Economics of Hybrid Poplar Plantations in Western Canada for Bioethanol Production

by

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Abstract

This two papers thesis explores the economics of hybrid poplar plantations as a potential bioethanol feedstock in Canada. The first paper (Chapter 2) is the stand-level analysis of the financial viability of producing hybrid poplar on private lands for both single-stem and coppice production systems. The results suggest that the coppice system is financially inferior to the single stem. But the single-stem production system could be financially feasible, given the current land and biomass prices and a real discount rate of less than 4.6%.

The second paper (Chapter 3) is the forest-level analysis. In this model, public lands are considered to investigate the impacts of different policies on the NPV of a stylized forestry firm for both juvenile and split mature initial forest inventories. The investigated policy variables include varying even-flow conditions, allowing the exotic plantations on public lands, and accounting for sequestered carbon. The results show that permitting hybrid poplar plantations on public lands not only results in higher NPVs, but also leads to more non-harvested lands. Also, the results indicate that accounting for sequestered carbon does not always lead to an increase in the firm`s total NPV. The reason is that carbon sequestration has a dynamic nature that depends on several factors in each scenario. In addition, when the forestry firm maximizes the timber NPV instead of both timber and carbon NPV, there is always a social cost of not considering carbon that actually has value.

Dedication

For

My beloved parents,

my lovely husband, Mohammad Reza,

and

my sweet son, Amir Reza

Acknowledgment

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Chapter 1. Introduction

The world of energy is changing. Biofuels are emerging as an alternative to fossil fuels that can potentially have a more stable market due to the renewable and predictable nature of their production. From environmental perspective, biofuels release less carbon to the atmosphere than fossil fuels (Gleeson, et al., 2009). Also providing biomass for bioenergy can increase farm incomes (Stupak , et al., 2011; Luo, et al., 2011) as a socioeconomic advantage of biofuel production.

Canada has been recognized as one of many countries with rapid growth in biofuel production. Ninety percent of the ethanol produced in Canada is made from grain, especially corn and wheat (Olar , et al., 2004). Though food-based (first generation) feedstocks are currently the primary means of producing ethanol, unfavourable environmental, social and economic effects of food-based biomass production (Erickson & Saket, 2007; Daschle, et al., 2007; Tenenbaum, 2008) have caused scientists to investigate non-food-based feedstocks. Substituting fossil fuel with cellulosic (second generation) ethanol has been estimated to reduce greenhouse gas (GHG) emissions by 86%, while substituting fossil fuel with food-based ethanol is estimated to decreases emissions by only 28% (Wang, et al., 2008). Currently, compared to food-based feedstocks, cellulosic feedstocks generally cost less, but tend to need higher capital investments per unit for processing (BioZio, 2011). But, the potential of cellulosic biofuels to address the above concerns has resulted in significant research efforts targeted towards its production.

Forest plantations are potential renewable and domestic source for feedstock in a country like Canada, where 60% of the land area is covered with forests. This potential feedstock has motivated researchers to explore making bioethanol from trees with high yield. For example, the Canadian Wood Fibre Centre and Genome Canada both are supporting studies of hybrid poplar plantations in Canada. However, there is little known about the financial viability of bioethanol production from forest plantations. Knowing the financial viability of hybrid poplar plantations for bioethanol production can be relevant to policy makers considering subsidies for second generation biofuel production.

In this thesis, I analyze the financial viability of producing hybrid poplar for use as a potential bioethanol feedstock in Canada. I investigate how forestry management, carbon and biofuel policies, the forest tenure system, and economic factors like production and silviculture costs affect the financial viability of hybrid poplar plantations of a forestry firm to produce bioethanol. I analyze growth and cost data for producing hybrid poplar in the Peace River region of northern Alberta and British Columbia – an area where poplar may be able to financially compete with agricultural land uses. This thesis is a collection of two papers.

In chapter 2, I conduct a stand-level analysis of the financial viability of hybrid poplar plantations on private lands. The financial returns are estimated for two hybrid poplar production systems: *(i)* a single-stem production system that involves the planting and harvesting of individual trees according to optimal economic rotations of 20 to 26 years; and *(ii)* a coppice (multi-stem) production system that involves multiple harvests of new shoots that sprout from a stump following harvest every 3 to 4 years. In this chapter, sensitivity analyses are conducted to investigate under what circumstances hybrid poplar plantations in private lands emerge as a viable feedstock source for bioethanol production.

In chapter 3, I add in considerations of public lands due to their low opportunity cost and because about 90% of forested lands in Canada are owned by provincial and territorial governments (Natural Resources Canada, 2014)**.** In Canada, there are developed policies to provide incentives to produce 2nd generation bioethanol. However, exotic trees such as hybrid poplars are not generally allowed on public lands in Canada (Johnston & Williamson, 2008) with some exceptions in British Columbia and Quebec (Anderson, et al., 2012). Also, native Canadian trees have potentially low yields (Anderson, et al., 2012) and are not financially viable in stand-level analysis (Adamowicz, et al., 2003). In this chapter, I study different policy scenarios to investigate their effects on the NPV of the forestry firm and the area of land is planted through the production of bioethanol from forest feedstocks. These policies include three main elements: the type of even-flow constraint, whether exotic plantations on public lands are allowed, and whether carbon benefits are accounted for in the NPV.

In the last chapter, the findings are summarized and some general conclusions are offered.

Chapter 2. Financial Analysis of Hybrid Poplar in Western Canada as a Potential Feedstock for Bioethanol: A Stand-level Analysis

2.1. Introduction

Ethanol, as an emerging biofuel, is attractive due to its potential to decrease greenhouse gases (GHG) emissions and reduce dependence on uncertain supplies of fossil fuels (Stupak , et al., 2011; Luo, et al., 2011). Canada has been recognized as one of many countries with rapid growth in biofuel production. Ninety percent of the ethanol produced in Canada is made from grain, especially corn and wheat (Olar , et al., 2004). Though food-based (first generation) feedstocks are currently the primary means of producing ethanol, unfavourable environmental, social and economic effects of food-based biomass production (Erickson & Saket, 2007; Daschle, et al., 2007; Tenenbaum, 2008) have caused scientists to investigate non-food-based feedstocks. Substituting fossil fuel with cellulosic (second generation) ethanol has been estimated to reduce greenhouse gas (GHG) emissions by 86%, while substituting fossil fuel with food-based ethanol is estimated to decreases emissions by only 28% (Wang, et al., 2008). Compared to food-based feedstocks, cellulosic feedstocks generally cost less, but tend to need higher capital investments per unit for processing (BioZio, 2011). But if improvements in cellulosic production continue, the financial viability gap between first-and second-generation technologies will narrow. The potential of cellulosic biofuels to address the above concerns has resulted in significant research efforts targeted towards its production.

Industrial bioethanol production using forest and agricultural residues (such as corn stover or wheat straw) needs large-scale production facilities with high investment requirements in order to be financially viable, and consequently, needs large quantities of feedstocks. Forests are a potential feedstock, especially in a country like Canada, where 60% of the land area is covered with forests. This potential feedstock has motivated researchers to explore making bioethanol from trees. For example, the Canadian Wood Fibre Centre has a long-term project evaluating different management options which could produce short rotation woody crops (e.g., willow and hybrid poplar) with desirable attributes for developing cellulosic based fuel, forest products and use for carbon capture. Similarly, Genome Canada is supporting a study aimed at increasing the quality and quantity of hybrid poplars for use as a feedstock in bioethanol production (Genome, 2010).

The objective of this study is to analyze the financial viability of producing hybrid poplar for use as a potential bioethanol feedstock in Canada. There are two studies (Anderson & Luckert, 2007; Miville, et al., 2013) that have conducted financial analyses of hybrid poplar plantations in Canada with regard to use in pulp and two further studies (Yemshanov & McKenney, 2008; Allen, et al., 2013) have done so in the context of bio-energy. Anderson and Luckert (2007) conducted a stand-level analysis of the financial viability of hybrid poplar plantations on private lands and found that financial returns were marginal but could be profitable with policies such as carbon credits. Miville, et al. (2013) evaluated the profitability of hybrid poplar profitability for private landowners in Quebec. Results showed that investment in poplar cultivation is profitable only in scenarios with grants and government support. Yemshanov and McKenney (2008) explored the economic feasibility of fast-growing hybrid poplar plantations on agricultural lands in Canada for producing bioenergy. In this study, a spatial bio-economic model was used in which various levels of biomass processing capacities were considered, with and without carbon values. Using the Canadian Forest Service afforestation feasibility model (CFS-AFM), they showed that with or without carbon incentives, the break-even cost of hybrid poplar plantations exceeded the current delivered price of low-grade coal. They also indicated that lower rental costs and larger agricultural land areas could make the western Prairie Provinces more attractive than eastern Canada. More recently, Allen et al. (2013) studied the financial viability of hybrid poplar plantations for bioenergy production using a coppice production system on agricultural lands in Ontario. They reported a range of break-even biomass prices of $82/odt[1] to $292/odt for different scenarios. The lower bound of this range roughly reflects the current biomass prices paid.

My approach differs from previous studies of financial analysis of poplar plantations in six major ways: First, all past studies except for Anderson and Luckert (2007), a study which is now dated, analyzed the financial viability of poplar plantations in eastern parts of Canada. I study poplar plantations in the Peace River region of British Columbia and Alberta. Second, this study compares values used in the analysis to findings in the global literature. Third, although I study the financial viability of poplar cultivation on private agricultural land, similar to previous studies, the perspective is different. Agricultural lands are investigated from a land value perspective to see whether poplar feedstock can compete with agricultural crops. Fourth, rather

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[1] odt is oven dry tonne

than treating the rotation age as constant, I investigate changes in rotation age with respect to changes in economic parameters such as discount rates, silvicultural costs, and biomass prices. Fifth, this study investigates the profitability of coppice and single stem management system. The Allen et al. (2013) is the only article that conducted financial analysis for coppice systems, but their results were not compared to traditional single stem management systems. Finally, this study differs from past research because I derive the value of land for wood for bioethanol based on values derived from a value added production chain for bioethanol rather than assuming a price for feedstock.

In the subsequent sections of this paper I first present the approach to evaluating, and comparing land values in competing agricultural and hybrid poplar production systems. Then, I review the needed data and related assumptions. Next, I present the results including a sensitivity analysis of changes in interest rates, biomass prices, silviculture costs and yields. The results show under what conditions hybrid poplars could potentially compete with agriculture on private land.

2.2. Methods

2.2.1. Model setup

My approach is to compare land values, as measured by the land expectation value (LEV), with different land uses and management systems. The LEV is an estimate of the value of forest bare land in perpetual timber production. Since hybrid poplar plantations are not generally permitted on Crown land in Canada, I assume that poplar plantations must compete with agricultural crop production within the private land market. Therefore, the LEV of poplar plantations was compared with the selling prices for agricultural land, as a means of investigating the financial viability of hybrid poplar plantations. LEV calculations are used to: *i)* estimate the value of forest land for growing tree in perpetuity , *ii)* identify changes in land values due to different silviculture regimes, and *iii)* determine the Optimal Economic Rotation (OER). The LEV can be calculated using the continuous-time version of the Faustmann formula e.g. (Pearse, 1990) as follows:

$$LEV = \frac{V_t P \ \ - C e^{rt}}{e^{rt} - 1} \qquad (2.1)$$

Where,

LEV = land expectation value in $ per hectare;

V_t = the stand volume of a hectare hybrid poplar in m^3 at rotation age "*t";*

P= the price of biomass in $ per m^3;

C = the present value of all silvicultural costs in $ per hectare;

e^{rt} = discount factor in continuous time with discount rate "r" and rotation age "t".

Following equation (2.1), the OER is the rotation age that maximizes the LEV.

2.2.2. Data

This section contains a description of the data needed to compute the *LEV*s. All introduced variables in Equation (2.1) are explained in the following sections. In addition, estimates of agricultural land values are presented.

2.2.2.1. Yield curve (V_t)

Table 2.1 shows reported yields for hybrid poplar from various studies in m^3/ha/year and odt/ha/year. Yields are expressed in both m^3/ha/year and odt/ha/year because of the bioethanol focus of this study. The stand volume is converted into odt/ha by multiplying the volume by the specific gravity of hybrid poplar. The literature indicates a range of 0.300 - 0.375 for the specific gravity of hybrid poplar (Beaudoin, et al., 1992; Olson, et al., 1985; Goyal, et al., 1999). Following Beaudoin et al. (1992), I use a mid-range value of 0.349 that a number of other studies have used (Zhang, et al., 2003; Wua, et al., 2014).

Table (2.1): Reported hybrid poplar yield in previous studies and different areas

Study	**Mean Annual Increment (MAI)**		**Region**
	(odt/ha/year)	**m^3/ha/year**	
(Samson, et al., 1999)	9.0-12.0	25.8-34.4	BC, Canada
	1.0-5.0	2.9-14.3	Prairie provinces, Canada
	2.5-7.0	7.2-20.1	ON and QB, Canada
	2.0-6.0	5.7-17.2	Atlantic provinces, Canada
(Kline & Coleman, 2010)	5.0	14.3	US
(Felix, et al., 2008)	5.5	15.8	Washington, DC, US
(Allen, et al., 2013)	3.6-8.5	10.3-24.4	ON, Canada
(Riemenschneider, et al., 2001)	6.2-14.9	17.8-42.7	North central US
(Downinga, et al., 2005)	10-15	28.7-43.0	Minnesota, US
(BioZio, 2011)	15.3 - 22.3	43.8-63.9	US, EU

The mean annual increment (MAI) of hybrid poplar is shown to vary among studies between 2.9 (Samson, et al., 1999) and 63.9 m^3/ha/year (BioZio, 2011). This variability is likely due to a number of factors including geographic location, soil type, and year of the harvest. While the MAI of hybrid poplar in the US seems higher than Canada, it is different among different parts of Canada as well. In Canada, the highest and the lowest MAI for hybrid poplar are reported in BC province (i.e. 25.8-34.4 m^3/ha/year or 9.0-12.0 odt/ha/year) and Prairie Provinces (i.e. 2.9-14.3 m^3/ha/year or 1.0-5.0 odt/ha/year), respectively.

Long-term growth and yield data for hybrid poplar production within Canada are scarce. The most recent data we found for Canada are those provided by the Canadian Wood Fibre Centre (CWFC) (Sidders, et al., 2012). This study uses the CWFC's hybrid poplar yield curve for the Peace River region of northern Alberta and British Columbia, a region where land prices are low, thereby, allowing for the potential for profitable poplar plantations. CWFC Hybrid poplar production data is analyzed for two management systems: single stem and coppice. There are significant differences between the two management systems. While the stem density is 1,600 trees per hectare (2.5 m × 2.5 m spacing) for single stem, the stem density is 15,625 trees per hectare (3-row plantations) for coppice. In addition, while there is only one harvest for single stem management systems before the stand must be replanted, several harvests are possible before the coppice management system must be replanted.

Figures 2.1 and 2.2 show the CWFC predicted[1] yield curves for single stem and coppice management systems for the Peace River region of northern Alberta and British Columbia (Keddy, 2013). Based on the yield curves in Figures 2.1 and 2.2, the MAI is 10.9 m^3/ha/yr (3.8

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[1] The CWFC have predicted yield curves for each region, based on different factors like site suitability, weather information, etc.

odt/ha/yr) for the single stem management system and 12.5 m^3/ha/yr (4.4 odt/ha/yr) for the coppice management system.

Figure (2.1): Hybrid poplar yield curve for single stem management system in the Peace River region of northern Alberta and British Columbia, (Keddy, 2013)

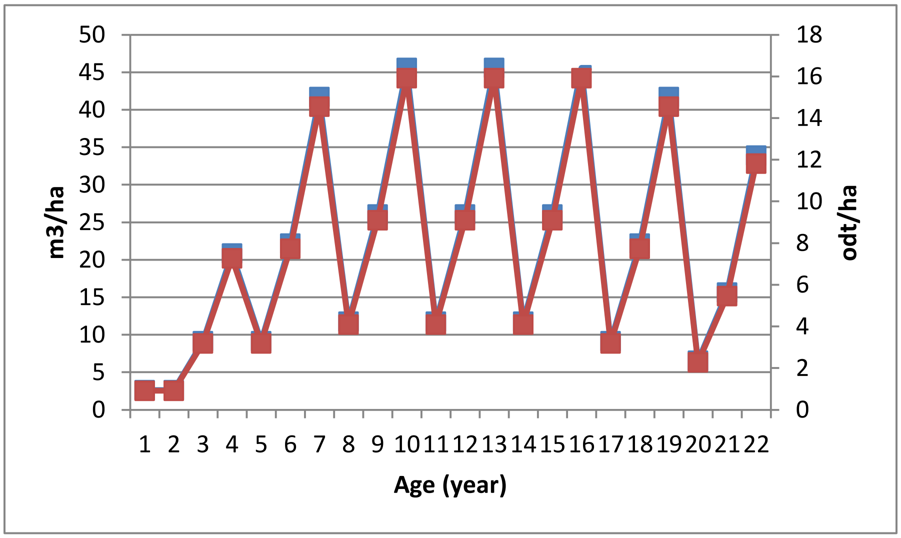

Figure (2.2): Hybrid poplar yield curve for coppice management system in the Peace River region of northern Alberta and British Columbia with harvest every 3 years, (Keddy, 2013)

2.2.2.2. Biomass price (P)

Given the absence of a robust market for biomass in the Peace River region, there are limited biomass price data. I began by reviewing the literature for biomass prices used in other studies. Walsh et al. (2003) reported a price range of \$32.9-\$48.26/odt hybrid poplar biomass. There are other studies that used a general price for all cellulosic biomass (BioZio, 2011), or used the price of other types of biomass such as aspen biomass (Deckard, 2012). These two studies considered biomass prices of \$50/odt and \$26.12/odt[1], respectively.

In addition to the literature review, I investigate the value chain of hybrid poplar biomass to estimate the maximum price that might be paid for hybrid poplar based on the residual value left over after all the costs of value added production are considered. Table 2.2 shows estimates of three value chains for harvested hybrid poplar timber: *(i)* pellets, *(ii)* pulp and power, and *(iii)* bioethanol. The first two value chains are from (Sidders, et al., 2012). Using Sidders, et al., (2012) and other data, I created the third value chain for hybrid poplar as a bioethanol feedstock.

In value chains, production paths are tracked backward from the final products (pellets, pulp and power, or bioethanol) all the way back to the original establishment of the plantations. The final product and the costs of each stage of production have known values. Subtracting the costs of each stage from the final product gives the maximum residual value that can be paid for the hybrid poplar feedstock for a given value chain to be financially viable. From Table 2.2, the maximum amount that a poplar producer could receive (selling stumpage) is \$108/odt – which is the \$85/odt residual value plus the \$23/odt cost of afforestation.

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[1] The reported price in the report is \$25.5 per cord. Considering one cord of aspen is 2160 lb (Kuhns & Schmidt, n.d.), the aspen stumpage price would be \$26.12/odt.

