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Bio-energy from Mountain Pine Beetle Timber and Forest Residuals: The Economics Story

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November 2008

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Bio-energy from Mountain Pine Beetle Timber and Forest Residuals: The Economics Story

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ABSTRACT

In light of the large volumes of pine killed in the Interior forests in British Columbia by the mountain pine beetle, many are keen to employ forest biomass as an energy source. To assess the feasibility of a wood biomass-fired power plant in the BC Interior it is necessary to know both how much physical biomass might be available over the life of a plant, but also its location because transportation costs are likely to be a major operating cost for any facility. To address these issues, we construct a mathematical programming model of fiber flows in the Quesnel Timber Supply Area of BC over a 25-year time horizon. The focus of the model is on minimizing the cost of supplying feedstock throughout space and time. Results indicate that over the life of the project feedstock costs will more than double, increasing from $54.60/BDt ($0.039/kWh) to $116.14/BDt ($0.083/kWh).

Introduction

The outbreak of mountain pine beetle (MPB) (*Dendrocutonus ponderosae* Hopkins) in the forests of central British Columbia (BC) is unprecedented in recorded history. Recent surveys indicate that over 13.5 million ha of forest have been infested, and that by 2015 almost four fifths of the primary host species (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) in BC is projected to be killed (BC Ministry of Forests and Range 2008a). In light of this catastrophic infestation and the associated projected fall down in harvests of timber for traditional forest products, there has been much interest in increasing the utilization of this resource for energy. Indeed, the use of MPB infested timber weighs heavily in the province's bio-energy strategy (BC Ministry of Energy, Mines and Petroleum Resources 2008). Facilitating this strategy, the publicly-owned utility corporation, BC Hydro, issued a call in early 2008 for independent production of electricity from biomass, with the BC Ministry of Forests and Range (MoFR) setting aside an additional 3.88 million m^3 of AAC for new bio-energy tenures (http://www.for.gov.bc.ca/hts/bioenergy/potential_tenure.htm). Anecdotal evidence suggests, however, that this power could be prohibitively expensive, largely due to the cost of procuring the necessary feedstock to operate any facility.[1]

As a result of the bulky nature of woody feedstock and the extensive nature of forestry in the BC interior, one of the most significant and variable factors influencing delivered costs is transportation. Prior studies have not dealt adequately with this issue, because they relied on simple average costs and average haul distances derived from historical data (Kumar et al. 2008; Kumar 2009; Stennes and McBeath 2006). This is problematic for several reasons.

[1] In reference to bio-energy production, a representative from a BC forest company, Canfor, stated: "The economics are not as simple and straightforward as some people think. Everybody presumes that fiber is just readily available in the form that it can be burned. It's there, and we all know it's there, but it takes significant dollars to bring that fiber into a source that will generate electricity." (Retrieved online 9/4/2008 http://www.financialpost.com/story-printer.html?id=721466).

First, historic averages may reflect harvesting activity in areas closer or further away from current and future bio-energy sources. As a result, it is necessary to assess delivered feedstock costs associated with shifting harvesting patterns across space and time. Further, average costs will vary with the quantity required to feed the biomass facility, because, as bio-energy capacity is increased, it will be necessary to source supplies from further distances, thereby significantly increasing costs. Finally, there is a need to consider the different sources of forest biomass (standing timber versus roadside logging residuals) and their characteristics, because they can be significant in determining extraction costs. Again, in this situation, historic averages can be misleading because bio-energy opportunities are expected to be in smaller, lower quality stands that have been overlooked by the lumber sector.

The purpose of the current research is to overcome these potential aggregation biases by explicitly costing the source of forest feedstock across space, quality and time. We do so by constructing a stand-level cost model that considers the yield, characteristics and location of the forest stand. Stands are aggregated to a forest estate (landscape) level that takes into account the spatial locations of stands. Our study region is the Quesnel Timber Supply Area (TSA), which is at the epicenter of the MPB outbreak and the MoFR has identified a significant volume in the TSA for new biomass tenures. In addition, this TSA has a high proportion of pine and therefore a large downfall in commercial timber production can be expected. The Quesnel forest estate model that we develop is used to analyze bio-energy production scenarios and derive feedstock cost flows delivered to a single point (town of Quesnel) over a 25-year planning period.

We proceed in the next section by providing details on the content and parameters of a stand level model, followed by a description of the associated landscape model. The mathematical programming model is then described and three scenarios are examined (maximization of commercial timber volume, even-flow of bio-energy fiber and cost minimization). We conclude with a short discussion of the implications.

