (units)	8	29	29	29	29	7	5	4	8	12	16	7

Pickling 80%

	u(51)	sq(73)	sq90	sq100	sq110	in60	in70	in75	sub(51)	sub1(59)	sub2(67)	tax(5)
Volume (m3)	87.6933	529.016	841.051	1003.71	1139.11	117.72	88.6495	101.371	87.6933	193.225	352.257	82.6
Revenue (\$)	2896.08	8096.07	7271.48	6310.79	5234.77	2797.5	1484.47	1433.18	4297.15	7803.24	11875.5	275.
Profit (\$)	157.697	2158.95	1939.06	1682.88	1395.94	119.868	28.8013	-15.4879	1558.76	3031.6	4781.43	72.
Bio-wildlife (\$)	200.417	1694.68	2348.79	2617.45	2787.83	234.372	149.97	163.745	200.417	440.853	826.469	188.
Carbon (\$)	127.79	489.924	603.394	645.854	674.919	139.326	86.0413	90.2126	127.79	234.861	361.231	121.
SWF1(no bio)	3023.87	3209.53	29.1822	-2551.84	-5441.42	2936.83	1570.51	1523.4	3023.87	n/a	n/a	289.
SWF2(with bio)	3224.29	4904.21	2377.97	65.6182	-2653.59	3171.2	1720.48	1687.14	3224.29	5473.88	7717.31	308.
Investment (units)	6	29	29	29	29	5	2	2	6	10	14	6

Tenure 70%

	u(48)	sq(73)	sq90	sq100	sq110	in60	in70	in75	sub(48)	sub1(57)	sub2(67)	tax
Volume (m3)	34.9152	529.016	841.051	1003.71	1139.11	n/a	n/a	n/a	34.9152	140.05	321.577	n/a
Revenue (\$)	1288.56	8096.07	7271.48	6310.79	5234.77				1650.65	5095.43	9183.45	
Profit (\$)	22.9742	1652.95	1484.59	1288.45	1068.77				385.059	1307.62	2421.76	
Bio-wildlife (\$)	76.3543	1694.68	2348.79	2617.45	2787.83				76.3543	304.004	720.613	
Carbon (\$)	41.9332	408.963	530.679	582.746	622.571				41.9332	139.516	271.282	
SWF1 (no bio)	1330.49	3128.57	-43.5326	-2614.94	-5493.77				1330.49	n/a	n/a	
SWF2 (with bio)	1406.85	4823.25	2305.26	2.51034	-2705.94				1406.85	4126.68	7007.49	
Investment (units)	2	29	29	29	29				2	7	12	

Investment cost +20%

	u(50)	sq(73)	sq90	sq100	sq110	in60	in70	in75	sub(50)	sub1(57)	sub(64)	tax(5)
Volume (m3)	69.2951	529.016	841.051	1003.71	1139.11	90.085	85.526	101.371	69.2951	153.359	280.872	57.6
Revenue (\$)	2375.33	8096.07	7271.48	6310.79	5234.77	2140.78	1432.16	1433.18	3086.17	5640.55	8585.95	202.6
Profit (\$)	114.353	2361.35	2120.85	1840.65	1526.81	73.5532	-6.06421	-59.1923	825.199	1563.17	2362.79	561.1
Bio-wildlife (\$)	156.019	1694.68	2348.79	2617.45	2787.83	173.942	144.401	163.745	156.019	343.625	639.635	128.1
Carbon (\$)	79.7587	408.963	530.679	582.746	622.571	85.2114	68.6881	75.8807	79.7587	153.892	247.713	67.2
SWF1(no bio)	2455.09	2053.28	-1612.67	-4516.64	-7763.99	2225.99	1500.85	1509.07	2455.09	n/a	n/a	212.1
SWF2(with bio)	2611.11	3747.96	736.12	-1899.19	-4976.16	2399.94	1645.25	1672.81	2611.11	4587.44	6669.29	225.1
Investment (units)	5	29	29	29	29	3	2	2	5	8	12	4