Table (2.2): Estimated biomass value chains for the production of pellets, pulp and power, and bioethanol

Final product		Pellets	Pulp and power	Bioethanol
Benefit ($/odt)		225[a]	394[a]	391.3[b]
Costs ($/odt)	**Conversion**	40[a]	198[a]	165.8[c]
	Preparation	-	18[a]	-
	Transportation	27[a]	30[a]	27[a]
	Handling	25[a]	15[a]	25[a]
	Harvesting	25[a]	25[a]	25[a]
	Silviculture	23[a]	23[a]	23[a]
Net benefit ($/odt)		85	85	125.5
Return to tree grower[d]		108	108	148.5

a: (Sidders, et al., 2012)

b: The benefit is derived by multiplying the bioethanol price, which is a sum of the global bioethanol price (Hofstrand, 2014) (i.e. $0.615/litre) and the subsidy from Government of Alberta (Government of Alberta, 2013) (i.e. $0.14/llitre), by the bioethanol production yield from Table 2.3 (i.e. 518 l/odt)

c: The conversion cost is derived by multiplying the bioethanol production yield from Table 2.3 (i.e. 518 l/odt) by the production cost of bioethanol from Table 2.4 (i.e. $0.32/litre after excluding the transportation and biomass purchasing cost from $0.47/litre)

d: The return to the tree grower is the sum of the previous two rows (i.e. silvicultural cost and net benefit)

I wish to compare this residual value with a residual value for bioethanol. A number of assumptions went into creating the bioethanol residual value chain. The three main parameters needed for calculating the net benefit of the bioethanol production chain are: *(i)* the bioethanol price, *(ii)* the conversion rate of biomass to bioethanol, and *(iii)* the production cost of converting biomass to bioethanol. Using market data for bioethanol (Hofstrand, 2014) I calculated the average price of bioethanol during the one-year period from March 1st, 2012 to March 1st, 2013 – which was C$0.615 per litre[1]. In addition, at the time of this study the government of Alberta's Bioenergy Producer Credit Program subsidized second-generation bioethanol production by C$0.14/litre (Government of Alberta, 2013). The program was designed to start in April 2011 and end in March 2016. In March 2013, the government decided to close the program to new applicants, but will continue to honour existing agreements. In this analysis I include the bioethanol subsidy, resulting in a total ethanol price of C$0.75 per litre.

The second assumption relates to the amount of ethanol that can be generated from an oven dry tonne of hybrid poplar (i.e. biomass conversion rate). This rate depends on factors such as the type of feedstock and the type of technology used for ethanol production. A literature review of conversion rates of biomass to bioethanol using different production technologies is summarized in Table 2.3. These rates varied from 189 to 1045 litres of ethanol per odt (l/odt) of biomass, depending on the applied technology and feedstock material. Although some studies do not specify the type of conversion technology and only report the conversion rate of biomass to cellulosic ethanol e.g. (Beach & McCarl, 2010), there are other studies that investigate the specific conversion technology. Enzymatic hydrolysis appears to be the most productive and popular technology for cellulosic bioethanol producers (Lane, 2010). The enzymatic hydrolysis process is being used operationally in Canada by the Iogen Company with a conversion rate between 318 and 518 l/odt of biomass. Iogen Company also applies gasification technology with a conversion rate of 518-1045 l/odt. Another operational company is ZeaChem Inc. in the United States, which has patented a hybrid process of biochemical and thermochemical processing with

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[1] The average exchange rate from US$ to CN$ during this period was 0.99 (Bank of Canada, 2014)

a conversion rate of 511 l/odt. Based on the operational conversion rate of Iogen company and ZeaChem Inc., I use 518 l/odt to create the residual value chain.

Table (2.3): Ethanol production yield from cellulosic biomass

Technology	**Yield *(l/odt)***	**Reference**
Hydrolysis (dilute acid)	189	(Badger, 2002)
Hydrolysis (concentrated acid)	227	(Badger, 2002)
Hydrolysis	450	(Basu, 2010)
Hybrid process of biochemical and thermochemical processing	511	(ZeaChem, 2011)
Enzymatic hydrolysis	312	(Piccolo & Bezzo, 2009)
Enzymatic hydrolysis	275	(Environment Canada , 1999)
Enzymatic hydrolysis	318-518	(The Energy Blog, 2006)
Gasification	318-477	(Spath & Dayton, 2003)
Gasification	334	(Phillips, et al., 2007)
Gasification	265-492	(Phillips, et al., 2007)
Gasification	203	(Piccolo & Bezzo, 2009)
Gasification	518-1045	(The Energy Blog, 2006)

The final parameter required to create the bioethanol value chain is the cellulosic ethanol production costs. Table 2.4 shows that although some studies (e.g. Stephen, et al., 2012) reported relatively high ethanol production costs ($1.09 per litre), BioZio (2011) indicated that the total cost of cellulosic ethanol production has fallen during the last decade from $2.38/litre in 2001 to $0.47-0.57/litre (depending on the conversion technology). The BioZio (2011) study is one of the rare studies that have investigated production costs for different technologies. As enzymatic hydrolysis is more common in bioethanol production, I used the production cost of bioethanol via enzymatic hydrolysis which is \$0.32/litre (BioZio, 2011). BioZio (2011) reports \$0.47 litre as the total production cost using enzymatic hydrolysis technology. The transportation and biomass purchase are excluded from this cost because it is already included in the value chain (Table 2.2).

Table (2.4) Estimate of production cost of cellulosic-based ethanol in different studies

Country	**Year**	**Production cost (\$/litre)** [a]	**Reference**
USA	1999	0.78	(Putsche, 1999)
USA[b]	1999	1.18	(Pimentel & Patzek, 2005)
USA	1999	1.27	(Pimentel & Patzek, 2005)
USA[c]	1999	0.87	(McAloon, et al., 2000)
N/A	2001	2.33	(BioZio, 2011)
	2010	0.47-0.57	
Sweden	2003	1.09-1.20	(Wingren, et al., 2003)
Canada	2007	1.09	(Stephen, et al., 2012)
Sweden	2008	0.68-0.92[d]	(Sassner, et al., 2008)
Canada, Iogen	2011	0.171-0.317	(The Energy Blog, 2006)

a: all production costs are adjusted to 2012 CN \$, using the annual average of Producer Price Index for chemicals and chemical products, 2002=100 collected from (Statistics of Canada, 2013) and the average exchange rate in 2012 collected from (Bank of Canada, 2014)

b: Switch grass-based ethanol

c: corn stover-based ethanol

d: based on average exchange rate of SEK to USD in 2007 = 0.148

Inserting the three parameters into the cellulosic ethanol value chain shown in Table 2.2, I find that the residual value available to the poplar producer could be as high as $148/odt. Because most biomass is currently derived from forestry and agricultural residuals and the reported prices are not nearly this high, in this paper I conduct a sensitivity analysis on biomass prices between $50 (BioZio, 2011) and $148/odt. The low price, $50/odt, is derived from the literature. The high price, $148/odt, is derived from the value chain of bioethanol production, assuming the continuation of Alberta's second-generation ethanol subsidy.

2.2.2.3. Discount rate (r)

When conducting a financial analysis for long-term projects such as a poplar plantation, it is important to select an appropriate discount rate. The discount rate reflects the opportunity cost of capital tied up while investing in the poplar plantation. Since the revenues and some costs from the poplar biomass production occur well into the future, they must be discounted into the present in order to be compared to the present day costs of establishing the plantation. The review of the literature (Table 2.5) indicates that the discount rate in previous financial studies of hybrid poplar ranged from 3.5% to 10%. The highest discount rates are associated with countries with higher risks of investment (as risk is frequently included as parts of discount rates), like Chile and Czech Republic. Given that previous studies on hybrid poplar in Canada chose a discount rate of around 4% (Anderson & Luckert, 2007; Yemshanov and McKenney, 2008; Allen, et al. 2013), I also opted to use 4% as the discount rate in the baseline analysis. However, I also conduct sensitivity analysis using discount rates ranging from 1% to 10%.

Table (2.5): The discount rate in previous hybrid poplar financial analysis studies, mostly cited in (Kasmioui & Ceulemans, 2012)

Reference	Discount rate (%)	Country
(Webb, et al., 2009)	3.5	Scotland
(Anderson & Luckert, 2007)	3.7	Canada
(Allen, et al., 2013)	4 and 8	Canada
(Yemshanov & McKenney, 2008)	4	Canada
(Manzone, et al., 2009)	4	Italy
(Gasol , et al., 2009)	4.75	Spain
(Strauss & Grado, 1997)	5	USA
(Van denhove, et al., 2002)	5	Ireland
(Styles, et al., 2008)	5	Ireland
(Goor, et al., 2000)	5	Belgium
(Witters, et al., 2009)	5	Belgium
(Van denhove, et al., 2002)	5	Belarus
(Valentine, et al., 2008)	6	UK
(Ledin, 1996)	6	Sweden
(Ericsson, et al., 2009)	6	European Union
(Ericsson, et al., 2006)	6	Poland
(Rosenqvist & Dawson, 2005)	6	Ireland
(Walsh, 1998)	6.5	USA
(Kuemmel, et al., 1998)	7	Denmark and Sweden
(Havlickova, et al., 2007)	9.2	Czech Republic
(Faundez, 2003)	10	Chile

2.2.2.4. Silviculture costs (C)

Table 2.6 presents high and low establishment costs of the two management systems based on data from the CWFC (Sidders, et al., 2012). For each management system high and low estimates account for variation in silvicultural costs in different regions. The silviculture costs are converted to a total present value production cost using a 4% discount rate. As shown in Table 2.6, there is approximately a %15-20 difference between the high and low estimates.

Table (2.6): Silviculture costs for the two hybrid poplar management systems

Type of cost	**Single Stem**			**Coppice**		
	Time of cost	**Low ($/ha)**	**High ($/ha)**	**Time of cost**	**Low ($/ha)**	**High ($/ha)**
Deep and Shallow discing	Year 0	235	350	Year 0	235	350
Marking	Year 0	65	100	Year 0	20	35
Planting stock	Year 0	880	960	Year 0	3480	4700
Planting operation	Year 0	288	428	Year 0	800	860
Vegetation management	Year 1	375	400	Year 1	700	800
	Year 2	300	320	Year 1	90	90
	Year 3	225	240	Year 2	550	650
	Year 4	150	160	Year 3-19	200	250
Present Value of the total silviculture cost	-	2434.2	2868.6	-	8052.7	10213.7

In this study, I choose the high silviculture cost as the baseline scenario, because experts at the Canadian Wood Fibre Centre indicated that it was appropriate to use the high silviculture costs for the Peace River area (Keddy, 2013). However, I also conduct sensitivity analysis using the low silviculture cost, as well as a 40% reduction in the low silviculture cost in anticipation of potential future technological advancements that reduce costs.

2.2.2.5. Land value

To assess the financial viability of hybrid poplar plantations, this study compares the calculated LEV for each management system with market values of agricultural land. If the LEV derived from agricultural land for hybrid poplar plantations is higher than the average selling price for agriculture land, then it would be financially viable to purchase the land and establish a plantation. I used Farm Credit Canada (FCC) data of land purchase prices as an estimate of the average cropland selling price. Pasture land was not considered because the yield curve is based on a higher level of soil quality in the study. Since this study is investigating poplar plantations in the Peace River region, I only selected land value data from the subareas of the Peace River region [1]. The average of land value for cropland in this region between March 2012 and March 2013 was $2527/ha. In the next sections, this land value is compared with the calculated LEVs from the two management systems plantations under different conditions to assess under what condition the plantations would be financially viable.

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[1] I consider the regions in the Peace River Area, as represented by the FCC area codes 505, 177, 504, 131, 107, 246, 503, 337, 133, 287, 172, and 325

2.2.3. Summary of baseline conditions

Table 2.7 summarizes the baseline and sensitivity analysis conditions. The baseline conditions include current yield curves from Figures 2.1 and 2.2, high biomass price from Table 2.2, high silviculture cost from Table 2.6 and a 4% discount rate. In the following section, I conduct sensitivity analysis of the discount rate. Next, I conduct the sensitivity analysis of biomass price for low and high silviculture costs. Finally, sensitivity analysis for biomass price is conducted in conjunction with improved growth and yield estimates and differences in silvicultural costs.

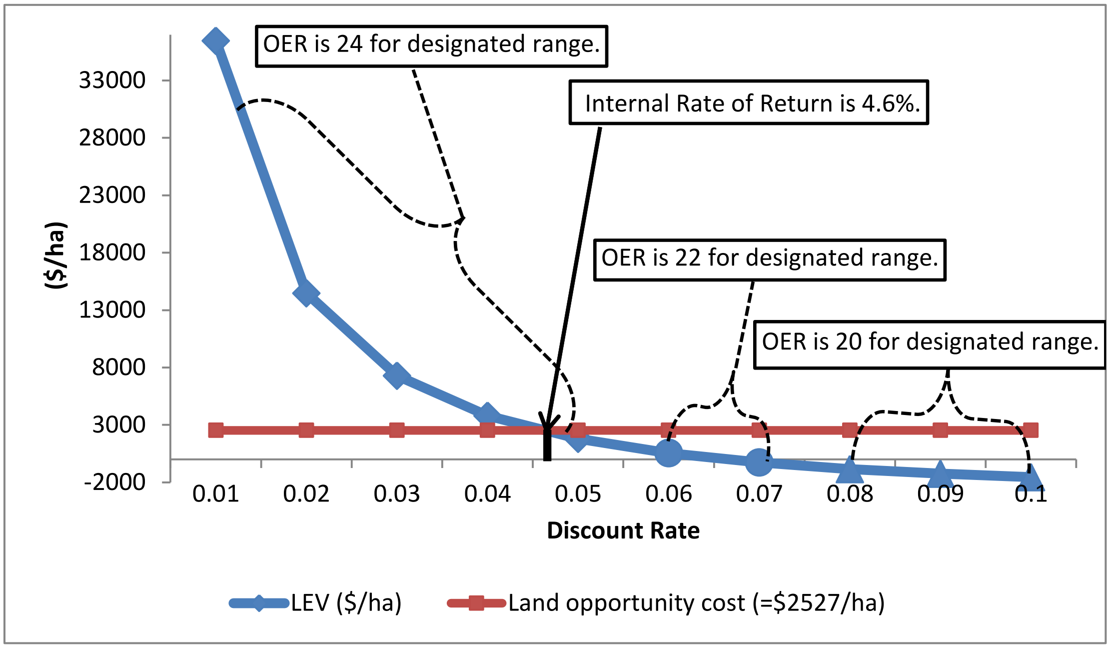
Table (2.7): Baseline and sensitivity analysis conditions

	Discount rate	**Biomass price**	**Silviculture cost**	**Yield curve**
Baseline	4%	High	High	current
Sensitivity to discount rate	-	High	High	current
Sensitivity to biomass price	4%	-	High	current
			Low	
Sensitivity to the biomass price, silviculture costs, and yield	4%	-	High	current
	4%	-	Low	current
	4%	-	40% less than low	current
	4%	-	High	40% higher than current
	4%	-	Low	40% higher than current
	4%	-	40% less than low	40% higher than current

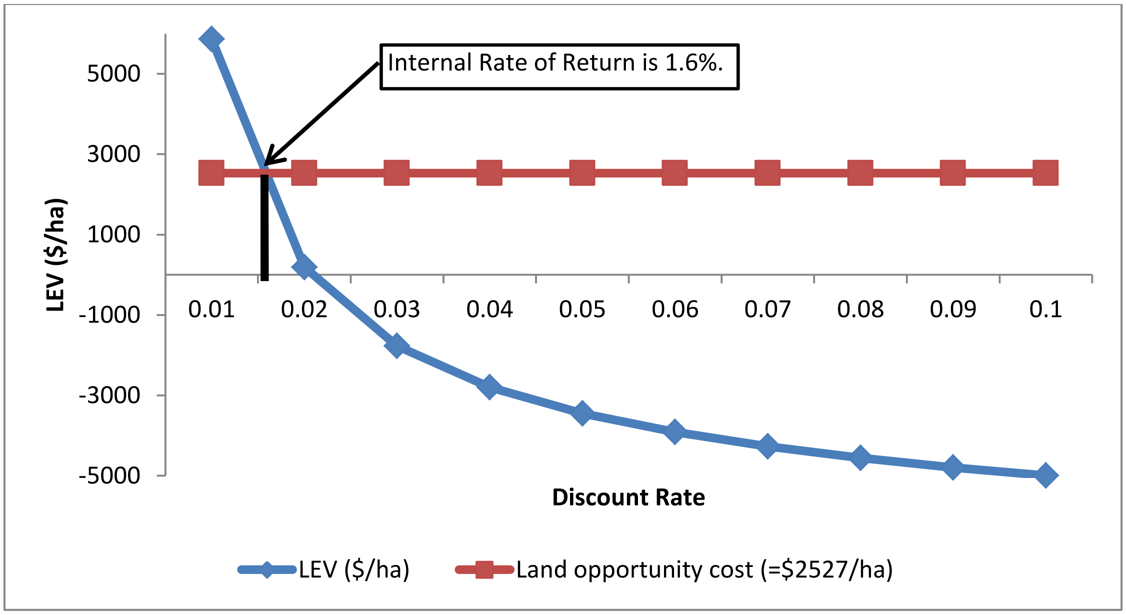
2.3. Results

2.3.1. Sensitivity of LEV to the discount rate

Sensitivity analysis of the discount rate is shown in Figures 2.3(a) and 2.3(b).



(a): Single stem



(b): Coppice

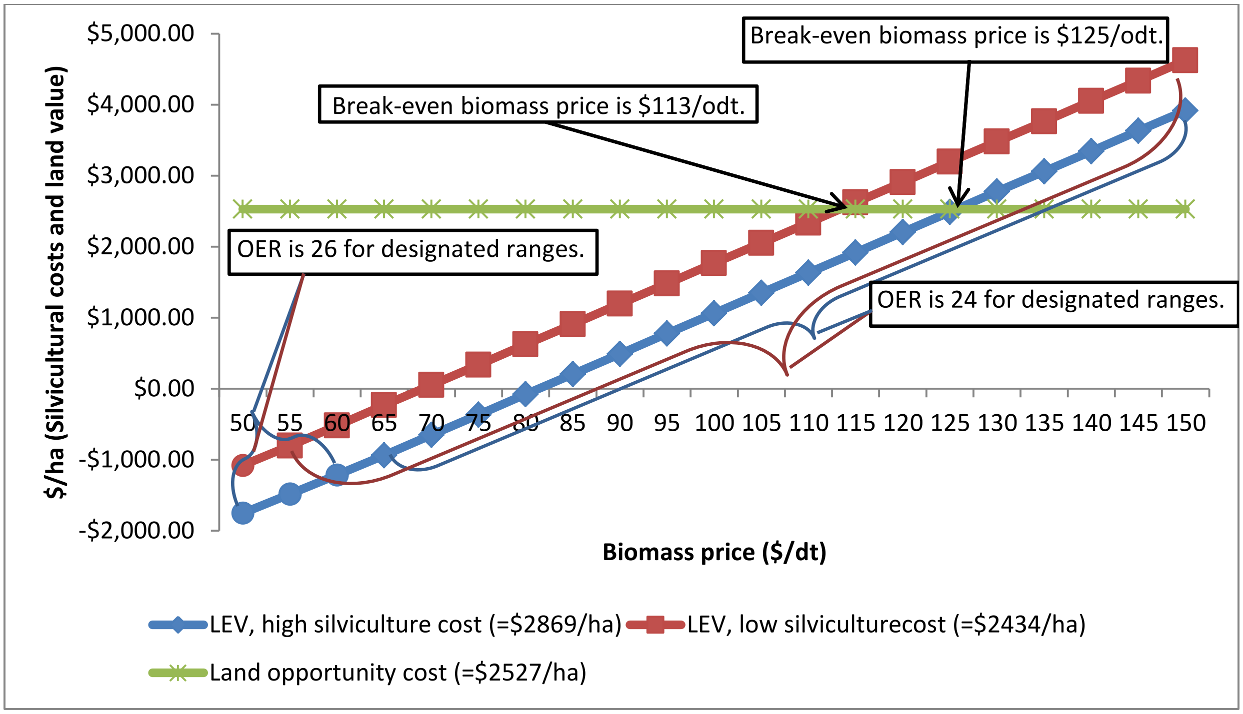
Figure (2.3): Sensitivity analysis for discount rate in single stem (a) and coppice (b), showing the internal rates of return for both management systems and the Economic Optimum Rotation (OER) for single stem

Since the analysis considers planting hybrid poplar on cropland, the discount rate where the LEV is equal to cropland is equal to the Internal Rate of Return (IRR) for the hybrid poplar plantation. In Figures 2.3(a) and 2.3(b), the IRRs are indicated by the vertical lines, which for the single stem and coppice management systems are 4.6% and 1.4%, respectively. Results indicate that if the discount rate was 4%, the single stem management system would be profitable, while the coppice system would not.