Stand Level Characteristics

The primary method of timber extraction in the Quesnel Forest District is whole tree, clear-cutting with conventional 'short-log' roadside harvesting. We assume that log extraction methods continue in the same manner with log production to a 10 cm top. Logs are presumed to be sorted into either sawlogs or bio-energy logs, with the latter having too many MPB-related defects to be used in lumber production.

This logging system employs the phases and associated equipment described in Table 1. Standard engineering costing techniques are employed to derive hourly equipment costs.[2] These rates are also summarized in Table 1, assuming a diesel fuel price of $1.25/litre and include wages for equipment operators.

Table 1: Machine rates by phase given fuel price of $1.25/litre

Description of phase	Equipment type	Hourly cost ($/hr)
Falling	Feller Buncher	$ 160.04
Skidding	Grapple Skidder	$ 112.76
Processing	Dangle-head processor	$ 136.27
Loading	'Butt n' top' loader	$ 140.41
Hauling	Super B train	$ 147.97

To derive the unit costs of logging ($\$/m^3$), productivity information is needed. While productivity in each phase depends on many characteristics, the stand's volume per tree (VPT) tends to explain most of the variation in logging productivity (Dyson and McMorland

[2] Cost information was provided from a survey of logging contractors operating in the BC Interior. Details are available from the authors upon request.

2008). Using information from Dyson and McMorland (2008), logging rates ($\$/m^3$) were developed for a range of tree sizes. These rates are summarized in Figure 1, and include allowances for road building ($\$1.46/m^3$) and road use and maintenance ($\$1.76/m^3$) that are based on district averages (http://ww.for.gov.bc.ca/hts/bioenergy/index.htm).

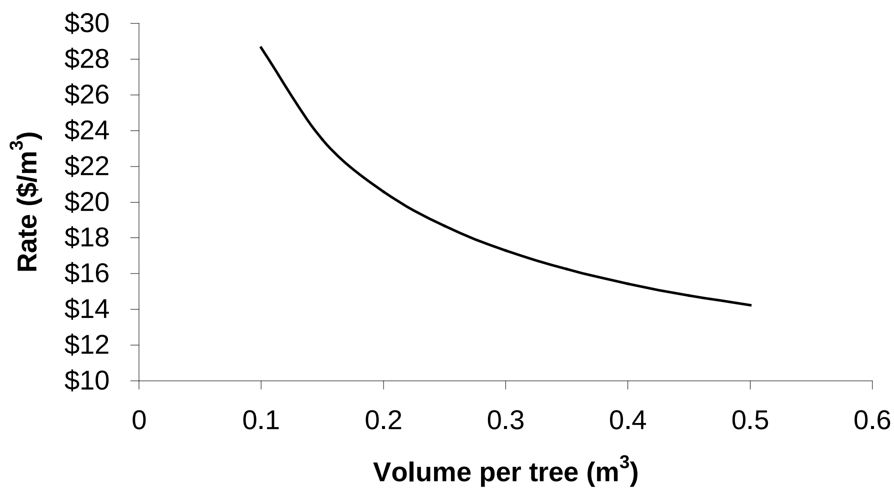

Figure 1: Logging rates ($\$/m^3$) by volume per tree.

Notice how costs rise rapidly once stands fall below a threshold of about 0.2 m^3/tree (Figure 1). This is indicative of mature, fire origin stands in the Western portion of the Quesnel TSA, where growing seasons are short and moisture is limited because of the rain-shadow effect from the Coastal Mountains. Further characterizing this operating area is its long distance from extant processing centers, making hauling costs a crucial consideration in feedstock supply. Based on a diesel price of $1.25/litre, we calculated a trucking rate for a short-log configuration of $147.97 per hour (wages for driver included). Assuming a payload of 42 tonnes (t) and a historical conversion of 0.7 t/m^3, the trucking rate is $\$2.22/m^3$ per hour.