Investment cost -20%

	u(54)	sq(73)	sq90	sq100	sq110	in60	in70	in75	sub(54)	sub1(62)	sub2(71)	tax(5)
Volume (m3)	149.109	529.016	841.051	1003.71	1139.11	189.715	228.679	216.141	149.109	279.28	458.579	137.1
Revenue (\$)	4383.61	8096.07	7271.48	6310.79	5234.77	4508.39	3829.3	3055.82	5879.02	8874.44	11896.1	413.1
Profit (\$)	416.906	2361.35	2120.85	1840.65	1526.81	390.106	242.083	146.131	1912.32	2997.27	3970.57	114.1
Bio-wildlife (\$)	357.423	1694.68	2348.79	2617.45	2787.83	416.239	428.767	373.37	357.423	674.461	1156.58	327.1
Carbon (\$)	157.594	408.963	530.679	582.746	622.571	179.451	183.657	161.792	157.594	253.857	363.206	107.1
SWF1(no bio)	4541.2	4203.86	1525.6	-713.247	-3223.55	4687.84	4012.96	3217.61	4541.2	n/a	n/a	434.1
SWF2(with bio)	4898.62	5898.54	3874.4	1904.21	-435.715	5104.08	4441.73	3590.98	4898.62	7050.77	8954.09	407.1
Investment (units)	9	29	29	29	29	8	6	5	9	13	18	9

Social Discount 1%

	u(52)	sq(73)	sq90	sq100	sq110	in60	in70	in75	sub(52)	sub1(59)	sub2(67)	tax
Volume (m3)	105.449	529.016	841.051	1003.71	1139.11	141.456	134.684	101.371	105.449	209.835	361.615	n/a
Revenue (\$)	18542.8	59452.9	69146.3	70096.1	68204.8	20647.5	15942.8	10890.3	23431.4	41385.3	63640.7	
Profit (\$)	236.101	2361.35	2120.85	1840.65	1526.81	197.098	75.8761	20.3417	5124.68	10381.3	17842.8	
Bio-wildlife (\$)	1347.46	12444.8	22335.2	29072.9	36323.2	1780.4	1660.39	1244.25	1347.46	2958.7	5844.85	
Carbon (\$)	404.803	1510.88	2049.46	2298.23	2497.91	476.302	396.629	282.171	404.803	714.047	1102.92	
SWF1(no bio)	18947.6	55587.3	63350.1	62885.8	59351.6	21123.8	16339.4	11172.5	18947.6	0	0	
SWF2(with bio)	20295	68032.1	85685.1	91958.8	95674.7	22904.2	17999.8	12416.7	20295	34781.8	52277.3	
Investment (units)	7	29	29	29	29	6	3	2	7	10	15	

Social Discount 0.1%

	u(52)	sq(73)	sq90	sq100	sq110	in60	in70	in75	sub(52)	sub1(59)	sub2(67)	tax
Volume (m3)	105.449	529.016	841.051	1003.71	1139.11	141.456	134.684	101.371	105.449	17.2901	14.9436	n/a
Revenue (\$)	236964	842484	1071700	1145230	1175580	274509	222899	156187	295123	3312136	3765439	
Profit (\$)	236.101	2361.35	2120.85	1840.65	1526.81	197.098	75.8761	20.3417	58395	1385540	1.1932	
Bio-wildlife (\$)	17219.5	176350	346173	474993	626065	23670.5	23214.3	17844.7	17219.5	8901440	8915890	
Carbon (\$)	4065.38	14718.1	19097.7	20694	21587.7	4739.81	3883.82	2735.16	4065.38	1893.95	1786.26	
SWF1(no bio)	241029	851826	1082950	1156410	1185810	279249	226783	158922	241029	n/a	n/a	
SWF2(with bio)	258249	1028180	1429120	1631410	1811880	302919	249998	176767	258249	1023213	1132432	
Investment (units)	7	29	29	29	29	6	3	2	7	95	98	