Though the Optimum Economic Rotation (OER) for the coppice system is not influenced by changing discount rates, for the single stem system, the discount rate has the potential to change the OER, as shown in Figure 2.3(a). The OER is 24 years for discount rates from 1% to 5% (diamond points in Figure 2.3a). As the discount rate increase to 6% and 7%, the OER reduces to 22 years (circle points in Figure 2.3a). The OER decreases even more, to 20 years, when the discount rate grows to 8% to 10% (triangle points in Figure 2.3a). As was mentioned in previous sections, the 4% discount rate was selected as the baseline, which results in an OER of 24 years. All of the subsequent calculations and discussions are based on the 4% discount rate.

2.3.2. Sensitivity of LEV to the biomass price

In this section, the sensitivity analysis of the biomass price, ranging from \$50 to \$150 per odt, is discussed with the consideration of high and low silviculture costs based on the assumptions of the 4% discount rate, and the baseline yield curve, as shown in Table 2.7. Figure 2.4 shows the results for both management systems. The break-even biomass price is that price that makes LEV equal to land value for agricultural cropland (i.e. \$2527/ha). As shown in Figure 2.4(a), for the single stem management system, a biomass price of \$125.7/odt is required for the project to break-even when silviculture costs are high. Similarly, the break-even biomass price for the low



(a): Single stem(b):Coppice

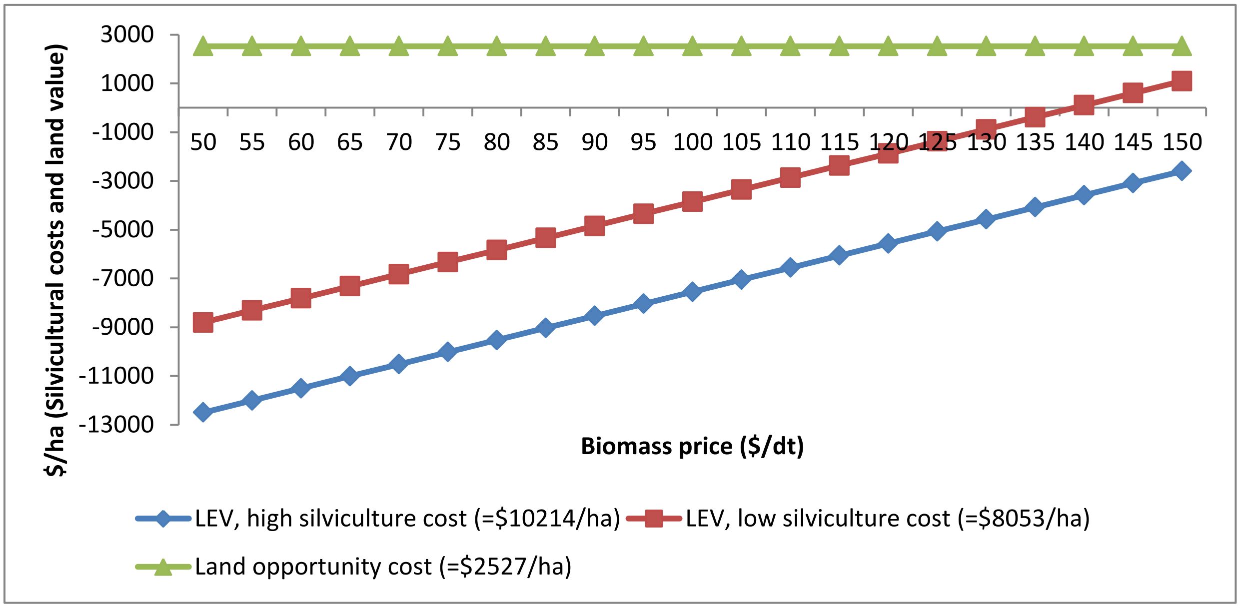


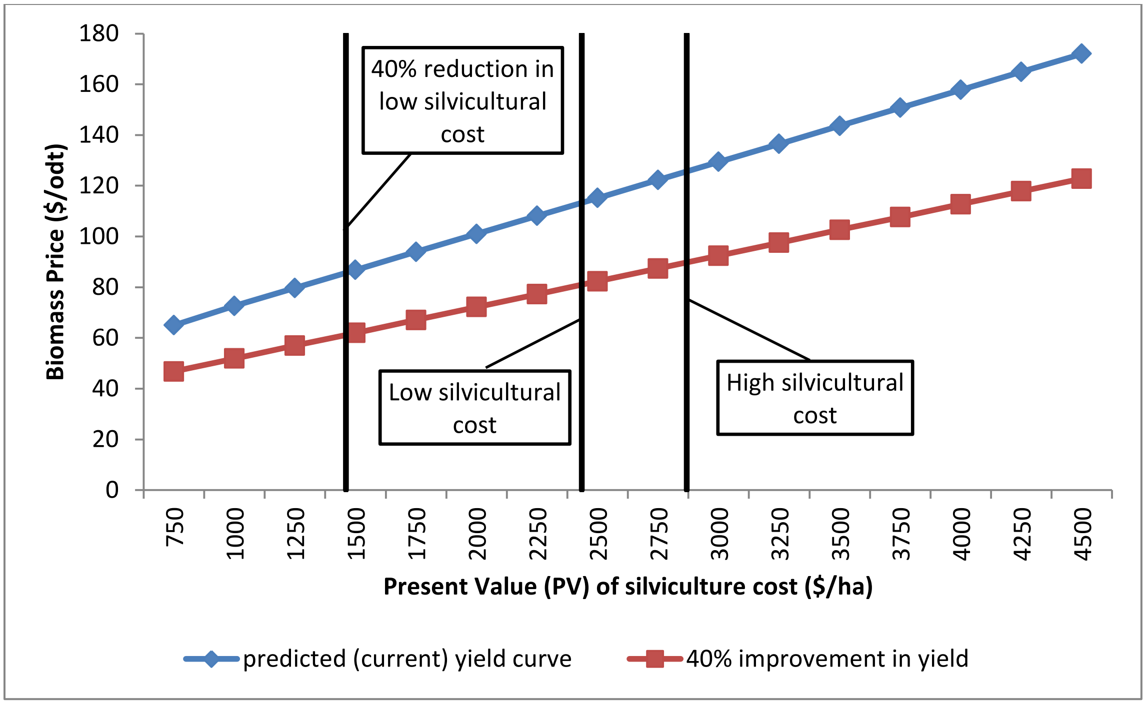
Figure (2.4): Sensitivity analysis of biomass price in single stem (a) and coppice (b) showing the Optimum Economic Rotation (OER) for single stem. The break-even price in coppice system is out of range of the figure.

silviculture cost scenario is $113.3/odt. For the coppice management system, the break-even biomass prices are off of the figures and $201.8/odt for the high silviculture cost and $164.5 /odt for the low silviculture cost, which are higher than the range of values presented in Figure 2.4(b). Note that for single stem management system, all of the break-even biomass prices are generally higher than current price of biomass (i.e. \$50/odt) and less than estimate of feedstock value from the bioethanol value chain (i.e. \$148/odt). Figure 2.4(a) also shows that the OER is not constant throughout the sensitivity analysis for single stem system. For the high silviculture cost scenario, the OER is 26 years when the biomass price is between \$50/odt and \$65/odt, and 24 years for biomass prices between \$65/odt and \$150/odt. In the case of the low silviculture cost, the OER is 26 years when the biomass price is \$50/odt and 24 years for the remaining range of biomass prices analyzed.

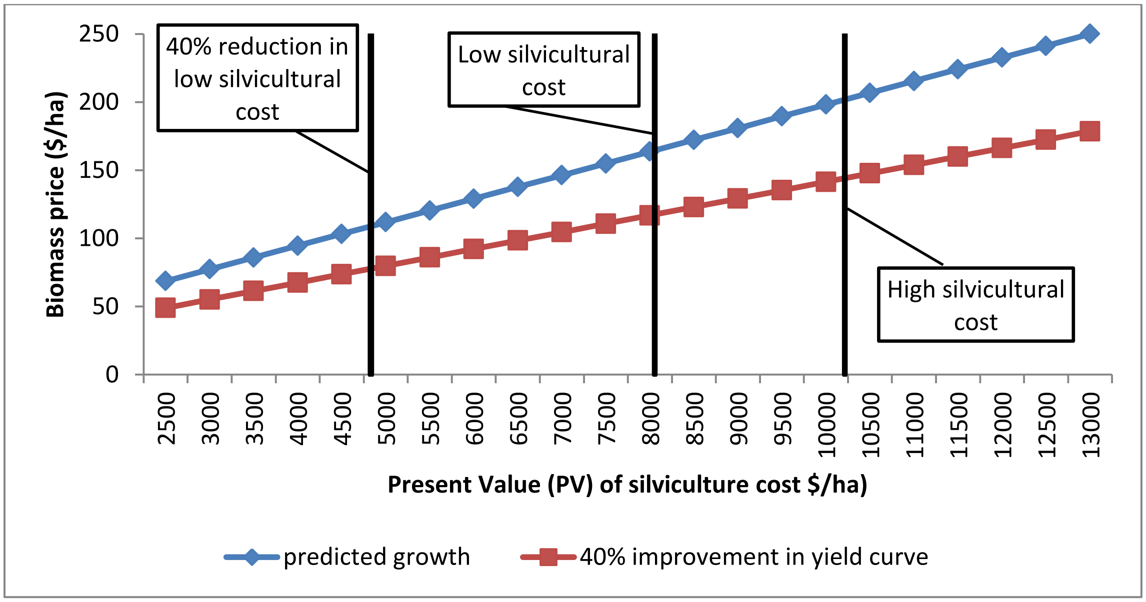
2.3.3. Sensitivity of LEV to the biomass price, silviculture costs, and yield

Given the current high land prices and low biomass prices, the coppice management system of hybrid poplar production appears not to be financially viable, and the single stem management system is only financially viable with discount rates less than 4.6%. However, the situation could be changed either by genomic research or the policy environment. Financial viability could be improved through: *(i)* increased growth rates and/or ethanol conversion rates from genomic research, *(ii)* decreased costs from technological improvements, *(iii)* increased bioethanol demand, and *(iv)* changes in forest and/or greenhouse gas policies.

To simulate the possibility for such changes, I conduct an analysis using a yield curve that has been increased by 40%, for different growth rates and silviculture costs, as shown in Figure 2.5. Plotted lines in this figure are break-even biomass prices taking into consideration three levels of silviculture costs and two different yield curves. Figure 2.5 summarizes four scenarios, each for 3 different levels of silviculture costs. The 12 different break-even biomass prices from these figures are summarized in Table 2.8.



(a): Single stem



(b): Coppice

Figure (2.5): break-even biomass prices due to possible changes in growth rates and silviculture cost for hybrid poplar plantations for single stem (a) and coppice (b)

Table (2.8): Break-even biomass price for 4 scenarios

Scenarios	**Break-even biomass price ($/odt)**		
	High silviculture cost	**Low silviculture cost**	**40%less than low silviculture cost**
1. Single stem and current yield	125.7	113.3	85.7
2. Single stem and 40% improvement in yields	89.7	80.9	61.2
3. Coppice and current yield	201.8	164.5	108.9
4. Coppice and 40% improvement in yields	144.1	117.5	77.8

Table 2.8 reveals that for the single stem production system, the break-even biomass price ranges between $125.7/odt and $61.2/odt. The highest break-even biomass price is in current situation, under the expected growth rate and the high silviculture cost. However, for the most optimistic scenario, the break-even biomass price could be decreased to $61.2/odt, if the silviculture costs were reduced by 40% below the low silviculture cost and the yield curve increased by 40%. Table 2.8 also indicates that the break-even biomass price for the coppice production system is always higher than that for single stem management system. Under the baseline condition, the break-even biomass price has the highest amount ($201.8/odt), while it could be reduced to the lowest amount ($77.8/odt), if the low silviculture costs were to decline by 40% and the yield curve improves by 40%. For coppice management system the break-even biomass price is higher than both current feedstock price (i.e. $50/odt) and bioethanol value feedstock price (i.e. $148/odt).

2.4. Conclusion

The financial viability of hybrid poplar plantations is analyzed by calculating the LEV under various market and biophysical conditions, and then comparing these values to the market price for agricultural cropland. The findings suggest that the coppice management system is not financially viable due to its high silviculture cost. But, single stem could be financially viable, if the discount rate is less than 4.6%.

Sensitivity analysis of LEV is conducted with respect to changes in various economic parameters. Assuming 4% of discount rate, I find the break-even biomass prices of $113.3/odt and $201.8/odt for single stem and coppice system management under the current situation, which is far higher than the current market prices for biomass of $50/odt. Given the current high land prices and low biomass prices, neither the coppice nor the single stem system of hybrid poplar production appears to be financially viable. However, future changes in market and biophysical conditions could improve the financial viability of hybrid poplar plantations. Such future changes could be genomic improvements, reductions in silviculture costs, reductions in production costs for cellulosic ethanol, and institutional changes to forest and/or greenhouse gas policies.

For example, for a single stem system, if the silviculture costs were to decline by 40%, then the breakeven biomass price would drop to $85.7/odt. The break-even biomass price would be even lower (i.e. $61.2/odt), if the yield curve was to improve by 40% and silviculture cost decrease to 40% of the low silviculture cost simultaneously. However, even with these optimistic changes, coppice management systems would not result in as low break-even prices as in the single stem system The most optimistic estimated break-even biomass price for coppice system is $77.8/odt, which is still high, relative to current biomass price. Nevertheless, demand for biomass in the market might be increased due to improvement in conversion technology or other changes in the fuel market. If this happens, coppice management system could compete in the biofuel energy market.

Chapter 3. Hybrid Poplar Plantations for Bioethanol Production and Carbon Sequestration: A Forest-level Analysis

3.1. Introduction

In the last chapter, I analyzed the financial viability of hybrid poplar plantations on private lands for producing bioethanol. I assessed both single stem and coppice management systems. The results of the stand-level model suggest that the coppice system is financially inferior to the single stem system, largely due to high establishment costs. But the single stem production system could be financially feasible, given the current land prices of \$2527/ha, a biomass prices of \$50/odt, and a real discount rate of less than 4.6%.

In this chapter, I add in considerations of public land. About 90% of forested lands in Canada are owned by provincial and territorial governments (Natural Resources Canada, 2014). Forests are generally managed by private firms under the supervision of the government, which maximizes sustained yield through the calculation of an Annual Allowable Cut (AAC). In Canadian forests, the Allowable Cut Effect (ACE), which is the immediate increase in the AAC resulting from silvicultural activities (Schweitzer, et al., 1972), may be used as a policy tool and incentive to practice enhanced forest management (Hegan & Luckert, 2000). In a sustained yield tenure system, the ACE affects the value of forests by potential increasing harvest volume over time. Hybrid poplar plantations on public land might be feasible for producing bioethanol because of the ACE and the low opportunity cost of public lands. However, exotic trees such as hybrid poplars are not generally allowed on public lands in Canada (Johnston & Williamson, 2008) with some exceptions in British Columbia and Quebec (Anderson, et al., 2012). Also, native Canadian trees have potentially low yields (Anderson, et al., 2012) and are not financially viable in stand-level analysis (Adamowicz, et al., 2003). Considering both public and private lands in a forest model can lead to a higher AAC and a greater value of the forest, if the private lands in the model cause an immediate increase in the ACE and a higher harvest level from the public lands.

Carbon sequestration has been identified as a benefit of forest plantations. Different forest carbon protocols have been developed, drafted or implemented in North America to provide a market mechanism for sequestered carbon in forestry projects (e.g. the Forest Project Protocol (Climate Action Reverse, 2012), the WCI Cap & Trade Program (Western Climate Initiative, 2013), the California Offset Program (California Environmental Protection Agency, 2011), Protocol for the Creation of Forest Carbon Offsets in British Columbia (British Columbia Ministry of Environment, 2010) and draft Conservation/Agroforestry Afforestation Protocol in Alberta (Alberta Environment, 2011). The various protocols differ in their goals, legislation, and regulating systems (Anderson, et al., In Press). However, not all of them have yet been approved; Alberta for example drafted the Conservation/Agroforestry Afforestation Protocol in 2011, but has not yet approved it. In this study, I include sequestered carbon benefits in some policy scenarios because a carbon market mechanism could potentially affect the AAC and the forest value.

In this chapter, I study the impacts of different policies on the Net Present Value (NPV) of forests in a forest-level model analysis. These policies include three main elements: the type of even-flow constraint, whether exotic plantations on public lands are allowed, and whether carbon benefits are accounted for in the NPV. Forest-level models can potentially incorporate different management intensities within the context of zoning systems. A zoning system that is frequently discussed in Canada is a triad system including zones defined as protected (to produce non-timber value in forests), intensive (to produce timber value in forests) and extensive (to produce some of both) (Anderson, et al., 2012). In the forest-level model, I investigate the potential of hybrid poplar plantations as a zone. Only a few previous studies have applied a forest-level framework to analyse forest zones in Canada (Montigny & MacLean, 2006; Krcmar, et al., 2003; Anderson, et al., 2012). While Montigniy and MacLean (2006) and Krcmar et al. (2003) used forest-level analysis in a triad zoning system, Anderson et al. (2012) analyzed policies to maximize the NPV of their action, allocating lands to five different management intensity zones. Also while Montignity and MacLean (2006) and Krcmar et al. (2003) allocated the lands to different zones exogenously, Anderson et al. (2012) applied the model to allocate the lands to different management intensities endogenously. In addition, Montignity and MacLean (2006) and Krcmar et al. (2003) studied only private or public lands. But Anderson et al. (2012) analyzed a forest-level framework that included both private and public lands. I build my work upon that of Anderson et al. (2012). However, my model differs from that of Anderson et al. (2012) in four ways. First, I study hybrid poplar plantations in the context of feedstocks for bioethanol production with updated data. Second, I add the value of the sequestered carbon to the timber benefits in a forestry project. Third, the yield curves I use are slightly different from those used in Anderson et al.'s (2012) study. Fourth, I study various policies for two different initial forest inventories, a juvenile and a split mature forest inventory. To the best of my knowledge, nobody has analyzed a forest-level model to study producing bioethanol from a forest based feedstock, and nobody has accounted for carbon benefits in such a study. I study different policy scenarios to see how they affect the NPV of the firm and the area of land is planted through the production of bioethanol from forest feedstocks.