Another potential source of biomass supply is roadside residuals left after logs are extracted. Field measurements of roadside residual volumes show a range of 14 to 55 percent, although experience by local companies is in the lower end of the range (McDonald 2006). We assume the same residual volume as Kumar et al. (2008), which is twenty percent of the stand's gross volume (25% of the net volume). We also assume that development, felling, skidding and processing costs are 'sunk' and covered by the logging rate. Therefore, only incremental costs are assigned to this fiber supply, namely, the costs of roadside chipping, loading and trucking them to the mill (electricity generating facility). Since roadside chipping is rare in British Columbia, cost and productivity information for this activity are sparse. Chipping and loading data have been estimated by McDonald (2006) for three residual density classes (light, medium, heavy). We assume that this chipped material is trucked to the bio-energy facility with a B train chip van (payload of 21.5 bone-dry tones, or BDt). Using a trucking rate of $116/hr (McDonald 2006), the unit rate for this phase is $5.40/BDt per hour, which is almost identical to the log hauling rate on a $\$/m^3$ per hour basis (assuming 2.44 m^3/BDt).

Landscape Level Characteristics

Forest stands are heterogeneous in space and time, while bio-energy facilities have potentially long payback periods. Thus, a stand level model is unable to assess the feasibility of bio-energy production because spatial and time dimensions are generally ignored. In this section, we investigate the expected overall cost of delivering feedstock to Quesnel by aggregating costs across a wide variety of spatially dispersed stands over a 25-year planning horizon, with a five-year time step.

Forest inventory data (BC Vegetation Resource Inventory) for the Quesnel TSA was retrieved from the MoFR. This area was netted down for parks, old-growth management and other inoperable areas, leaving a land base of 921,527 ha for timber harvesting that consists of

236,171 stands (polygons). To avoid the curse of dimensionality, stands were aggregated into types and broken down into age classes (ages 0 to 140+ divided into 5-year increments). Stand types are distinguished by biogeoclimatic zone, species class, and cycle time zone. The categories associated with each of these types are summarized in Table 2, while the relevant GIS maps are found in Appendix A.

Table 2: Quesnel TSA stand types

Type	Category
Biogeoclimatic Zone	ESSF – Englemenn spruce, sub-alpine fir
	ICH – Interior cedar hemlock
	IDF – Interior Douglas fir
	MS – Montane spruce
	SBPS – Sub-boreal pine spruce
	SBS – Sub-boreal spruce
Species group	Pine1 – stands with >70 % pine
	Pine2 – stands with 40 to 70% pine
	Other – stands with less than 40% pine
Cycle time zone	0-3 – stands between 0 to 3 hours from Quesnel
	3-5 – stands between 3 to 5 hours from Quesnel
	5-7 – stands between 5 to 7 hours from Quesnel
	7+ - stands greater than 7 hours from Quesnel

Logging operations were restricted to Pine1 stands more than sixty years old and Pine2 stands more than 80 years old that are located in the timber harvest land base. All stands are assumed to be infested by the MPB. Therefore, we make total yield and the proportion of sawlogs in the stand time dependent, anticipating the effects that the infestation will have on stand merchantability over time. These merchantability factors vary according to biogeoclimatic zone and species group, reflecting the different decay rates for MPB-infected timber affected by varying climatic conditions and the amount of pine in the stand (see Appendix Tables B1 and B2).

The inventory data contain information on a stand's log volume per hectare (VPH) but not volume per tree (VPT). This is somewhat problematic given that extraction cost estimates rely on VPT. To get around this, timber cruise information for 812 past cutting permits in the BC central Interior are used to estimate the following relation between VPH and VPT:

$$\text{VPH} = \underset{(6.33)}{467.60} + \underset{(8.22)}{173.15}\ \ln(\text{VPT}) \qquad R^2 = 0.48,\ n = 812 \tag{1}$$

where standard errors of the estimated parameters are provided in parentheses. Using this relation and that in Figure 1, we derive logging costs by biogeoclimatic zone and age class corresponding to their VPH (and provided in Table B3).

For the cost of processing roadside residuals, we assume that stands with a VPH less than 150 m^3 fall into McDonald's (2006) light density category, stands between 150 m^3 and 250 m^3 per ha are medium density, and stands with more than 250 m^3/ha are high density (Table B4). Hauling costs, on the other hand, are solely a function of truck cycle times, representing the cost ($/$m^3$) of the mid-point cycle time for the zone and the stand-level trucking costs derived earlier (Table B5). Further, for all the bio-energy logs, an allowance of $8/BDt is made for whole log chipping/grinding at the bio-energy facility (Stennes and McBeath 2006). Finally, silviculture costs per hectare vary by biogeoclimatic zone (Table B6), while development and administration costs are set at $8/$m^3$ for all stand types.