Harvest cost \$40

	u(59)	sq(73)	sq90	sq100	sq110	in60	in70	in75	sub(59)	sub1(63)	sub2(68)	tax(\$)
Volume (m3)	247.254	529.016	841.051	1003.71	1139.11	260.426	367.932	409.562	247.254	328.344	425.791	242.
Revenue (\$)	6129.11	8096.07	7271.48	6310.79	5234.77	6188.78	6161.15	5790.41	8547.94	10131.5	11734.1	606.
Profit (\$)	1929.9	5060.04	4544.67	3944.24	3271.73	1926.83	1666.88	1408.3	4348.73	5040.15	5596.3	370.
Bio-wildlife (\$)	637.183	1694.68	2348.79	2617.45	2787.83	659.821	805.022	830.95	637.183	853.934	1130.7	62.
Carbon (\$)	238.922	408.963	530.679	582.746	622.571	246.337	295.495	306.576	238.922	292.601	350.332	235.
SWF1(no bio)	6368.03	3128.57	-43.5326	-2614.94	-5493.77	6435.12	6456.64	6096.98	6368.03	n/a	n/a	639.
SWF2(with bio)	7005.21	4823.25	2305.26	2.51034	-2705.94	7094.94	7261.67	6927.93	7005.21	8054.7	9015.31	702.
Investment (units)	14	29	29	29	29	14	12	11	14	17	20	14

Timber Price \$140

	u(56)	sq(73)	sq90	sq100	sq110	in60	in70	in75	sub(56)	sub1(62)	sub1(68)	tax(\$)
Volume (m3)	314.096	529.016	841.051	1003.71	1139.11	288.247	423.686	487.823	314.096	378.686	452.067	311.
Revenue (\$)	11609.5	13493.4	12119.1	10518	8724.62	11416.5	11824.6	11494.8	14633.7	16064.2	17427.3	1150.
Profit (\$)	4133.13	7758.73	6968.5	6047.84	5016.65	4119.27	3903.08	3554.41	7157.28	7724.59	8154.42	655.
Bio-wildlife (\$)	849.806	1694.68	2348.79	2617.45	2787.83	801.004	1025.37	1100.59	849.806	1035.79	1259.04	841.
Carbon (\$)	287.115	408.963	530.679	582.746	622.571	272.653	340.273	365.158	287.115	326.461	367.485	28.
SWF1(no bio)	11896.6	8525.95	4804.12	1592.25	-2003.92	11689.2	12164.9	11859.9	11896.6	n/a	n/a	1190.
SWF2(with bio)	12746.4	10220.6	7152.91	4209.7	783.909	12490.2	13190.3	12960.5	12746.4	13739	14598.5	1280.
Investment (units)	12	29	29	29	29	11	9	8	12	14	18	

## Appendix C: Heterogeneity Results for Indifference Cost ( $\beta$ ) by Policy

### *Discount Rate of 3%*

A=100  
 $\alpha=1$   
P=120  
H=80  
 $\lambda=0.5$   
W=10  
r=0.02  
a=1  
b=1  
c=1  
d=1  
Pb=20  
Pc=20  
Pj=20  
 $\gamma=0.2$

#### **Unconstrained (u)**

t1=56  
s1=6

NSolve[((( $\alpha$  (P-H- $\lambda$ \*W) (((s1\*t1<sup>5</sup>) (Exp[-0.035\*(t1+s1)])) (Exp[-r\*t1])-(s1\*t1\*t1\*10<sup>5</sup>))-  
 $\beta$ ))/(1-Exp[-r\*t1])]==0,  $\beta$ ]

$\beta=5.7948*10^8$

Calibrated  $\beta=579480000/(10^{6.5})=183.248$

#### **Status Quo (sq)**

t1=74  
s1=28.5

NSolve[((( $\alpha$  (P-H- $\lambda$ \*W) (((s1\*t1<sup>5</sup>) (Exp[-0.035\*(t1+s1)])) (Exp[-r\*t1])-  $\beta$ ))/(1-Exp[-  
r\*t1])]==0,  $\beta$ ]