In the sections that follow, I describe the policy scenarios to be analyzed and the timber supply model that is used. Next, I describe the data I use in my model. I then explain and compare the results for all scenarios. I conclude with a discussion of the policy significance of my results.

3.2. Policy scenario description

I design policy scenarios to explore their effects on harvest levels and forest values. Each scenario is made up of a combination of the following four components, which are denoted using four digits and letters as follows:

- The first letter indicates the objective—that is, of maximizing either total harvest volume (V) or net present value (D).
- The second letter indicates whether the exotic plantations is not permitted (N), permitted only on private lands (P), or permitted on both private and public land (B).
- The third letter indicates the kind of even-flow constraint imposed in the model: even-flow with flexible AAC (F), even-flow at baseline AAC (B), or completely unconstrained (U).
- The last letter indicates whether the model accounts for carbon on both private and public land (C) or not (N).

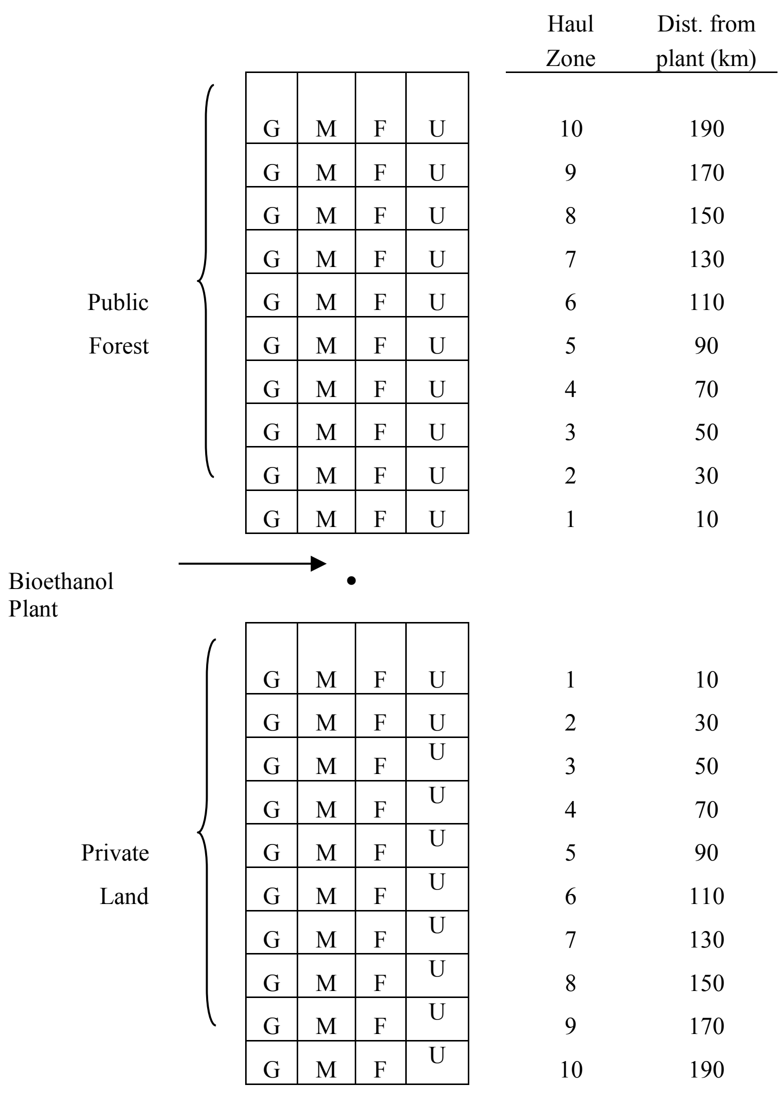
Table 3.1 shows 12 policies combining these components that I use to produce my results.

Table (3.1): Summary of policy scenarios

Policy scenario	Objective	Exotic Plantations	Even-flow	Carbon
VNFN	Maximizing Volume (V)	Not permitted (N)	Flexible even-flow (F)	Not included (N)
DNBN	Maximizing NPV (D)	Not permitted (N)	Even-flow at the baseline AAC (B)	Included (C)
DPFN	Maximizing NPV (D)	Only on private (P)	Flexible even-flow (F)	Not included (N)
DPFC	Maximizing NPV (D)	Only on private (P)	Flexible even-flow (F)	Included (C)
DPBN	Maximizing NPV (D)	Only on private (P)	Even-flow at the baseline AAC (B)	Not included (N)
DPBC	Maximizing NPV (D)	Only on private (P)	Even-flow at the baseline AAC (B)	Included (C)
DBFN	Maximizing NPV (D)	Both private and public (B)	Flexible even-flow (F)	Not included (N)
DBFC	Maximizing NPV (D)	Both private and public (B)	Flexible even-flow (F)	Included (C)
DBBN	Maximizing NPV (D)	Both private and public (B)	Even-flow at the baseline AAC (B)	Not included (N)
DBBC	Maximizing NPV (D)	Both private and public (B)	Even-flow at the baseline AAC (B)	Included (C)
DBUN	Maximizing NPV (D)	Both private and public (B)	Unconstrained	Not included (N)
DBUC	Maximizing NPV (D)	Both private and public (B)	Unconstrained	Included (C)

3.3. Timber Supply Model

I simulate a stylized representation of a bioethanol production site which uses realistic values but simplifies the model relative to what a real firm would face. I assume two million hectares of surrounding land. Half of the surrounding land is private and the other half is public. The bioethanol production plant is located between the public and private lands. Figure 3.1 visualises the stylized plant site and its surrounding areas. I assume that the forest is managed under the current policy of sustained yield. The harvested level of the baseline scenario is Maximum Sustained Yield (MSY). Then, I examine additional volume from hybrid poplar plantations, under various policy scenarios.



				Haul Zone	Dist. from plant (km)
G	M	F	U	10	190
G	M	F	U	9	170
G	M	F	U	8	150
G	M	F	U	7	130
G	M	F	U	6	110
G	M	F	U	5	90
G	M	F	U	4	70
G	M	F	U	3	50
G	M	F	U	2	30
G	M	F	U	1	10

				Haul Zone	Dist. from plant (km)
G	M	F	U	1	10
G	M	F	U	2	30
G	M	F	U	3	50
G	M	F	U	4	70
G	M	F	U	5	90
G	M	F	U	6	110
G	M	F	U	7	130
G	M	F	U	8	150
G	M	F	U	9	170
G	M	F	U	10	190

Figure (3.1): Visualized description of bioethanol production plant and its surrounding areas with four productivity rate of good (G), medium (M), fair (F), and unproductive (U)

The two million ha of land are segmented into "development types". Each development type is identified by the following attributes:

i. ***Ownership:*** either private or public ownership.

ii. ***Haul zone:*** each development is located in one of 10 haul zones, each zone 20 km wide. In the model, the midpoint of each haul zone is used in calculating hauling cost.

iii. ***Management intensity:*** there are five management intensities in this study, "leave for natural", "superior native", "hybrid poplar", "agriculture", and "protected". With "leave for natural" suckers regenerate stands. But in the context of "superior native", selective breeding is used from within the seed zone using observed traits. In the model all private land starts as "agriculture", and all public land starts as native species growing under "leave for natural" management intensity. Table 3.2 indicates the possible transitions for each management intensity and land type.

Table (3.2): Possible modeling transitions for each management intensity

Ownership	**From/To**	Leave for natural	Superior native	Hybrid poplar	Unproductive
Public	Leave for natural	Y	Y	Y	Y
	Superior native	Y	Y	Y	Y
	Hybrid poplar	N	N	Y	N
	Preservation	N	N	N	Y
Private	Agriculture	N	N	Y	N
	Hybrid Poplar	N	N	Y	N

iv. ***Timber productivity rating:*** I consider four types of timber productivity ratings: good, medium, fair and unproductive, and assume that every haul zone has four equal areas of each (Figure 3.1). The unproductive land is not capable of timber production. Trees under "leave for natural" intensity, native and hybrid poplar can grow at three types of productivity rates: good, medium, and fair. The related yield curves are different for each productivity type. Figures 3.2, 3.3, and 3.4 show the yield curve for each management intensity development type on good, medium and fair productive land. The yield curve for "leave for natural" management intensity comes from the Timber Damage Assessment AVI volume tables (Alberta Environment and Sustainable Resource , 2009) and the height and site index models developed by Huang et al. (Huang, et al., 1994; Huang, et al., 1997). For "superior native" management intensity, I used Anderson et al.'s (2012) yield curves. The "hybrid poplar" yield curve was compiled by the Canadian Wood Fibre Centre in the Peace River region (Sidders, et al., 2012). The yield curve developed by the Canadian Wood Fibre Centre assumes a good productivity rate (Keddy, 2013). I extrapolated medium and fare yield curve based on the good yield curve from the Canadian Wood Fibre Centre using the good, medium and fair yield curves employed in the Anderson et al. (2012) study.

v. **Age:** I assign 5-year age classes for forest development types. Based on the age classes, I consider two initial forest inventories. In the first step of the analysis, I assume an initial forest type comprising a mixture of young and old timber to be representative of the Canadian boreal forest (Figure 3.5-a). In my study, I refer this initial forest to the "split mature" inventory. Knowing that the initial forest inventory could potentially change the results of a forest-level model (Hegan & Luckert, 2000), I also assume a young forest in which none of the stands is older than 80 years. This forest inventory is shown in Figure 3.5(b). In my study, I refer this initial forest to the "juvenile" inventory.

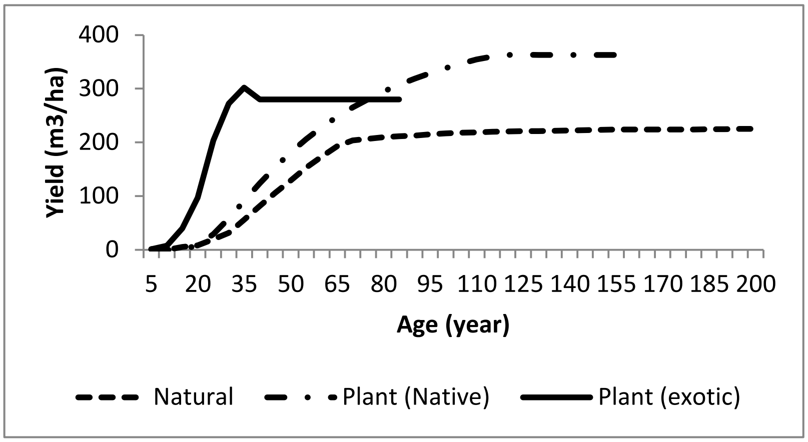


Figure (3.2): Yield curves for good productivity rate sites

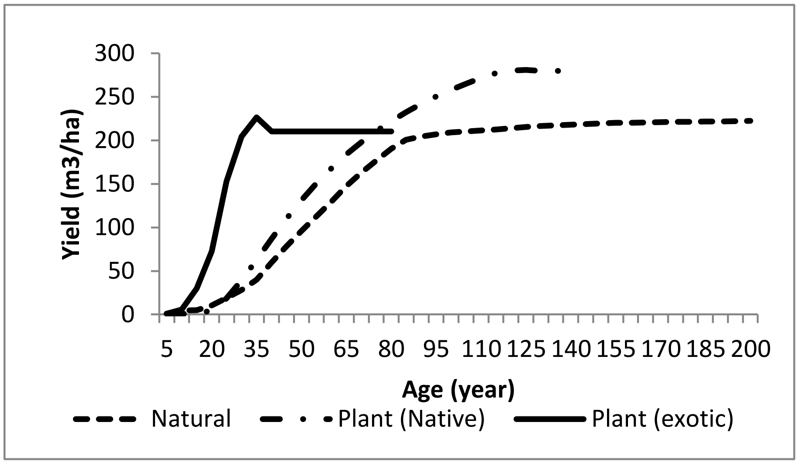


Figure (3.3): Yield curves for medium productivity rate sites

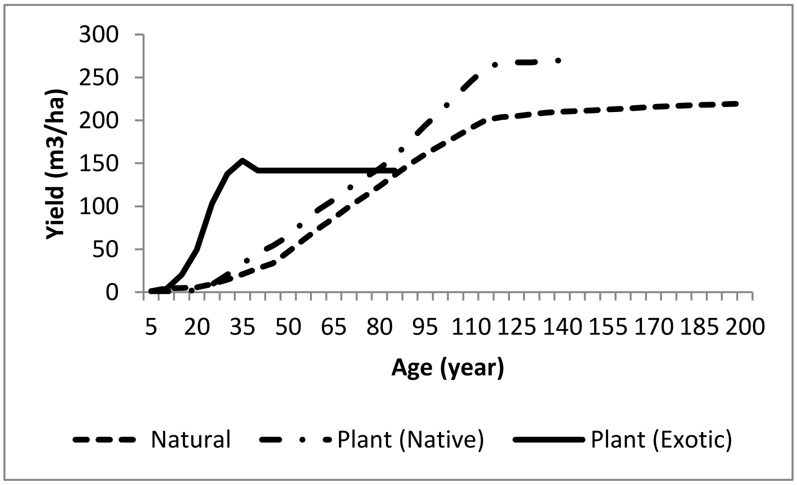
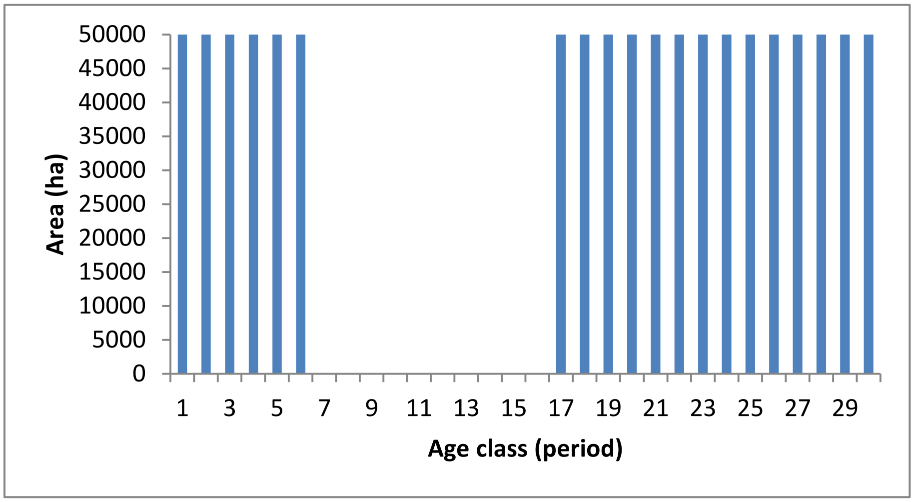
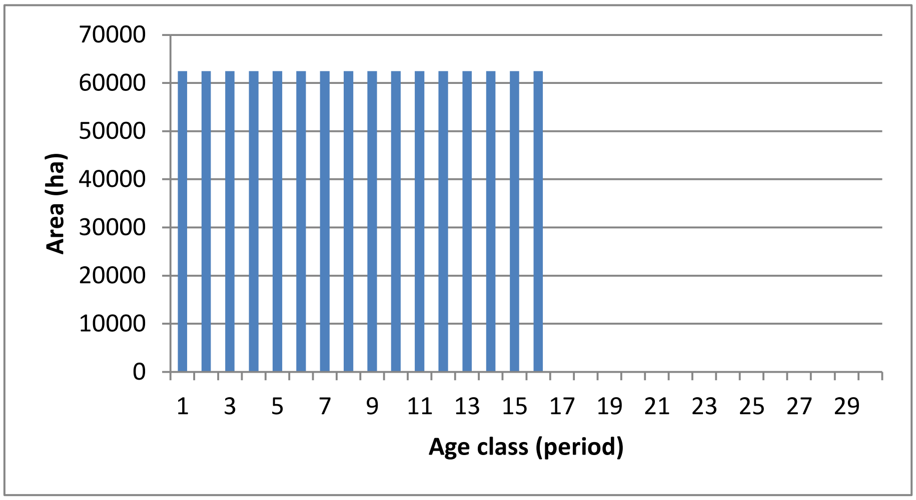


Figure (3.4): Yield curves for fair productivity rate sites



(a): Split mature forest inventory: a mixture of young and old trees



(b): juvenile forest inventory: young trees

Figure (3.5): Starting age class distribution for stylized forest. Age classes are in five-year wide periods

3.3.1 Carbon accounting in the model

For the scenarios with C at the fourth digit, the model accounts for the benefits of sequestered carbon. The discounted net revenue ($/ha) for sequestered carbon in the project relative to the baseline scenario are measured as follows:

$$CNPV = \sum_{t=1}^{k} \frac{P_c \Delta\Delta C_t}{(1+r)^t} \quad (3.1)$$

Where,

P_c = the price of carbon ($/m^3);

$\Delta\Delta C_t$ = net change in sequestered carbon in forestry project relative to the baseline (m^3);

r = discount rate;

k = number of periods in the model.

I follow Asante (2011) to calculate the sequestered carbon in each scenario relative to the baseline, using a “business-as-usual” baseline. In this method, the periodic change in the baseline carbon stocks at time t is considered as ΔC_t^b. Similarly, the periodic change in the project carbon stock at time t is considered as ΔC_t. The periodic change in carbon stock at time t for either the baseline or the project scenario is calculated by subtracting the sequestered carbon in current period (C_t or C_t^b) from the sequestered carbon in the last period (C_{t-1} or C_{t-1}^b):

$$\Delta C_t = C_t - C_{t-1} \quad (3.2)$$

$$\Delta C_t^b = C_t^b - C_{t-1}^b \quad (3.3)$$

Additionality is estimated as the net change in carbon stock of the forestry project relative to the baseline (Asante, 2011):

$$\Delta\Delta C_t = \Delta C_t^b - \Delta C_t \qquad (3.4)$$

I consider the VNFN scenario as the baseline scenario. The objective in this scenario is maximizing volume. I measure periodic change in the carbon stock for this scenario and consider the related amounts as the baseline (ΔC_t^b). Other scenarios that are referred to "project" scenarios are compared with the baseline scenario. If the net change in carbon stock at period t ($\Delta\Delta C_t$) is positive, a forestry project has increased the sequestered carbon for that period compared with the baseline condition, and the forestry firm is paid via the carbon market. If ΔC_t is less than ΔC_t^b and the net change ($\Delta\Delta C_t$) is negative, a forestry project has not been able to store more carbon than the baseline condition in that period. Hence the forestry project is penalized for the carbon emissions.