$\beta=6.6513*10^9$

Calibrated  $\beta=6651300000/(10^{6.5})=2103.33$

**Status Quo 100 (sq100)**

t1=100

s1=28.5

$$\text{NSolve}[(\alpha (P-H-\lambda*W) ((s1*t1^5)) (\text{Exp}[-0.035*(t1+s1)]) (\text{Exp}[-r*t1]) - \beta)) / (1 - \text{Exp}[-r*t1]) == 0, \beta]$$

$$\beta = 5.53083 * 10^9$$

$$\text{Calibrated } \beta = 5530830000 / (10^{6.5}) = 1749$$

**Status Quo 110 (sq110)**

t1=110

s1=28.5

$$\text{NSolve}[(\alpha (P-H-\lambda*W) ((s1*t1^5)) (\text{Exp}[-0.035*(t1+s1)]) (\text{Exp}[-r*t1]) - \beta)) / (1 - \text{Exp}[-r*t1]) == 0, \beta]$$

$$\beta = 4.6501 * 10^9$$

$$\text{Calibrated } \beta = 4650100000 / (10^{6.5}) = 1470.49$$

**Status Quo 120 (sq120)**

t1=120

s1=28.5

$$\text{NSolve}[(\alpha (P-H-\lambda*W) ((s1*t1^5)) (\text{Exp}[-0.035*(t1+s1)]) (\text{Exp}[-r*t1]) - \beta)) / (1 - \text{Exp}[-r*t1]) == 0, \beta]$$

$$\beta = 3.75071 * 10^9$$

$$\text{Calibrated } \beta = 3750710000 / (10^{6.5}) = 1186.08$$

**Input 75 (in75)**

t1=75

s1=2

$$\text{NSolve}[(\alpha (P-H-\lambda*W) (((s1*t1^5)) (\text{Exp}[-0.035*(t1+s1)])) (\text{Exp}[-r*t1]) - (s1*t1^2*10^5) - \beta)) / (1 - \text{Exp}[-r*t1]) == 0, \beta]$$

$$\beta = 5.75463 * 10^7$$

$$\text{Calibrated } \beta = 57546300 / (10^{6.5}) = 18.1977$$

**Input 70 (in70)**

t1=70

s1=3

$$\text{NSolve}[(\alpha (P-H-\lambda*W) ((s1*t1^5) (\text{Exp}[-0.035*(t1+s1)])) (\text{Exp}[-r*t1])-(s1*t1^2*10^5)-\beta))/(1-\text{Exp}[-r*t1])]==0, \beta]$$

$$\beta=2.08954*10^8$$

$$\text{Calibrated } \beta = 208954000/(10^{6.5})=66.0771$$
**Input 60 (in60)**

t1=60

s1=6

$$\text{NSolve}[(\alpha (P-H-\lambda*W) ((s1*t1^5) (\text{Exp}[-0.035*(t1+s1)])) (\text{Exp}[-r*t1])-(s1*t1^2*10^5)-\beta))/(1-\text{Exp}[-r*t1])]==0, \beta]$$

$$\beta=5.19324*10^8$$

$$\text{Calibrated } \beta = 519324000/(10^{6.5})=164.225$$
**Carbon Subsidy (sub)**

t1=52

s2=6.8

$$\text{NSolve}[(\alpha (P-H-\lambda*W) ((s2*t1^5) (\text{Exp}[-0.035*(t1+s2)])) (\text{Exp}[-r*t1])-(s2*t1*t1*10^5)-\beta))/(1-\text{Exp}[-r*t1])+\text{NIntegrate}[(Pc)*(\gamma)*(r)*((s2*t^5) (\text{Exp}[-0.035*(t+s2)]))*(\text{Exp}[-r*t])/(1-\text{Exp}[-r*t])]+\lambda*Pc*\gamma*((s2*t^5) (\text{Exp}[-0.035*(t+s2)])) (\text{Exp}[-r*t])/(1-\text{Exp}[-r*t])], \{t,0,t1\}]==0, \beta]$$

$$\beta=3.23707*10^9$$

$$\text{Calibrated } \beta=3237070000/(10^{6.5})=1023.65$$

Subsidy 10% (sub1)

t1=59

s1=10

NSolve[(( $\alpha$  (P-H- $\lambda$ \*W) ((s1\*t1<sup>5</sup>)) (Exp[-0.035\*(t1+s1)]) (Exp[-r\*t1])-(s1\*t1\*t1\*10<sup>5</sup>)- $\beta$ ))/(1-Exp[-r\*t1])+NIntegrate[((Pc)\*( $\gamma$ )\*(r)\*((s1\*t<sup>5</sup>)) (Exp[-0.035\*(t+s1)])\*(Exp[-r\*t])/(1-Exp[-r\*t]))+ $\lambda$ \*Pc\* $\gamma$ \*((s1\*t<sup>5</sup>)) (Exp[-0.035\*(t+s1)]) (Exp[-r\*t])/(1-Exp[-r\*t])],{t,0,t1}]+0.1 (Pb\*s1\*t1<sup>5</sup>\*Exp[-0.010\*(t1+s1)] Exp[-r\*t1]/(1-Exp[-r\*t1]))==0,  $\beta$ ]

$\beta=6.73059*10^9$

Calibrated  $\beta=6730590000/(10^{6.5})=2128.4$

Subsidy 20% (sub2)

t1=67

s1=15

NSolve[(( $\alpha$  (P-H- $\lambda$ \*W) ((s1\*t1<sup>5</sup>)) (Exp[-0.035\*(t1+s1)]) (Exp[-r\*t1])-(s1\*t1\*t1\*10<sup>5</sup>)- $\beta$ ))/(1-Exp[-r\*t1])+NIntegrate[((Pc)\*( $\gamma$ )\*(r)\*((s1\*t<sup>5</sup>)) (Exp[-0.035\*(t+s1)])\*(Exp[-r\*t])/(1-Exp[-r\*t]))+ $\lambda$ \*Pc\* $\gamma$ \*((s1\*t<sup>5</sup>)) (Exp[-0.035\*(t+s1)]) (Exp[-r\*t])/(1-Exp[-r\*t])],{t,0,t1}]+0.2 (Pb\*s1\*t1<sup>5</sup>\*Exp[-0.010\*(t1+s1)] Exp[-r\*t1]/(1-Exp[-r\*t1]))==0,  $\beta$ ]

$\beta=1.27725*10^{10}$

Calibrated  $\beta=12772500000/(10^{6.5})=4039.02$

Tax (tax)

t1=51

s1=6

NSolve[(( $\alpha$  (P-H- $\lambda$ \*W) ((s1\*t1<sup>5</sup>)) (Exp[-0.035\*(t1+s1)]) (Exp[-r\*t1])-(s1\*t1\*t1\*10<sup>5</sup>)- $\beta$ ))/(1-Exp[-r\*t1])-(Pc\*( $\gamma$ ) (1- $\lambda$ ))\*((s1\*t1<sup>5</sup>)) (Exp[-0.035\*(t1+s1)])\*(Exp[-r\*t1])-s1\*w)/(1-Exp[-r\*t1])==0,  $\beta$ ]

$\beta=4.514*10^8$

Calibrated  $\beta=45140000/(10^{6.5})=14.2745$

## Appendix D: Heterogeneity Results for Indifference Cost ( $\beta$ ) by Policy

### *Discount Rate of 2%*

A=100  
 $\alpha=1$   
P=120  
H=80  
 $\lambda=0.5$   
W=10  
r=0.02  
a=1  
b=1  
c=1  
d=1  
Pb=20  
Pc=20  
Pj=20  
 $\gamma=0.2$