To calculate the periodic change in a carbon stock at time t (for baseline and project scenarios), I follow draft Alberta carbon protocol (Alberta Environment, 2011). In this protocol, Carbon pools include the above ground, and the below ground pools but not soil. I calculate the total sequestered carbon in the t^{th} period by adding the amount of the sequestered carbon in the above and below ground carbon pools:

$$C_t = C_t^{above} + C_t^{below} \qquad (3.5)$$

Where,

C_t^{above} is the sequestered carbon in above ground pools in the period t;

C_t^{below} is the sequestered carbon in below ground pools in the period t.

Sequestered carbon in above and below ground pools is a function of dry ton biomass. Following California and Alberta carbon protocols, Equations (3.6) and (3.7) show the estimated amounts of sequestered carbon in above and below ground pools, respectively.

$$C_t^{above} = AREA_t \times Yield_t \times 0.349 \times 0.5 \times 3.667 \times 0.9 \qquad (3.6)$$

Where,

C_t^{above} is ton of CO_2 equivalent sequestered in above ground pools during the period t;

$AREA_t$ is the area of forest in ha in period t;

$Yield_t$ is total above ground biomass density in m^3/ha;

0.349 is specific gravity of hybrid poplar in odt/m^3;

0.5 is the conversion coefficient of carbon in ton per odt of biomass, based on IPCC standard;

3.667 is the conversion to CO_2 equivalent in tonne per tonne of carbon, based on IPCC standard of 44/12;

0.9 is the risk based assurance factor to account for the potential reversal of carbon due to unforeseen events that may affect the growing trees;

and,

$$C_t^{below} = AREA_t \times Yield_t^{below} \times 0.349 \times 0.5 \times 3.667 \qquad (3.7)$$

Where,

C_t^{below} is ton of CO_2 equivalent sequestered in below ground pools during the priod t;

$Yield_t^{below}$ is the below ground-biomass density in ton/ha at the period *t;*

Other coefficients are already defined in equation (3.6).

(Zhong, et al., 2003) developed an equation to measure the below ground biomass density of hardwoods as shown in equation (3.8). In their equation the below ground biomass is a function of the above ground biomass.

$$Yield_t^{below} = 1.576 \times Yield_t^{0.615} \tag{3.8}$$

Where,

$Yield_t^{below}$ is the below ground (root) biomass density in ton/ha during the period *t.*

3.3.2 Model II Specification

I apply a linear programming model under different policy conditions that is an implementation of timber harvest scheduling Model II (Johnson & Scheurman, 1977). Model II forestry programming has been used by other researchers (Dykstra, 1984; Armstrong & Cumming, 2003; Anderson, et al., 2012). In this model, development types are redefined from time to time. In fact, each hectare of land in the first period is considered as a development type until it is regeneration harvested. After harvesting, there is possible management transition for each development type and they are assigned by the new age class and management intensity until they are regeneration harvested again. Hence, a development type in each period of planning has two aspects in this model: (i) a regeneration harvest at some time during the planning horizon or left non-harvested at the end of that period, (ii) the associated management intensity. Two decision variables are defined in the basic form of this model (Dykstra, 1984):

x_{ij} : hectares regenerated in the period *i* and harvested at the period *j.*

w_{iN} : hectares regenerated in the period *i* and left at the end of planning horizon.

The first set of decision variables (x_{ij}) identifies the harvesting activities of either the existing age classes in the initial inventory or future age classes that are created early enough in the planning horizon to be considered again for harvest. The second set of decision variables (w_{iN}) identifies remaining uncut activities of either the existing age classes in the initial inventory or future age classes created during the planning horizon. The objective function in this model is:

$$Max: \quad \sum_{j=1}^{N} \sum_{i=-M}^{j-Z} D_{ij} x_{ij} + \sum_{i=-M}^{N} E_{iN} w_{iN} \qquad (3.9)$$

Where,

N = minimum number of periods between harvests;

M = number of periods before period zero in which the oldest age class present in period one was regenerated;

D_{ij} = discounted net revenue (\$/ha) for hectares regenerated in period *i* and harvested in period *j* that is calculated by: $D_{ij} = \sum_{k=\max(i,1)}^{j} \frac{P_{ikj} V_{ikj} - C_{ikj}}{\gamma^t}$ (3.10)

Where,

P_{ikj} = unit price of volume harvested in period *k* on hectares regenerated in period *i* and harvested in period *j* (\$/m^3);

V_{ijk} = volume per hectare harvested in period *k* on hectares regenerated in period *i* and harvested in period *j* (m^3/ha);

C_{ijk} = Silvicultural costs per hectare in period k on hectares regenerated in period i and harvested in period j in (\$/ha);

γ^t = discount factor at the mid-point of period t that for the discount rate of r is calculated by:

$$\gamma^t = (1+r)^{[(period\ lenght/2)+(Period\ lenght\ (t-1))]} \qquad (3.11)$$

E_{iN} = discounted net revenue per hectare during the planning horizon from hectares regenerated in period i and left as the ending inventory hectares in period N plus discounted net value per hectare of leaving these hectares as the ending inventory. (In this study, only harvested timber is considered and E_{iN} is zero).

Two sets of constraints are designed in Model II. The first set specifies the area constraint and the second one represents the even-flow constraints. The area constraints contain the initial area constraint (Equation 3.12) and the establishment-harvest transfer constraint (Equation 3.13). These two constraints ensure that the harvested area from each development type is not greater than the initial available land, and that all available land is either harvested or not harvested.

$$\sum_{j=1}^{N} x_{ij} + w_{iN} = A_i \qquad i = -M, \dots, 0 \qquad (3.12)$$

$$\sum_{k=j+Z}^{N} x_{jk} + w_{jN} = \sum_{i=-M}^{j-Z} x_{ij} \qquad j = 1, \dots, N \qquad (3.13)$$

Where,

Z = minimum number of periods between regeneration harvests;

A_i = number of hectares present in period one that were established in period i, $i = -M, \dots, 0$. A_i is constant in period 1 and is the area of initial forest inventory.

The harvest flow constraints are considered by the following equations:

$$(1-\alpha)h_j - h_{j+1} \leq 0 \qquad j = 1, \dots, N-1 \qquad (3.14)$$

$$(1+\beta)h_j - h_{j+1} \geq 0 \qquad j = 1, \dots, N-1 \qquad (3.15)$$

Where,

α = maximum decrease in harvest from period to period;

β = maximum increase in harvest from period to period;

h_j = total harvest in period j that is calculated as:

$$h_j = \sum_{k=j}^{N} \sum_{i=-M}^{j-Z} V_{ijk} x_{ik} + \sum_{i=-M}^{N} V_{ijN} w_{iN} \qquad (3.16)$$

α and β are set to zero for the even-flow scenarios (all scenarios except for DBUN and DBUC).

As the model is linear programming, non-negativity constraints apply to each activity:

$$x_{ij} \geq 0 \qquad all\ i\ and\ j \qquad (3.17)$$

$$w_{iN} \geq 0 \qquad all\ i \qquad (3.18)$$

3.3.3. Woodstock management system formulation

The underlying form of my model is the model II representation described above, but is more complicated. Because the development types in the model are not only identified by age, they are also identified by ownership, haul zone, management intensity and timber productivity rating.

Therefore, I use the Woodstock management system (Remsoft, 2013) to develop the model. This software not only allows transfers of area when a stand is harvested but also allows transfers of silvicultural treatments and other aspects of development types like haul zones. Developed model in this study is able to reflect the way the forest is managed in current situation and under different scenario policies and considers the spatial allocation of land (private and public) for different land uses. This model has three main outputs: (i) the financial value of the produced timber, (ii) the financial value of the sequestered carbon compared with that of the sequestered carbon in the baseline policy and (iii) the spatial allocation of management intensities of each land type and ownership. In the following section, I first review getting started the programing in Woodstock by preparing data and then describe the optimization coding including all of the various objective functions and constraints for different policy scenarios.

3.3.3.1. Preparing data in Woodstock management system

Different interfaces of Woodstock are used to simulate the stylized forestry firm in the software as described in the following paragraphs.

a. Landscape

The essential components of the model are defined in the Landscape section. As described in last section, each development type in the model is defined by five attributes that are called themes in Woodstock. Themes in the model are coded as following:

```
; Landscape
*THEME Landtype
public
private
```

```
*THEME Crop
lfn
plant
exotic
ag
*AGGREGATE treednative
lfn plant
*THEME Site
g
m
f
u
*THEME Haulclass
h1
h2
h3
h4
h5
h6
h7
h8
h9
h10
```

where,

Landtype represents the ownership of the land which is private or public;

Crop represents the management intensities which are “leave for natural” coded by “lfn”, “superior native” coded by “plant”, “hybrid poplar” coded by “exotic”, and “agriculture” coded by “ag”;

Site represents the timber productivity ratings which are good coded by “g”, medium coded by “m”, fair coded by “f” and unproductive coded by “u”;

Haul class represents the 10 haul zones in the model and coded by h1 to h10.

b. Actions

In this software, decision variables are defined as the area allocated to action X in period Y. Thus, I use Actions interface to define the eligible management intensities for each development type. Declaration of Actions for the development types makes the Woodstock aware of all of the possible conditions that might exist. The Actions coding in Woodstock for the model includes 6 different actions as following:

```
; Actions
*ACTION cut2lfn Y harvest timber
*OPERABLE cut2lfn
? treednative ? ? vol >= 50

*ACTION cut2plant Y harvest timber
*OPERABLE cut2plant
? treednative ? ? vol >= 50

*ACTION cut2exoticpri Y harvest timber
*OPERABLE cut2exoticpri
private exotic ? ? vol >= 50

*ACTION cut2exoticpub Y harvest timber
*OPERABLE cut2exoticpub
public exotic ? ? vol >= 50

*ACTION convertpri Y convert forage TO plantation
*OPERABLE convertpri
private ag ? ? _AGE >= 1
```

```
*ACTION cut2convert Y harvest timber and convert TO plantation
*OPERABLE cut2convert
public treednative ? ? vol >= 50
```

Where,

Cut2lfn: foresting with “leave for natural” on natural forests;

Cut2plant: foresting with “superior native” on natural forests;

Cut2exoticpri: “hybrid poplar” plantations after harvesting last “hybrid poplar” trees on private lands

Cut2exoticpub: “hybrid poplar” plantations after harvesting last “hybrid poplar” trees on public lands

Convertpri: “hybrid poplar” plantations after converting the private agricultural lands to poplar

Cut2convert: “hybrid poplar” plantations after clearing the natural forests on public lands

c. Transitions

After declaring all possible activities in the forest in the Actions section, Transitions section is used to declare the outcomes of those activities. Applying Table 3.2 of the possible transitions for each management intensity and land type, Transitions are coded as follows:

```
; Transitions

*CASE _DEATH

*SOURCE ? ? ? ?

*TARGET ? ? ? ? 100
```

```
*CASE cut2lfn
*SOURCE ? ? ? ?
*TARGET ? lfn ? ? 100

*CASE cut2plant
*SOURCE ? ? ? ?
*TARGET ? plant ? ? 100

*CASE cut2exoticpri
*SOURCE ? ? ? ?
*TARGET private exotic ? ? 100

*CASE cut2exoticpub
*SOURCE ? ? ? ?
*TARGET public exotic ? ? 100

*CASE convertpri
*SOURCE private ag ? ?
*TARGET private exotic ? ? 100

*CASE cut2convert
*SOURCE public treednative ? ?
*TARGET public exotic ? ? 100
```

These codes represent that the action “*cut2lfn*” is possible only on “leave for natural” lands, the action “*cut2plnt*” is possible on the lands forested by “superior native”, the action“*cut2exoticpri*” can happen only on private lands that were already planted by “poplar plantation” and now regenerated by “poplar plantation” again, the action “*cut2exoticpub*” can only happen only on public lands that were already planted by “poplar plantation” and now regenerated again by “poplar plantation”, the action “*convertpri*” happens on the private agricultural land, and the action “*cut2convert*” happens on public lands that forested by either “Leave for natural” or “superior native” trees.

d. Areas

The Areas section is used to declare the forest area by initial development type (combinations of ownership, crop type, site class, and haul zone) and age class structure of initial forest inventory. The areas coding in the model is dependent on the initial forest inventory. This study investigates various policy scenarios for two forest inventories including juvenile initial forest inventory and split mature initial forest inventory. The coding for both forest initial inventories are available from the University of Alberta's Education and Research Archive at the permalink http://hdl.handle.net/10402/era.40776 .

e. Yields

Yields section provides growth information to the model by indicating how the development types change through time. I declare yield curves for management intensities in each productivity rate, discount factor at the mid of each period, hauling cost for each haul zone, discounted carbon prices at the mid of each period, and below and above ground sequestered carbon in each period as a function of yield curves. All codes are available from the University of Alberta's Education and Research Archive at the permalink http://hdl.handle.net/10402/era.40776. The above and below ground sequestered carbon are calculated using Equations (3.7) and (3.8).

f. Outputs

The outputs section provides a method of defining indicators of interest to the modeler or decision maker. These indicators are used in the objective function and constraints, and reported as conditions of the forest at different points in time. I use Outputs section to calculate the total harvested volume in public, private and total lands, area of hybrid poplar plantations in private, public and total lands, discounted revenue from harvested timer, discounted silvicultural costs in different management intensities, discounted haul costs, discounted conversion costs (from "leave for natural", "superior native" and "agriculture" management intensities to "hybrid poplar" plantations), NPV of harvested timber, above ground (C_t^{above}), below ground (C_t^{below}) and total (C_t) sequestered carbon for the scenario, periodic change in sequestered carbon for scenario (ΔC_t), periodic change in sequestered carbon for baseline scenario which is saved from the baseline results (ΔC_t^b), net change in the sequestered carbon in policy scenario relative to the baseline ($\Delta\Delta C_t$), NPV of sequestered carbon in the scenario, and total NPV which is the sum of NPV of timber income and NPV of carbon income. All of these outputs are calculated for each period in planning horizon based on the land use pattern in each run. All the codes are available from the University of Alberta's Education and Research Archive at the permalink http://hdl.handle.net/10402/era.40776.

g. Constants

The Constants section provides a tool for users to declare their own values that can be used throughout their models. In this model, Constants section includes stumpage value, discount rate, land procurement cost, conversion cost, reforestation cost, price of carbon, and haul cost that all are described in Data section of this paper.

3.3.3.2. *Modeling scenarios in Woodstock management system*

The Optimize interface in Woodstock formulates the forestry policy scenario. This section declares the objective function and constraints of the model.

a. The formulation of objective function

Depending on the scenario, the objective function is to maximize:

i. the total volume of the harvested timber (m^3) for the baseline scenario with "V" at the first digit (VNFN). Objective code for this policy scenario in the Optimization section is coded as follows :

```
*OBJECTIVE

_MAX totvolume 1.. _LENGTH
```

ii. the discounted net present value ($/ha) of timber income for 6 scenario policies with "N" at the fourth digit (DNBN, DPFN, DPBN, DBFN, DBBN, and DBUN). The objective function for these policy scenarios is the subtraction of discounted all related costs from discounted timber revenue and can be coded as follows (The non-negativity requirement forces to bring all the costs and revenues separately in the objective function):

```
*OBJECTIVE
_MAX dlogrevenue - dcutcost - dhaulcost - dconvertpricost -
dcut2convertcost - dlfncost - dplantcost - dexoticcost 1.._LENGTH
```

Where,

Dlogrevenue: discounted revenue from harvested timber;

Dcutcost: discounted logging cost for cut area;

Dhaulcost: discounted hauling cost for harvested timber;

Dconvertpricost: discounted costs of establishing poplar plantations on an agricultural land which includes both the land purchase cost and silvicultural costs of poplar plantations;

dcut2convertcost: discounted cost of clearing native forests for poplar plantations which includes both land procurement and conversion costs;

dlfncost: discounted reforestation cost for the "leave for natural" forest which includes data management and monitoring costs;

dplantcost: discounted reforestation cost for the "superior native" forest which includes site preparation, nursery stock and planting costs;

dexoticcost: discounted reforestation cost for "hybrid poplar" plantations which includes both poplar plantation silvicultural and stumping costs.

iii. the discounted total net present value of both timber and sequestered carbon income ($/ha) for those 5 policy scenarios with "C" at the fourth digit (DPFC, DPBC, DBFC, DBBC, and DBUC). The objective function for these scenarios consists discounted value of both timber and carbon. The NPV of timber is coded similar to last objective function. However, in order to code the NPV of carbon, two free variables (CO2plus and CO2minus) are defined due to non-negativity requirement. Also, accounting rows should be added to the constraints. Hence, the following codes are used to formulate this objective:

```
*VARIABLE
co2plus _ARRAY
co2minus _ARRAY


*OBJECTIVE
_MAX co2plus - co2minus + dlogrevenue - dcutcost - dhaulcost -
dconvertpricost - dcut2convertcost - dlfncost - dplantcost -
dexoticcost 1.._LENGTH

*CONSTRAINTS
pdf*oco2total  - pdf*oco2total[-1] -co2plus + co2minus = 0 1.._LENGTH
```

Where, the constraint calculates the discounted value of net change in periodic sequestered carbon in the project relative to the baseline for each period. If the net change is positive, then the CO2minus variable is zero and the carbon revenue for that period contributes to the objective function. If the project does not store more carbon than the baseline, the CO2plus variable is zero and the objective is penalized by CO2minus variable.

b. The formulation of the "hybrid poplar" plantations permission

The "hybrid poplar" plantations are not permitted in all scenarios. Depending on the scenario, the *EXCLUDE keyword in the Optimization section can exclude the undesirable Actions from decision variables. The second digit in the policy scenarios shows whether "hybrid poplar" plantations are:

i. not allowed for baseline scenario (VNFN, and DNBN) with "N" at the second digit. The Optimization section for this scenario contains the following codes:

```
*EXCLUDE

convertpri 1.._LENGTH
```

```
cut2convert 1.._LENGTH
cut2exoticpub 1.._LENGTH
```

ii. allowed only on private lands for those 4 scenario policies with “P” at the second digit (DPFN, DPFC, DPBN, and DPBC). So, the actions containing plantations on public lands are excluded and the coding is:

```
*EXCLUDE
cut2convert 1.._LENGTH
cut2exoticpub 1.._LENGTH
```

iii. allowed on both public and private lands for other 6 policy scenarios with “B” at the second digit (DBBN, DBBC, DBFN, DBFC, DBUN, and DBUC). There is not any EXCLUDE coding for this policy scenarios.

c. The formulation of even-flow constraint

The even-flow constraint should be coded in the Optimization section as a Constraint. Depending on the policy scenario, the imposed even-flow can be:

i. at the baseline AAC for those 5 policy scenarios with “B” at the third digit (DNBD, DPBN, DPBC, DBBN, and DBBC). For the split mature forest inventory, the even-flow constraint for these policies is coded as:

```
*CONSTRAINTS
_EVEN(totvolume) 1.._LENGTH
totvolume = 1.25e7 1.._LENGTH
```

Where 1.25e7 (m^3/period) is the baseline AAC for the forest with split mature inventory. The baseline AAC for the juvenile forest inventory models is 1.173e7 (m^3/period).

ii. Flexible even-flow for those 5 other scenarios with “F” at their third digit (VNFN, DPFN, DPFC, DBFN, and DBFC). In these scenarios, although the total harvested volumes in each period are equal, they are not equal to a specified amount harvest volume. So, the constraints in the Optimization interface includes:

```
*CONSTRAINTS
_EVEN(totvolume) 1.._LENGTH
```

iii. Completely unconstrained for 2 policy scenarios with “U” at the third digit (DBUN, and DBUC). Obviously, constraints in the Optimization section do not contain any even-flow constraint.