### **Unconstrained (u)**

t1=68  
s1=12

NSolve[ $((\alpha (P-H-\lambda*W) (((s1*t1^5)) (Exp[-0.035*(t1+s1)])) (Exp[-r*t1])-(s1*t1*t1*10^5)-\beta))/(1-Exp[-r*t1])=0, \beta]$

$\beta=3.98199*10^9$

Calibrated  $\beta = 3981990000/(10^{6.5}) = 1259.22$

### **Status Quo (sq)**

t1=85  
s1=28.5

NSolve[ $((\alpha (P-H-\lambda*W) (((s1*t1^5)) (Exp[-0.035*(t1+s1)])) (Exp[-r*t1])-\beta))/(1-Exp[-r*t1])=0, \beta]$

$\beta=1.5222*10^{10}$

Calibrated  $\beta = 1.5222*10^{10}/(10^{6.5}) = 4813.62$

**Status Quo 100 (sq100)**

t1=100

s1=28.5

$$\text{NSolve}[((\alpha (P-H-\lambda*W) ((s1*t1^5)) (\text{Exp}[-0.035*(t1+s1)]) (\text{Exp}[-r*t1]) - \beta))/(1-\text{Exp}[-r*t1]) == 0, \beta]$$

$$\beta = 1.50343 * 10^{10}$$

$$\text{Calibrated } \beta = 1.50343 * 10^{10} / (10^{6.5}) = 4754.26$$

**Status Quo 110 (sq110)**

t1=110

s1=28.5

$$\text{NSolve}[((\alpha (P-H-\lambda*W) ((s1*t1^5)) (\text{Exp}[-0.035*(t1+s1)]) (\text{Exp}[-r*t1]) - \beta))/(1-\text{Exp}[-r*t1]) == 0, \beta]$$

$$\beta = 1.39697 * 10^{10}$$

$$\text{Calibrated } \beta = 13969700000 / (10^{6.5}) = 4417.61$$

**Status Quo 120 (sq120)**

t1=120

s1=28.5

$$\text{NSolve}[((\alpha (P-H-\lambda*W) ((s1*t1^5)) (\text{Exp}[-0.035*(t1+s1)]) (\text{Exp}[-r*t1]) - \beta))/(1-\text{Exp}[-r*t1]) == 0, \beta]$$

$$\beta = 1.24528 * 10^{10}$$

$$\text{Calibrated } \beta = 12452800000 / (10^{6.5}) = 3937.92$$

**Input 75 (in75)**

t1=75

s1=11

$$\text{NSolve}[((\alpha (P-H-\lambda*W) (((s1*t1^5)) (\text{Exp}[-0.035*(t1+s1)])) (\text{Exp}[-r*t1]) - (s1*t1^2*10^5) - \beta))/(1-\text{Exp}[-r*t1]) == 0, \beta]$$

$$\beta = 3.86095 * 10^9$$

$$\text{Calibrated } \beta = 1378450000 / (10^{6.5}) = 435.904$$

**Input 70 (in70)**

t1=70

s1=12

$$\text{NSolve}[(\alpha (P-H-\lambda*W) ((s1*t1^5)) (\text{Exp}[-0.035*(t1+s1)]) (\text{Exp}[-r*t1])-(s1*t1^2*10^5)-\beta))/(1-\text{Exp}[-r*t1])=0, \beta]$$

$$\beta=3.98966*10^9$$

$$\text{Calibrated } \beta=3989660000/(10^{6.5})=1261.64$$
**Input 60 (in60)**

t1=60

s1=13

$$\text{NSolve}[(\alpha (P-H-\lambda*W) ((s1*t1^5)) (\text{Exp}[-0.035*(t1+s1)]) (\text{Exp}[-r*t1])-(s1*t1^2*10^5)-\beta))/(1-\text{Exp}[-r*t1])=0, \beta]$$

$$\beta=3.59927*10^9$$

$$\text{Calibrated } \beta=3599270000/(10^{6.5})=1138.19$$
**Carbon Subsidy (sub)**