MOSEK[1] is the solver for mathematical optimization problems like LP that I use for all scenarios (MOSEK ApS, n.d.). The following code in the Optimize section makes the Woodstock to solve the LP programming using MOSEK:

```
*FORMAT MOSEK
```

To this end, modeling different policy scenarios involves choosing the appropriate objective function and related free variables, choosing from the EXCLUDE actions and choosing the periodic harvest volume constraint. Here, I show the modeling of the “hybrid poplar” plantations on private lands with even-flow constraint at the baseline AAC and with-carbon (DPBC) policy scenario for juvenile forest inventory. Free variables are used to account for sequestered carbon in the scenario and carbon related accounting constraint is added to the

---

[1]) all information are available at www.mosek.com

constraints of the model. Since "hybrid poplar" plantations are permitted only on private lands in the policy, two actions related to plantations on public lands are excluded from the model. Also, even-flow constraint is set to be equal at the baseline AAC in the juvenile forest.

```
*VARIABLE
co2plus _ARRAY
co2minus _ARRAY

*OBJECTIVE
_MAX co2plus - co2minus + dlogrevenue - dcutcost - dhaulcost -
dconvertpricost - dcut2convertcost - dlfncost - dplantcost -
dexoticcost 1.._LENGTH

*CONSTRAINTS
_EVEN(totvolume) 1.._LENGTH
totvolume = 1.173e7 1.._LENGTH
pdf*oco2total - pdf*oco2total[-1] - co2plus + co2minus = 0  1.._LENGTH

*EXCLUDE
cut2convert 1.._LENGTH
cut2exoticpub 1.._LENGTH
*FORMAT MOSEK
```

The modeling for other policy scenarios is available from the University of Alberta's Education and Research Archive at the permalink http://hdl.handle.net/10402/era.40776.

3.4. Data

The planning horizon for this model is 200 years represented by 40 periods of 5 years each. The following values are used to calculate timber and carbon revenue and related costs in the model.

3.4.1. Stumpage value

I use the biomass price value calculated in the last chapter as a proxy for stumpage value. In this, the biomass price is the maximum price that might be paid for hybrid poplar based on the residual value left over after all the costs are considered. I do not consider any price differentiation for different qualities of wood. This price at the mill gate is \$148/odt, which is equal to \$51.7/m^3. The cost of timber harvesting, road construction and log loading is assumed to be \$3060/ha (Anderson, 2008). This cost is subtracted from the timber gate price. In accounting for log hauling, I follow Anderson et al. (2012), using a figure of \$0.07/m^3/km. Based on this figure, the log haul costs for different haul zones are calculated and shown in Table 3.3.

Table (3.3): log haul cost for each haul zone

Haul Zone	1	2	3	4	5	6	7	8	9	10
Haul Cost (\$/km)	*0.7*	*2.1*	*3.5*	*4.9*	*6.3*	*7.7*	*9.1*	*10.5*	*11.9*	*13.3*

3.4.2. Discount rate

I use a 4% discount rate in my analysis which follows the rate used in the stand-level analysis presented in Chapter 2. The 4% discount rate is based on the previous studies of hybrid poplar in Canada (Yemshanov & McKenney, 2008; Allen, et al., 2013; Anderson & Luckert, 2007).

3.4.3. Land procurement costs

When exotic plantations are established either on private or on public land, procurement costs are incurred. For public land, I use a cost based on grazing lease rate in Alberta of \$2/ha/year (SRD, 2003). A 4% discount rate is applied to turn the perpetual payment into a lump-sum present value of \$50/ha. For private land I use the land purchasing cost from stand-level analysis data. The average value of cropland in the Peace River region, based on Farm Credit Canada (FCC) data is \$2527/ha (Farm Credit Canada, 2013), reflecting the one-year period between March 2012 and March 2013. I do not consider price differentiation for differing soil quality.

3.4.4. Conversion cost

This cost is incurred when the firm makes a decision to convert public land into a hybrid poplar plantation. The conversion cost, paid only once, is the cost of clearing land under the previous management intensity in order to convert the public forest into bare land. I use $300/ha (Westworth & Associates, 1994).

3.4.5. Reforestation cost

The reforestation cost varies according to different management intensities. The reforestation cost for "leave for natural" management intensity includes data management and monitoring. I use the figure of $5/ha suggested by (Insley, et al., 2002). The reforestation cost for "superior native" management intensity includes the present value of site preparation, nursery stock and planting (Insley, et al., 2002). I set $930/ha as the reforestation cost at this management intensity (Anderson, et al., 2012). For "hybrid poplar" management intensity, I use The Canadian Wood Fibre Centre data (Sidders, et al., 2012) on the silvicultural cost for hybrid poplar single stem plantations in the Peace River region. The present value for the silvicultural cost of "hybrid poplar" plantations is $2868/ha, applying a 4% discount rate. Also, following Anderson et al. (2012), I add a $175/ha to the silvicultural cost as the post-harvest cost of unearthing and burning the stumps. Hence the reforestation cost for hybrid poplar is $3043/ha.

3.4.6. Price of Carbon

I use the price of $15/ton of equivalent CO_2 for sequestered carbon, which is payable into the Climate Change and Emissions Management Fund for over-target emission, based on the

Greenhouse Gas Reduction Program in Alberta (AB Environment & Sustainable Resource Development, 2015)

3.5. Results

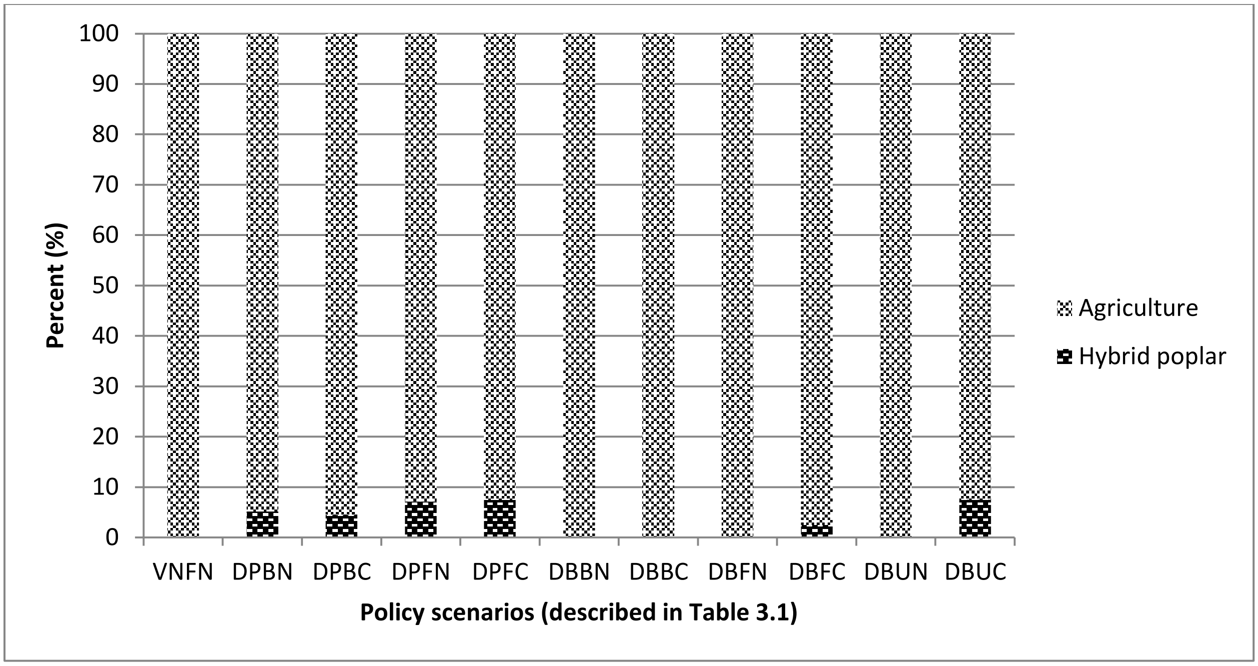
In this section, the results of the optimization model are described for both juvenile and split mature forest inventories. For each set of policy scenarios, I describe the non-spatial results of AACs and NPVs comparing with the baseline scenario (Table 3.4). Then, I show the proportion of various land uses for both forest inventories in the last period of planning time (Figures 3.6 and 3.7).

This model is designed to reach a steady-state harvesting volume. In the model, once land is converted to hybrid poplar plantations, it will not change to other management intensities. In addition, the even-flow constraint helps to reach a steady-state harvested volume. For all scenarios, a steady-state condition with respect to hybrid poplar plantations area is reached before the end of 40th period (Figures 3.8 and 3.9). In the following sections, the results for each scenario are explained.

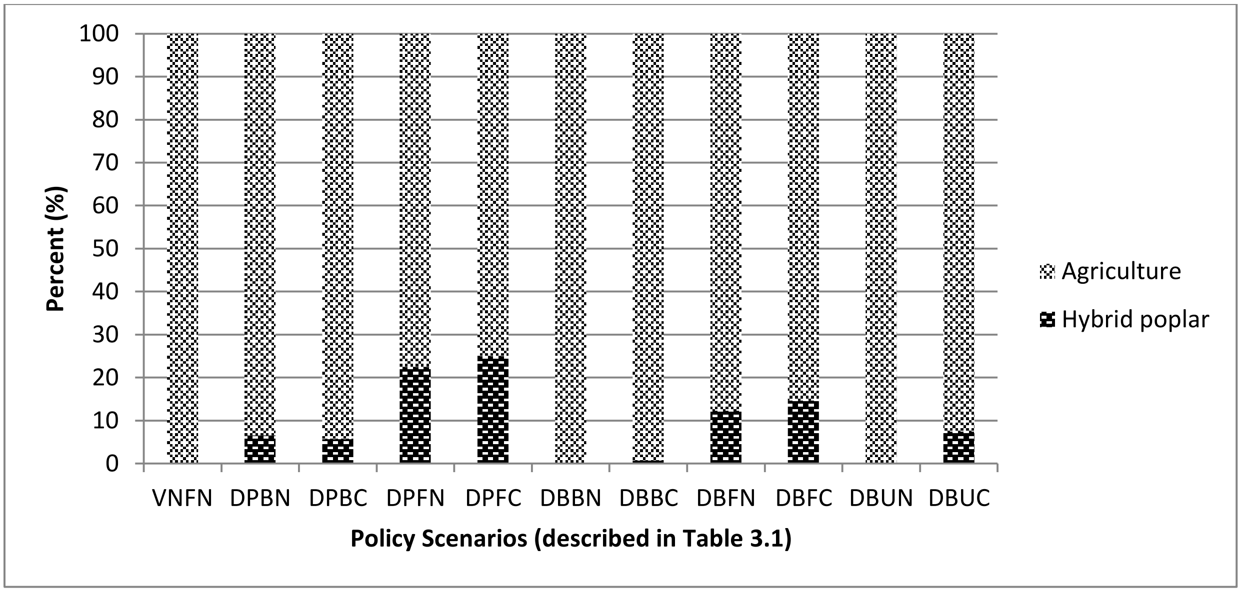
Table (3.4): Model setup and non- spatial results for each policy and initial inventory

Policy scenario	Exotic on public land?	Juvenile inventory		Split Mature inventory	
		AAC (Mill. m^3/yr)	NPV ($Mill.)	AAC (Mill. m^3/yr)	NPV ($Mill.)
VNFN	N	2.35	1358.67	2.50	1656.52
DNBN	N	2.35	1363.56	2.50	1679.70
DPBN	N	2.35	1591.53	2.50	1947.63
DPBC	N	2.35	1626.22	2.50	1928.81
DPFN	N	2.56	1592.85	4.17	2264.89
DPFC	N	2.58	1632.77	4.35	2220.98
DBBN	Y	2.35	1632.10	2.50	1959.89
DBBC	Y	2.35	1656.59	2.50	1937.00
DBFN	Y	2.85	1650.74	4.67	2470.70
DBFC	Y	2.80	1683.90	4.73	2415.52
DBUN	Y	2.73[a]	1623.03	2.93 [a]	3362.43
DBUC	Y	4.08 [a]	1735.66	4.30 [a]	2942.95

a: these values are average harvest volume (as described in section 3.5.6)

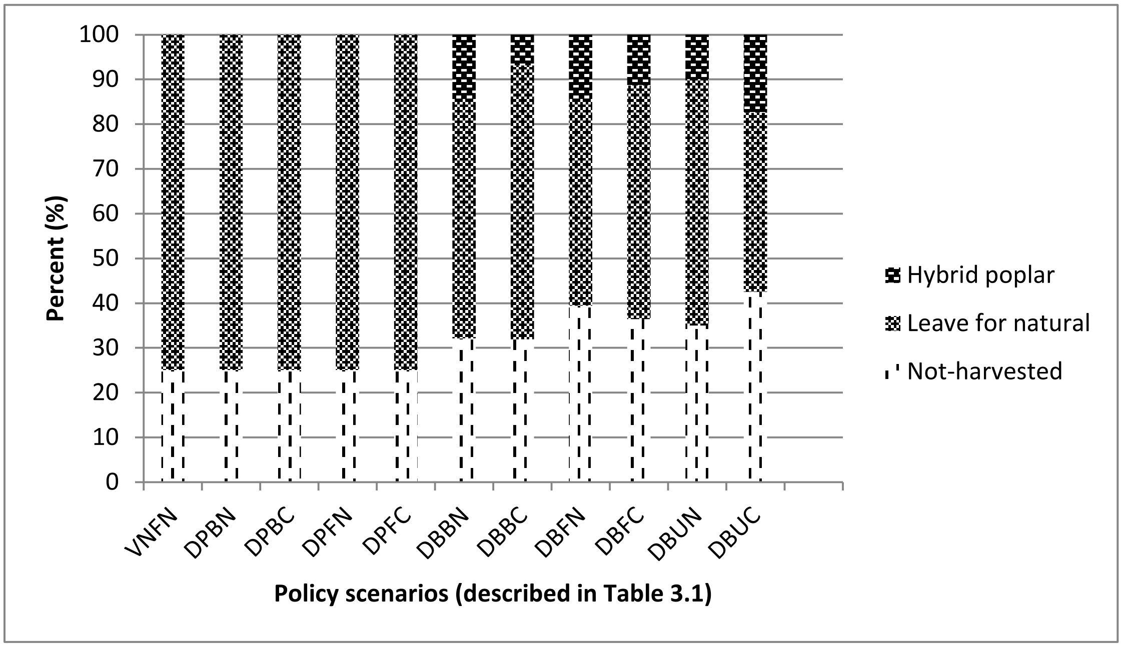


(a): juvenile initial inventory forest

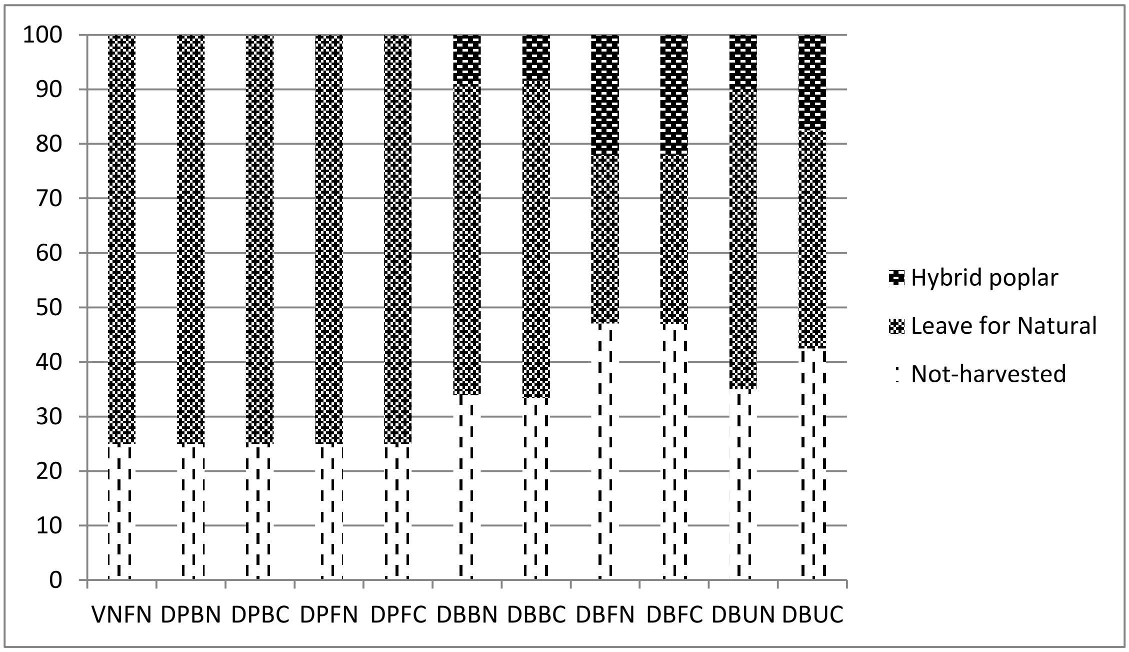


(b): Split mature initial inventory forest

Figure (3.6): Proportion of private land allocated to the different land uses for each policy with (a) juvenile and (b) split mature initial inventory

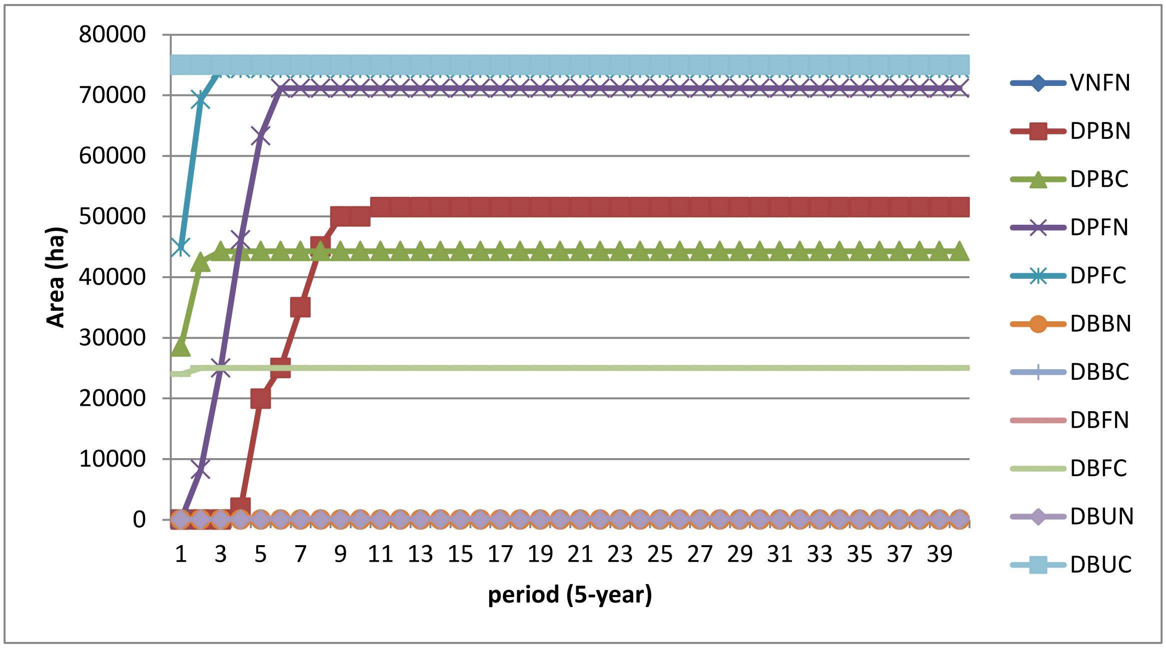


(a): Juvenile initial inventory forest

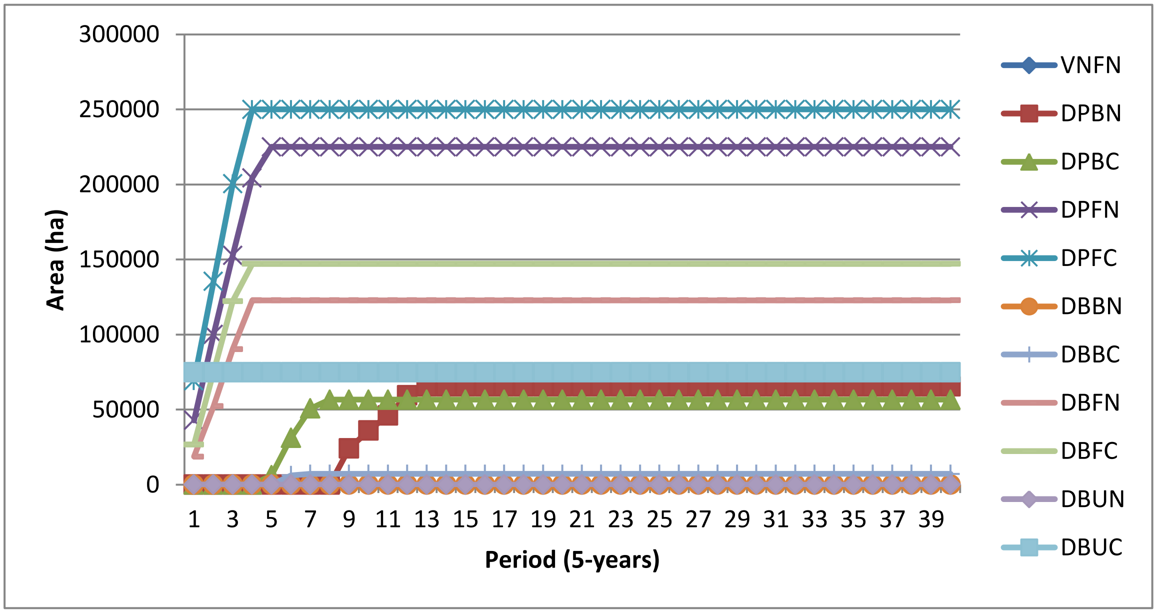


(b): Split mature initial inventory forest

Figure (3.7): Proportion of public land allocated to the different land uses for each policy with (a) juvenile and (b) split mature initial inventory

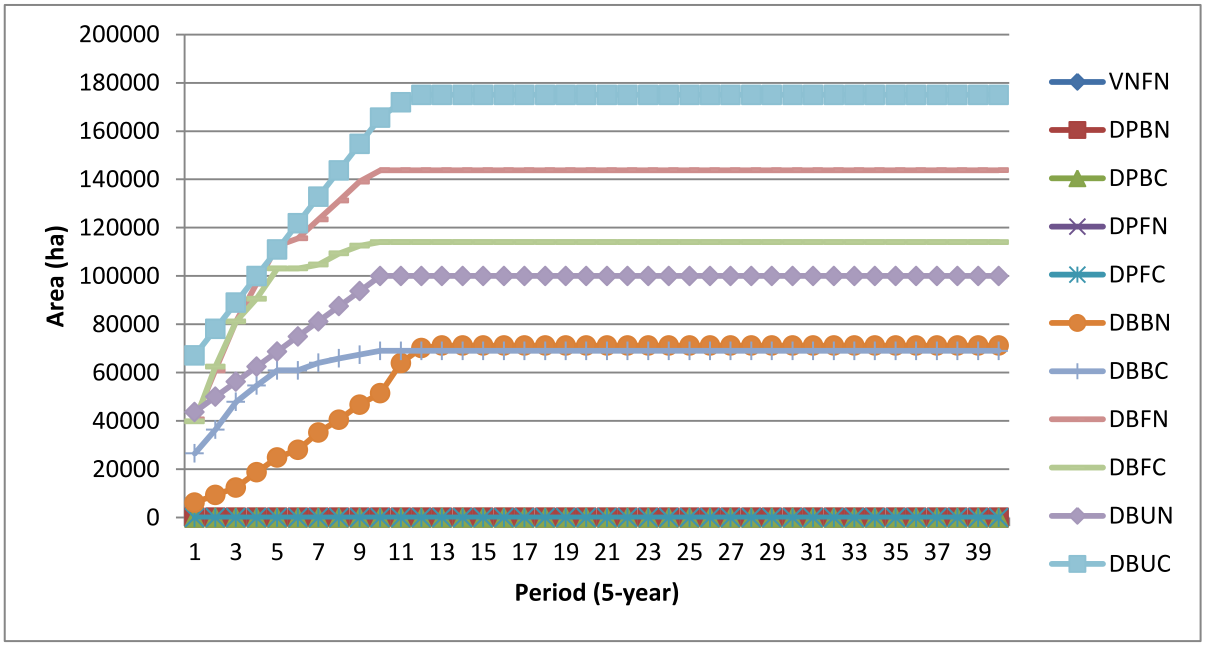


(a) Juvenile forest inventory

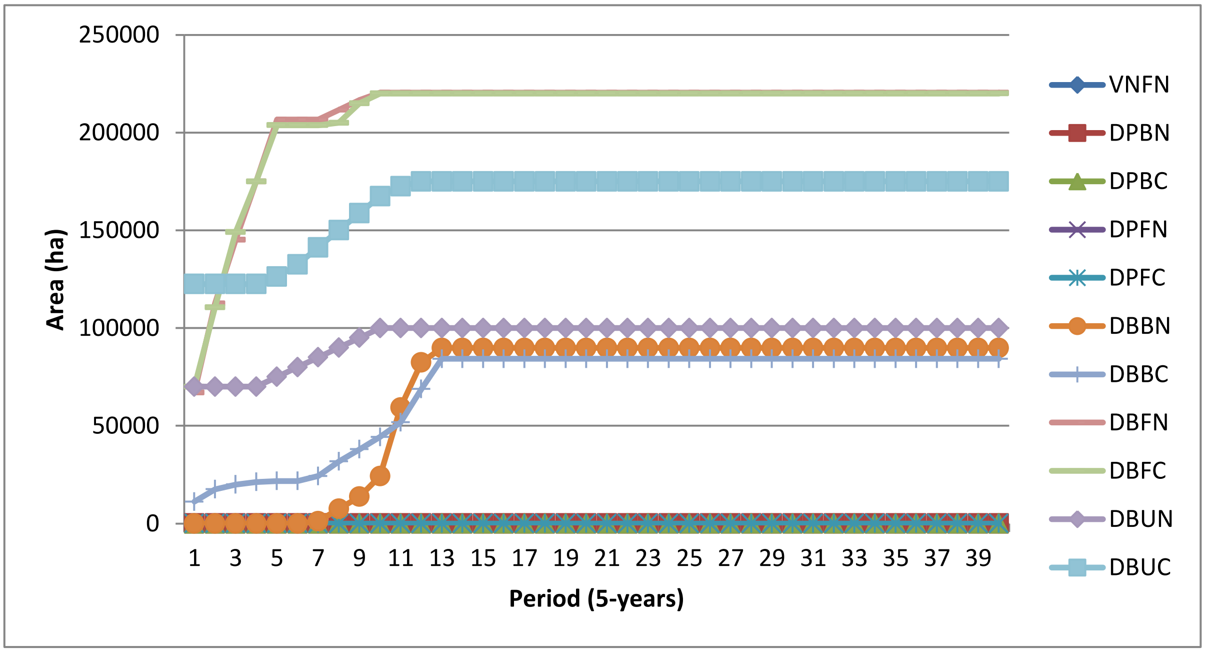


(b) Split mature forest inventory

Figure (3.8): Hybrid poplar plantations area over time on private land for (a) juvenile and (b) split mature forest inventory for various policy scenarios (described in Table 3.1)



(a) Juvenile forest inventory



(b) Split mature forest inventory

Figure (3.9): Hybrid poplar plantations area over time on public land for (a) juvenile and (b)split mature forest inventory for various policy scenarios (described in Table 3.1)

3.5.1. Baseline volume and NPV scenarios: No hybrid poplar on private and public lands, even-flow constraint *(VNFN and DNBN)*

First, I consider the VNFN policy scenario. For this scenario, the model maximizes the volume of harvested timber from a native forest on public land. This policy represents the current practice in Alberta. The objective function in this policy is to maximize the total harvest volume under the even-flow conditions. No exotics are permitted and no carbon is accounted for. The total harvested volume resulting from this scenario is the baseline AAC which leads to a Maximum Sustained Yield (MSY) situation. The maximum harvested timber in this policy is 2.35 million m^3/year for juvenile and 2.50 million m^3/year for split mature forest inventory (Table 3.4), all from public lands.

I assume that both “superior native” and “leave for natural” plantations are permitted on public lands in this policy scenario. Since the VNFN scenario does not consider the NPV, it allocates all productive lands (75% of public lands) to “superior native” plantations at first and then they convert to “leave for natural” in such a way that at the end of the planning horizon there is only “leave for natural”. In addition, sequestered carbon in each period is calculated and saved as the periodic sequestered carbon in the baseline condition ($C_{\Delta t}^{b}$) for future simulations.

The NPV is simulated in the objective function for the NPV maximization (DNBN) scenario. This model allocates public lands to “superior native” and “leave for natural” plantations in such a way that the NPV of harvested timber is maximized. This policy scenario indicates the value of the baseline scenario. The even-flow constraint is set at the baseline AAC level. Since the model considers revenue and cost of forestry operations, lands closer to the bioethanol production plant with a lower haul cost to be chosen. For juvenile forests, producing

2.35 million m^3/year generates a NPV of $1.36 billion (Table 3.4). For split mature forest inventory, harvesting 2.50 million m^3/year results in a NPV of $1.68 billion (Table 3.4). Land uses in this scenario are similar to those in the volume maximization (VNFN) scenario (Figures 3.6 and 3.7).

3.5.2. Hybrid poplar plantations on private land, even-flow at baseline AAC *(DPBN and DPBC)*

These two policy scenarios represent situations in which hybrid poplar plantations are permitted only on private land. On public lands, “leave for natural”, “superior native” and “preservation” are the different management intensities. The harvest level is even-flow, whether or not sequestered carbon is accounted for. The model maximizes timber NPV for DPBN and total NPV (timber and carbon NPV) for DPBC, while the even-flow constraint is set at the AAC amount from the baseline scenario.

Under the non-carbon policy scenario (DPBN), allocating private lands to hybrid poplar plantations results in an NPV of $1.59 billion (a 17% increase in NPV from the baseline scenario) for the juvenile inventory and $1.95 billion (a 17.5% increase in NPV from the baseline scenario) for the split mature forest inventory (Table 3.4). Maximizing total NPV in the with-carbon policy scenario (DPBC) results in $1.63 billion (a 20% increase in NPV from the baseline scenario) for the juvenile inventory and $1.93 billion (a 16% increase in NPV from the baseline scenario) for the split mature inventory (Table 3.4). When the initial forest is young, the total NPV in the with-carbon scenario (DPBC) is higher than the firm`s NPV from the timber in the non-carbon scenario (DPBN). However, with a more mature initial forest, the total NPV under the with-carbon scenario (DPBC) is lower than the timber NPV under the non-carbon policy scenario (DPBN). The reason is that with carbon included, the timing of harvests is different between the two models, which will be discussed below.

Under the non-carbon (DPBN) policy, 5.1% and 6.6% of private land is allocated to hybrid poplar plantations for juvenile and split mature forest inventories, respectively (Figure 3.6). All productive public lands (75% of public lands) are allocated to “leave for natural”, and 25% of public lands are not harvested because they are unproductive (Figure 3.7). In this set of scenarios, although the AAC does not change relative to the baseline scenario, a small portion of the private lands is planted due to the lower yield of “leave for nature” which is selected under these scenarios than the “superior native” which is selected under the baseline policy scenario.

Under the with-carbon policy scenario (DPBC), land use patterns are similar to those under the non-carbon policy (DPBN). A small portion of private land (4.4% in the juvenile forests and 5.7% in the split mature forests) is allocated to hybrid poplar plantations (Figure 3.6). Also, like the non-carbon scenario (DPBN), under the with-carbon scenario (DPBC), 75% of public lands which are productive are reforested with the “leave for natural” and 25% of public lands are unproductive.

3.5.3. Hybrid poplar plantations on private land and flexible even-flow *(DPFN and DPFC)*

These sets of policy scenarios impose sustained yield on a forest with an even-flow constraint. However, even-flow is not constrained at the baseline AAC level; I allow the model to harvest more timber than the baseline AAC. The model in these scenarios allocates private land to hybrid poplar plantations if it is financially viable and leads to higher NPVs. The non-carbon scenario (DPFN) maximizes timber NPV and the with-carbon scenario (DPFC) maximizes timber and carbon NPV.

As expected for both scenarios with either juvenile or split mature forest inventory, the AAC is higher than the baseline AAC (Table 3.4). Comparing to baseline scenario, the AAC for the non-carbon scenario (DPFN) increases by 9% (from 2.35 to 2.56 million m^3/year) in the forest with the juvenile inventory and 67% (from 2.50 to 4.17 million m^3/year) in the forest with the split mature inventory (Table 3.4). Increasing the AAC results in NPV enhancements of 17% (from \$1.36 to \$1.59 billion) for the juvenile initial forest inventory and 37% (from \$1.66 to \$2.27 billion) for the split mature forest inventory (Table 3.4). Adding in values for sequestered carbon in the with-carbon scenario (DPFC) leads to a 10% increase in AAC relative to baseline scenario (from 2.35 to 2.58 million m^3/year) for the juvenile forest initial inventory and a 74% increase in AAC (from 2.50 to 4.35 million m^3/year) for the split mature forest initial inventory (Table 3.4). Under the with-carbon scenario (DPFC), the NPV for juvenile forest inventory increases 20% relative to the baseline scenario (from \$1.36 to \$1.63 billion) which is greater than the increase in the NPV under the non-carbon scenario (DPFN). Accounting for sequestered carbon increases the NPV by 34% (from \$1.66 to \$2.22 billion) which is less than the increase in the NPV under the non-carbon scenario (DPFN) due to the social cost of not considering carbon in the non-carbon scenario (as discussed in section 3.5.2) and negative carbon NPV in the with-carbon scenario (DPFC).

Figure 3.6 shows the increased AACs from flexible even-flow come from the increases in poplar plantations in private lands. For the juvenile forest inventory, 7.1% and 7.4% of private lands are allocated to poplar plantations under the non-carbon (DPFN) and with-carbon (DPFC) scenarios, respectively (Figure 3.6). The increase in poplar plantations is higher in the split mature than the juvenile forest inventory. In the split mature forest inventory, 22.5% and 25% of lands are allocated to poplar plantations under the non-carbon (DPFN) and with-carbon (DPFC) policies respectively. Non-harvested lands (which are all unproductive lands in these scenarios) under both non-carbon (DPFN) and with-carbon (DPFC) scenarios do not increase relative to the baseline scenario and all 75% of productive public lands are forested with “leave for natural” (Figure 3.7).

Figure 3.8 indicates that compared to the non-carbon policy with even-flow at the baseline AAC (DPBN), the non-carbon with flexible even-flow policy (DPFN) reaches a steady-state condition in a shorter period of time for both juvenile and split mature inventories. Similarly, the with-carbon scenario with even-flow set at the baseline AAC (DPFC) achieves the steady-state condition earlier than the with-carbon and flexible even-flow policy (DPBC) for both juvenile and split mature inventories. This is due to the fact that the AAC in the non-carbon (DPFN) and with-carbon (DPFC) scenarios are flexible and higher than the AAC in the non-carbon (DPBN) and with-carbon (DPBC) scenarios.

3.5.4. Hybrid poplar plantations on both private and public lands Even-flow at the baseline AAC *(DBBN and DBBC)*

The DBBN and DBBC policies maximize timber NPV and total NPV while limiting the AAC to the baseline AAC level of 2.35 million m^3/year for juvenile forest and 2.50 million m^3/year for split mature forest. In this set of scenarios, the possibility of replacing hybrid poplar plantations on private land with hybrid poplar plantations on public land is investigated. Private land is allocated to poplar plantations only if the public land poplar plantations (which is cheaper than that on private land) does not produce the required AAC.

Allowing poplar plantations on public land to achieve the AAC results in higher NPV with and without carbon accounting and for both forestry inventories. For the forest with juvenile initial inventory, relative to the baseline scenario, the NPV increased by 19% (from $1.36 to $1.62 billion) under the non-carbon (DBBN) policy scenario and by 22% (from $1.36 to $1.66 billion) under the with-carbon (DBBC) policy scenario (Table 3.4). For the forest with split mature initial inventory, the increase in the NPV relative to the baseline scenario is less than that in juvenile forest inventory (Table 3.4). For the split mature forest inventory, the NPV increases by 18% (from $1.66 to $1.96 billion) under the non-carbon (DBBN) policy scenario and by 17% (from $1.66 to $1.94 billion) under the with-carbon (DBBC) policy scenario.

Another interesting result is that the area under plantations on private land is almost zero under both the non-carbon (DBBN) and with-carbon (DBBC) scenarios for both forest inventories (Figure 3.6). In other words, an increase in the NPV results from reducing forestry on private land. In addition, intensified production on public land causes an increase in the amount of non-harvested land. In previous policies, the entire portion (75%) of public lands that are productive are forested under either “leave for natural” or “superior native” management intensities, and only 25% of public lands that are unproductive are not allocated. In the present scenarios, non-harvested lands increase for both inventories under both the non-carbon (DBBN) and with-carbon (DBBC) policy scenarios. Therefore, approximately one third of public lands is left non-harvested (Figure 3.7).