t1=68

s2=12

$$\text{NSolve}[(\alpha (P-H-\lambda*W) ((s2*t1^5)) (\text{Exp}[-0.035*(t1+s2)]) (\text{Exp}[-r*t1])-(s2*t1*t1*10^5)-\beta))/(1-\text{Exp}[-r*t1])+\text{NIntegrate}[(Pc)*(\gamma)*(r)*((s2*t^5)) (\text{Exp}[-0.035*(t+s2)])*(\text{Exp}[-r*t])/(1-\text{Exp}[-r*t])]+\lambda*Pc*\gamma*((s2*t^5)) (\text{Exp}[-0.035*(t+s2)]) (\text{Exp}[-r*t])/(1-\text{Exp}[-r*t]), \{t,0,t1\}]=0, \beta]$$

$$\beta=1.87438*10^{10}$$

$$\text{Calibrated } \beta=18743800000/(10^{6.5})=5927.31$$

### Subsidy 10% (sub1)

t1=85

s1=19

NSolve[(((α (P-H-λ\*W) ((s1\*t1<sup>5</sup>)) (Exp[-0.035\*(t1+s1)]) (Exp[-r\*t1])-(s1\*t1\*t1\*10<sup>5</sup>)-β))/(1-Exp[-r\*t1])+NIntegrate[((Pc)\*(γ)\*(r)\*((s1\*t<sup>5</sup>)) (Exp[-0.035\*(t+s1)])\*(Exp[-r\*t])/(1-Exp[-r\*t]))+λ\*Pc\*γ\*((s1\*t<sup>5</sup>)) (Exp[-0.035\*(t+s1)]) (Exp[-r\*t])/(1-Exp[-r\*t])],{t,0,t1}]+0.1 (Pb\*s1\*t1<sup>5</sup>\*Exp[-0.010\*(t1+s1)] Exp[-r\*t1]/(1-Exp[-r\*t1]))==0, β]

$$\beta=4.53645*10^{10}$$

$$\text{Calibrated } \beta=45364500000/(10^{6.5})=14345.5$$

### Subsidy 20% (sub2)

t1=107

s1=30

NSolve[(((α (P-H-λ\*W) ((s1\*t1<sup>5</sup>)) (Exp[-0.035\*(t1+s1)]) (Exp[-r\*t1])-(s1\*t1\*t1\*10<sup>5</sup>)-β))/(1-Exp[-r\*t1])+NIntegrate[((Pc)\*(γ)\*(r)\*((s1\*t<sup>5</sup>)) (Exp[-0.035\*(t+s1)])\*(Exp[-r\*t])/(1-Exp[-r\*t]))+λ\*Pc\*γ\*((s1\*t<sup>5</sup>)) (Exp[-0.035\*(t+s1)]) (Exp[-r\*t])/(1-Exp[-r\*t])],{t,0,t1}]+0.1 (Pb\*s1\*t1<sup>5</sup>\*Exp[-0.010\*(t1+s1)] Exp[-r\*t1]/(1-Exp[-r\*t1]))==0, β]

$$\beta=6.50901*10^{10}$$

$$\text{Calibrated } \beta=65090100000/(10^{6.5})=20583.3$$

### Tax (tax)

t1=63

s1=12

NSolve[(((α (P-H-λ\*W) ((s1\*t1<sup>5</sup>)) (Exp[-0.035\*(t1+s1)]) (Exp[-r\*t1])-(s1\*t1\*t1\*10<sup>5</sup>)-β))/(1-Exp[-r\*t1])-(Pc\*(γ) (1-λ))\*((s1\*t1<sup>5</sup>)) (Exp[-0.035\*(t1+s1)])\*(Exp[-r\*t1])-s1\*w)/(1-Exp[-r\*t1])==0, β]