All hybrid poplar plantations occurred on sites with good productivity that were close to the bioethanol production plant (haul zones one to three). Other public lands are allocated to “leave for natural” management intensity in almost all haul zones. However, far haul zones with fair productivity are not harvested. Once again, there is no “superior native” plantation due to its high costs. Also, there are almost not poplar plantations on private lands because producing timber is cheaper on public land than on private lands.

Reaching the steady-state condition for both scenarios with even-flow set at the base line AAC with and without carbon (DBBC and DBBN) takes almost 11 periods in a forest with a juvenile inventory (Figure 3.9). For those beginning with a split mature inventory, it takes a little longer (about 12 periods) to get to steady-state condition.

3.5.5. Hybrid poplar plantations on both private and public land with flexible even-flow on private and public land *(DBFN and DBFC)*

I model these two policies to maximize the NPV while there is an even-flow AAC for both public and private forests, and hybrid poplar plantations are permitted on both public and private lands. Simulating these scenarios shows the maximum amount of produced biomass in under even-flow conditions.

The AAC increases under these two policy scenarios for both inventories, relative to the baseline scenario. For juvenile forest inventory, the AAC increases by 21% (2.35 to 2.85 million m^3/year) under the non-carbon (DBFN) policy scenario and by 19% (2.35 to 2.80 million m^3/year) under the with-carbon (DBFC) policy scenario (Table 3.4). The increase in the AAC is even higher for the forest with split mature inventory. Under the non-carbon (DBFN) and with-carbon (DBFC) policy scenarios, the AAC for split mature inventory increases from 2.50 to 4.67 and 4.73 million m^3/year (87% and 89% of the baseline AAC), respectively.

Increases in AACs relative to the baseline scenario lead to increase in NPVs (Table 3.4). While the NPV for the juvenile forest increased 21% (from \$1.36 to \$1.65 billion) under the non-carbon (DBFN) and 23% (from \$1.36 to \$1.68 billion) under the with-carbon (DBFC) policies, the model with split mature forest inventory witnessed an NPV increase of 49% (from \$1.66 to \$2.47 billion) under the non-carbon (DBFN) policy and 46% (from \$1.66 to \$2.42 billion) under the with-carbon (DBFC) policy scenario.

On private lands, hybrid poplar plantations increased, as there was no constraint on the AAC (Figure 3.6). For the split mature initial inventory, 12.3% and 14.7% of private lands are allocated to poplar plantations under the non-carbon (DBFN) and with-carbon (DBFC) policy scenarios, respectively. For juvenile inventory, poplar forests are established on only 2.5% of private lands under the non-carbon (DBFN) policy scenario, while only a small portion of private lands (less than 1%) is allocated to poplar plantations under the with-carbon (DBFC) policy scenario.

Once again, an increase in the NPV results from a reduction in the forest harvesting footprint. The quantity of non-harvested public lands is greater than in the baseline scenario, and even than in the even-flow at the baseline AAC non-carbon (DBBN) and with-carbon (DBBC) policy scenarios (Figure 3.7). For forests with split mature inventory, about half of public lands are not harvested under both flexible even-flow non-carbon (DBFN) and with-carbon (DBFC) policy scenarios (the proportion of non-harvested land in the baseline scenario is 25%). For the juvenile forest inventory, non-harvested lands accounted for 39.4% of public lands under the non-carbon (DBFN) and 36.4% of public lands under the with-carbon (DBFC) policy scenarios (Figure 3.7). The non-harvested public land in this set of scenarios (with flexible even-flow) is high. This fact is due to the ACE in private lands that results in smaller forest harvesting footprint in public lands.

3.5.6. Hybrid Poplar plantations on both public and private land and no constraint on even-flow *(DBUN and DBUC)*

These two policy scenarios are designed to investigate what happens if there is no AAC constraint on the forestry firm. In this set of policies, I assume that the forestry firm is maximizing its NPV under the condition that hybrid poplar plantation is permitted on public and private lands.

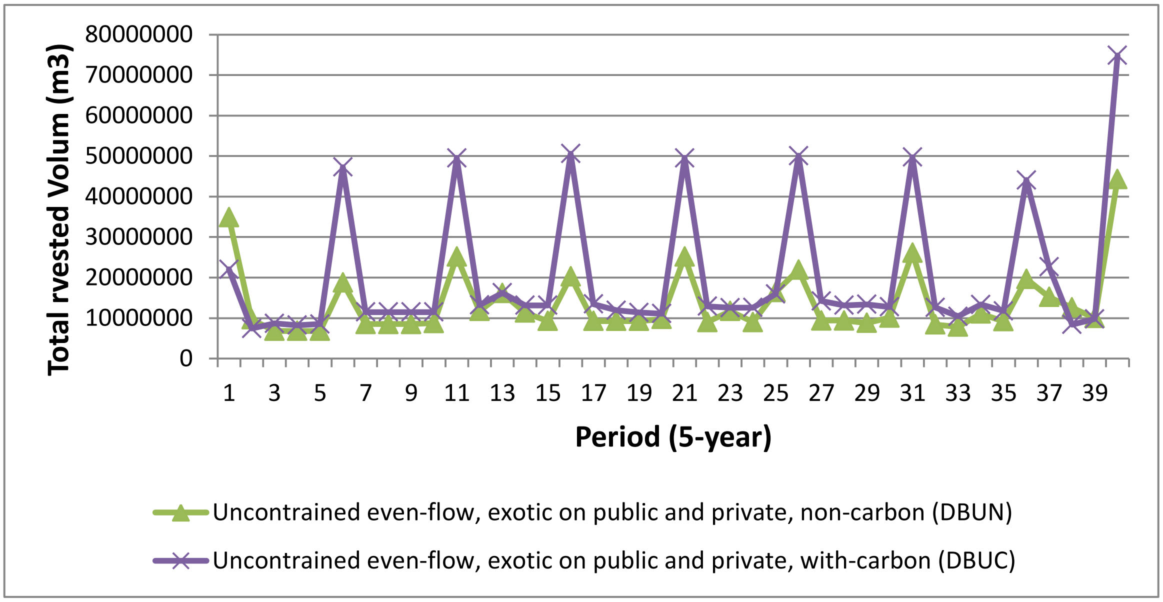
Because there is no AAC in these models I report the average harvested volume by dividing the total harvested volume by 200 years. The average volume harvested each year under the non-carbon (DBUN) and with-carbon (DBUC) policy scenarios is higher than the baseline

AAC and some other scenarios for both juvenile and split mature forest inventories (Table 3.4). Compared with the baseline scenario, the average harvested volume under the non-carbon (DBUN) policy increases by 16% (from 2.35 to 2.73 million m^3/year) in the juvenile forest and by 17% (from 2.50 to 2.93 million m^3/year) in the split mature forest. For the with-carbon (DBUC) policy scenario, the average harvested volume increases by 74% (from 2.35 to 4.08 million m^3/year) in the juvenile and by 72% (from 2.5 to 4.30 million m^3/year) relative to the base line AAC. For the juvenile forest inventory, the average harvested volume in unconstrained even-flow scenarios with and without carbon (DBUN and DBUC) is higher than all other scenarios but the flexible even-flow with public and private plantations non-carbon and with-carbon (DBFN and DBFC) policy scenarios. For split mature forest inventory, the average harvested volume under the non-carbon (DBUN) and with-carbon (DBUC) policy scenarios is higher than the AAC under all simulated policy scenarios except for four scenarios with the flexible even-flow with and without carbon (DPFN, DPFC, DBFN and DBFC) policy scenarios (Table 3.4).

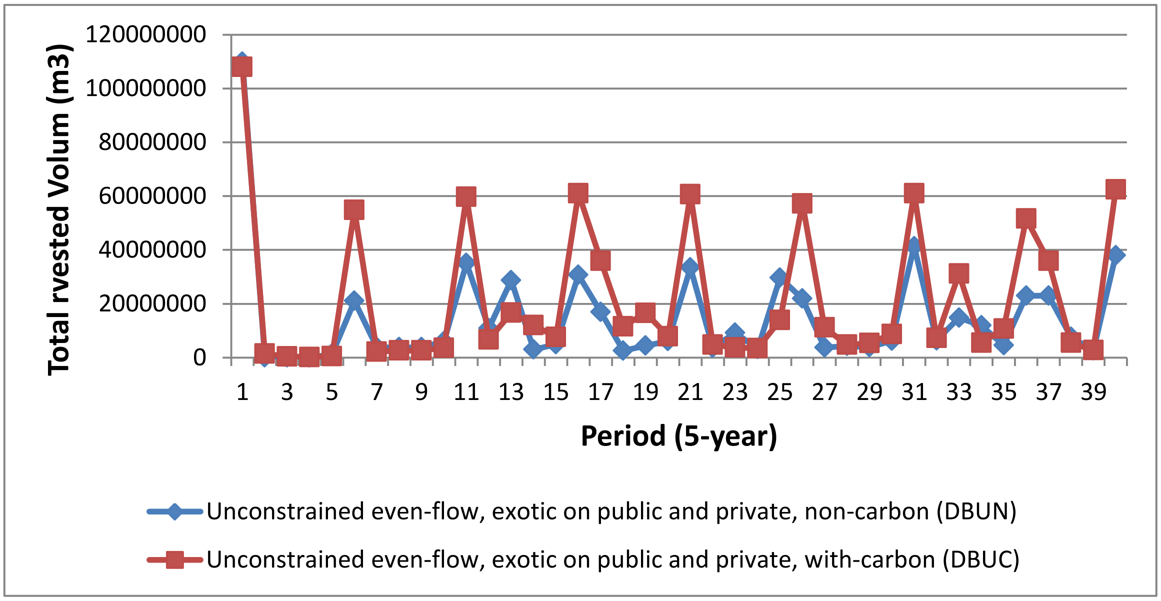
However, the NPVs under these two policies are higher than the NPV of the baseline and other policies. Relaxing the even-flow constraint positively influence NPVs, especially when the initial forest inventory is split mature. Compared with the baseline scenario, the NPV under the non-carbon policy (DBUN) and the with-carbon policy (DBUC) increases by 102% (from \$1.66 to \$3.36 billion) and 77% (from \$1.66 to \$2.94 billion), respectively, in the split mature forest inventory (Table 3.4). The increase in NPV under the non-carbon policy (DBUN) in the juvenile forest inventory is 19% of the NPV under the baseline scenario. In the juvenile forest inventory, the NPV increased by 28% (from \$1.36 to \$1.74 billion) under with-carbon scenario (DBUC); this is the highest NPV for this inventory among all simulated policy scenarios (Table 3.4).

Although the highest NPVs among all scenarios are achieved in unconstrained even-flow policy scenario with and without carbon (DBUN and DBUC), the average harvested volume in these two scenarios is not the highest one. This is due to the relaxation of even-flow constraint in these scenarios. In fact, the model harvests as much as possible volume at the first period and then the harvested volume remains at the lowest level for a while, and again, high volume of timber is harvest and so on to make the highest possible NPV level (Figure 3.10). Additionally, relaxation of the even-flow constraint results in reducing the forest harvesting footprint. For both inventories, the non-harvested public lands increases to 35% of total public lands under non-carbon (DBUN) and 43% of total public lands under with-carbon (DBUC) policy scenarios (Figure 3.7). Also, for both inventories, only 7.5% of private lands are allocated to poplar plantations under the with-carbon (DBUC) policy, and there is no private lands plantations under the non-carbon (DBUN) policy scenario (Figure 3.6).

Figure 3.9(a) shows that for the juvenile inventory, forestry on public land takes almost 10 periods to reach a steady-state condition with respect to area of poplar plantations in the non-carbon (DBUN) scenario, while it takes longer (about 12 periods) for the with-carbon (DBUC) policy scenario to reach the steady-state condition. In split mature forest with a different pattern than that of the juvenile forest, reaching the steady-state condition takes 10 and 11 periods under the non-carbon (DBUN) and with-carbon (DBUC) policy scenarios respectively (Figure 3.9-b).



(a) Juvenile forest inventory



(b) Split Mature forest inventory

Figure (3.10): Total harvested volume over time on private and public land for (a) juvenile and (b) split mature forest inventory for unconstrained even-flow policy scenarios

3.6. Discussion

Findings of the forest-level model add support to the stand-level analysis of last chapter. The stand-level analysis showed that although the single stem hybrid poplar plantations are financially viable, its benefit is not high due to the high purchase price of private lands combined with the high silvicultural costs and discount factor of 4%. Similarly, in the forest-level analysis, when “hybrid poplar” plantations are permitted on private lands, only a small portion of private lands are allocated to poplar plantations, showing that the opportunity cost of allocating private lands to forestry plantations is high. However, the results showed that hybrid poplar plantations on private lands and maximizing the NPV instead of maximizing the harvested volume can increase the NPV by 20% in the juvenile inventory model, and by 37% in the split mature forest inventory model. For policies where small areas of private lands are planted with poplar, plantations are grown close to the bioethanol production plant due to hauling costs.

Permitting hybrid poplar plantations on public lands results in both higher benefits and more non-harvested land. When the hybrid poplar plantations are permitted on both private and public lands, relative to the baseline scenario, the NPV increases 19%-23% in juvenile and 17-50% in split mature forest inventory. Also, non-harvested land increases from 25% in the baseline scenario to 32%-43% in juvenile and 33% -47% in split mature forest inventories. The analyses of policy alternatives support previous work by Anderson et al. (2012) who discussed: “Our model results suggest that current tenure systems require reforestation efforts that are inconsistent with both profit maximization and the establishment of protected forest areas.” Anderson et al. (2012) also pointed that: “There are also costs associated with policies preventing exotic plantations on public land.” The results of the current study show that permitting hybrid poplar plantations on public land not only increases the economic benefit of the forestry firm, but also leaves more lands not harvested . This result occurs for both juvenile and split mature forest initial inventories, regardless of whether carbon is included in the analysis.

The results also show that accounting for sequestered carbon increases the baseline AAC in the scenarios with flexible even-flow constraints. However, including carbon does not always lead to an increase in the firm`s total NPV, because the inclusion of carbon changes harvest patterns over time. In the with-carbon scenarios, the objective function is to maximize the total NPV which is the sum of the timber and carbon NPVs. For the juvenile forest inventory, adding carbon NPV to the timber NPV in the objective function under with-carbon scenarios results in higher forest values compare with similar non-carbon scenarios in which the objective function is to maximize timber NPV. Although the timber NPV in with-carbon scenarios is less than that in non-carbon scenarios, large positive carbon NPV in the juvenile forests leads to higher total NPV in with-carbon scenarios than that in non-carbon scenarios. For the split mature forest inventory, adding carbon NPV to the timber NPV in the objective function for with-carbon scenarios results in less forest value relative to non-carbon scenarios. In this forest inventory, not only the timber NPV in with-carbon scenarios is less than that in non-carbon scenarios, but also carbon NPV is either small positive or large negative. The results show that for the split mature forest inventory the social cost of not considering carbon in non-carbon scenario is high.

Other interesting results come from comparisons between two forest inventories. The results indicate that split mature inventory has higher AAC (6% in baseline AAC and 62-69% in flexible even-flow scenarios) and higher NPVs (22-50% in all scenarios but the unconstrained AAC scenarios). Also relative to juvenile inventory, the split mature inventory results in more hybrid poplar plantations on private lands and more non-harvested lands on public lands.

Variations in land ownership, initial forest inventory and the constraints for each scenario result in different lengths of time being required to reach a steady-state condition with respect to area of hybrid poplar plantations. When the land is owned privately, the longest time required to reach the steady-state condition is related to the even-flow at the baseline AAC and non-carbon (DPBN) policy scenario for both inventories. These results are repeated when the poplar plantations are allowed on both public and private lands. The longest time required to reach the steady-state condition is related to the even-flow at the baseline AAC and non-carbon (DBBN) policy scenario for both inventories. The reason is that in these scenarios, the AAC is at the baseline AAC level which is less than the flexible AAC in both forest inventories with and without plantations on public lands. Increase in AAC in the policies with flexible or unconstrained even-flow results in higher areas allocated to the plantations and a shorter time to reach the steady state condition. In addition, for both inventories, the with-carbon scenario policies reach the steady-state condition earlier than a similar non-carbon policy scenario due to higher AAC in with-carbon policy scenarios. For instance in the juvenile initial forest, it takes almost 60 years to reach a steady state in the DPBN scenario, while for DPBC, reaching a steady state takes about 20 years.

Chapter 4. Conclusion

This thesis presents two studies related to the financial viability of planting hybrid poplar as a feedstock for bioethanol in the Peace River region of northern Alberta and British Columbia – an area where poplar may be able to financially compete with agricultural land uses.

In the first study (Chapter 2), the stand-level analysis is applied to estimate the financial returns of hybrid poplar for both single-stem and coppice production systems. The findings suggest that the coppice system is financially inferior to the single stem system, largely due to the high establishment costs. The single stem production system could be financially feasible, given the current land prices of $2527/ha, a biomass prices of $50/odt, and a real discount rate of less than 4.6%. However, if bioethanol prices and subsidies remain at or above their current levels, technology of converting cellulosic feedstock's to the bioethanol improves, silvicultural cost of poplar plantations reduces by technology growth, and or yield curves of poplar improves via genetic researches, there is a possibility that hybrid poplar production to produce bioethanol becomes more financially feasible.

In the second study (Chapter 3), public lands are considered due to the fact that under current situation, the opportunity cost of poplar plantations on private lands is high. This study investigates the impacts of different policies on the NPV of a forestry firm in a forest-level analysis. Using a timber supply model based on the timber harvest scheduling model II, a number of policy variables are investigated including varying even-flow conditions, allowing the exotic plantations on public lands and accounting for sequestered carbon. Hybrid poplar plantations in the model are considered as land use and both private and public lands are allocated to different management intensities endogenously for two initial forest inventories.

The baseline model is a presentation of the current situation in the Canadian forest system; no exotic allowed on public lands with even-flow condition to reach sustained yield. The model first considers poplar plantations on private lands with even-flow at the baseline AAC or flexible even-flow conditions. The results show that in this sets of scenarios, only a small part of private lands is planted due to the high opportunity cost of these lands. The model is then run while permits plantations on public lands with various even-flow constraints including set at the baseline AAC, flexible AAC and unconstrained AAC. The results indicate that permitting hybrid poplar plantations on public lands not only results in higher NPVs, but also leads to more non-harvested lands.

This thesis contributes to the understanding the economics of hybrid poplar plantations at both stand and forest-level. The first study differs from past researches basically because I derive the value of land for wood for bioethanol based on values from a value added production chain for bioethanol, rather than assuming a price for feedstock. The second study extends the existing literature on the land use studies at the forest-level, by adding a carbon values to the forest value.

To my best knowledge, it is the first forest-level study that investigates the poplar plantations to produce bioethanol in Canada.

There is substantial room for further research. Short rotation crops are emerging in the forestry industry. Other species of short rotation crops like switch grass could compete with hybrid poplar as a feedstock for bioethanol production. Comparing the economic forest values of poplar plantations with other competitors may shed some lights for policy makers regarding the future development to the bioethanol industry.

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