$$\beta=3.3126*10^9$$

$$\text{Calibrated } \beta=3312600000/(10^{6.5})=1047.54$$

## Appendix E: Heterogeneity Results for Unharvested Stand

### *Discount Rate 3%*

r=0.03  
b=1  
c=1  
Pb=20  
Pc=20  
γ=0.2  
t1=250  
s1=1

$$bd=(1/10^{7.5} Pb*b*s1*t1^5*Exp[-0.010*(t1+s1)]) Exp[-r*t1]/(1-Exp[-r*t1])$$

$$cs=Pc*\gamma*c*r (NIntegrate[1/10^{6.5} (s1*t^5) Exp[-0.035*(t+s1)] (Exp[-r*t])/(1-Exp[-r*t]),\{t,10,t1\}])$$

$$swf=bd+cs$$

### **Results:**

bd= 27.7768  
cs= 65.8684  
swf= 93.6452

### *Discount Rate 2%*

r=0.02  
b=1  
c=1  
Pb=20  
Pc=20  
γ=0.2  
t1=250  
s1=1

$$bd=(1/10^{7.5} Pb*b*s1*t1^5*Exp[-0.010*(t1+s1)]) Exp[-r*t1]/(1-Exp[-r*t1])$$

$$cs=Pc*\gamma*c*r (NIntegrate[1/10^{6.5} (s1*t^5) Exp[-0.035*(t+s1)] (Exp[-r*t])/(1-Exp[-r*t]),\{t,10,t1\}])$$

$$swf=bd+cs$$

### **Results:**

bd= 340.498  
cs= 127.843  
swf= 468.34

## Appendix F: Simulation Results for all three stand types by policy

### Old Growth Stand

Bio-Wildlife (\$)	7216
Carbon (\$)	66
SWF (\$)	7281

### Timber Stand

	u(51)	sq(73)	sq90	sq100	sq110	in60	In70	In75	sub(51)	sub1(59)	sub2(67)	tax(5)
Volume (m3)	87.6933	529.016	841.051	1003.71	1139.11	117.72	88.6495	101.371	87.6933	193.225	352.257	85.
Revenue (\$)	2896.08	8096.07	7271.48	6310.79	5234.77	2797.5	1484.47	1433.18	4465.95	8159.99	12499.7	2827
Profit (\$)	157.697	2158.95	1939.06	1682.88	1395.94	119.868	28.8013	15.4879	1727.56	3388.35	5405.6	751.
Bio (\$)	200.417	1694.68	2348.79	2617.45	2787.83	234.372	149.97	163.745	200.417	440.853	826.469	194.
Carbon (\$)	137.444	516.911	627.632	666.89	692.368	148.651	90.9895	94.9899	137.444	250.855	382.996	133.
SWF (\$)	3233.94	4931.2	2402.21	86.6542	2636.14	3180.52	1725.43	1691.92	3233.94	5489.87	7739.08	3165
Investment (units)	6	29	29	29	29	5	2	2	6	10	14	

### Timber Quality/Habitat Stand

	u(64)	sq(82)	sq90	sq100	sq110	in60	In70	In75	sub(64)	sub1(69)	sub2(74)	tax(5)
Volume (m3)	284.58	696.142	841.051	1003.71	1139.11	238.94	342.204	383.941	284.58	394.117	512.119	283
Revenue (\$)	7677.47	11047.6	10543	9465.66	8113.5	7380.84	7735.25	7463.13	12429.8	16431.1	19568.5	765
Profit (\$)	1249.49	4656.94	4556.25	4206.77	3698.92	1221.48	1199.66	1080.18	6001.86	8454.27	10031.6	302
Bio (\$)	647.582	2066.04	2348.79	2617.45	2787.83	574.429	722.541	758.154	647.582	920.39	1246.44	644
Carbon (\$)	327.498	582.999	627.632	666.89	692.368	301.723	351.237	359.773	327.498	409.52	485.435	326
SWF (\$)	8652.55	7074.02	5673.7	3241.52	242.586	8257	8809.03	8581.06	8652.55	10415	11884	864
Investment (units)	12	29	29	29	29	12	11	10	11	15	18	