Bio-energy Forest Management Model

Let x_{sazct} denote the hectares of timber species *s* of age *a* in biogeoclimatic zone *z* with truck cycle time *c* that are harvested in period *t*. Let v_{sazct} be the associated total merchantable volume (m^3/ha) of the stand in time *t* that is composed of log volume $v_{sazct}^{\log}$ and roadside residual volume v_{sazct}^{res}. Log volume is composed of sawlogs v_{sazct}^{saw} and bio-energy logs v_{sazct}^{bio}.

Let p_{sazct} be the proportion of the stand's initial volume (v_{sazc0}) that is merchantable in period t=0, s_{sazct} the proportion of the stand's merchantable volume that is sawlog, and r_{sazct} the proportion of the stand's volume that are roadside residuals (20%). Define outputs as follows:

(2) $$H_t = \sum_{s \in S} \sum_{a \in A} \sum_{z \in Z} \sum_{c \in C} p_{sazct} v_{sazc0} x_{sazct}$$ total harvest in period t.

(3) $$SLH_t = \sum_{s \in S} \sum_{a \in A} \sum_{z \in Z} \sum_{c \in C} s_{sazct} v_{sazct}^{\log} x_{sazct}$$ sawlog harvest in period t.

(4) $$BLH_t = \sum_{s \in S} \sum_{a \in A} \sum_{z \in Z} \sum_{c \in C} (1 - s_{sazct}) v_{sazct}^{\log} x_{sazct}$$ bio-energy log harvest in period t.

(5) $RH_t = rH_t$ roadside residual harvest in period t.

(6) $BH_t = BLH_t + RH_t$ total bio-energy harvest in period t.

where S is the set of species groups, A the set of age classes, Z the set of biogeoclimatic zones, and C the set of cycle time zones.

Now let total costs (C_t) in period t be given by:

(7) $$C_t = C_t^{\log} + C_t^{res} + C_t^{haul} + C_t^{silv} + C_t^{adm}$$

where $$C_t^{\log} = \sum_{s \in S} \sum_{a \in A} \sum_{z \in Z} \sum_{c \in C} c_{sazct}^{\log} v_{sazct}^{\log} x_{sazct}$$ total logging costs in period t

$$C_t^{res} = \sum_{s \in S} \sum_{a \in A} \sum_{z \in Z} \sum_{c \in C} c_{sazct}^{res} v_{sazct}^{res} x_{sazct}$$ total roadside residual chipping costs in period t

$$C_t^{haul} = \sum_{s \in S} \sum_{a \in A} \sum_{z \in Z} \sum_{c \in C} c_{sazct}^{haul} v_{sazct} x_{sazct}$$ total hauling costs in period t

$$C_t^{silv} = \sum_{s \in S} \sum_{a \in A} \sum_{z \in Z} \sum_{c \in C} c_{sazct}^{silv} x_{sazct}$$ total silviculture costs in period t

$$C_t^{adm} = \sum_{s \in S} \sum_{a \in A} \sum_{z \in Z} \sum_{c \in C} c_{sazct}^{adm} v_{sazct}^{\log} x_{sazct}$$ total administration costs in period t

with $c_{sazct}^{\log}$ = logging costs per m^3 for stand described by *s*, *a*, *z*, *c*

c_{sazct}^{res} = roadside residual costs per m^3 for stand described by *s*, *a*, *z*, *c*

c_{sazct}^{haul} = hauling costs per m^3 for stand described by *s*, *a*, *z*, *c*

c_{sazct}^{silv} = silviculture costs per ha for stand described by *s*, *a*, *z*, *c*

c_{sazct}^{adm} = administration and development costs per m^3 for stand described by *s*, *a*, *z*, *c*.

All modeling was conducted with Woodstock (Remsoft Inc. 2006) and utilized the MOSEK solver (Andersen and Andersen 2000).

Bio-energy production scenarios

Maximization of total commercial volume

Our first scenario aims to liquidate the operable Pine1 and Pine2 stands over the planning horizon. This is done by setting the objective of the model as maximizing the sum of sawlog and bio-energy feedstock volumes (i.e., merchantable harvest) subject to an even flow of harvesting constraint, but not necessarily even flow of bio-energy biomass (which is considered in the next scenario). The even flow constraint is meant to meet government employment and community stability targets, although its relaxation often leads to much higher net revenues (Hof 1993). Formally, the management model is given as:

(8) $$\max_{x_{sazct}} \sum_{t=1}^{T} H_t$$

Subject to:

(9) $$\sum_{t=1}^{T} x_{sazct} \leq \overline{X},\ \forall s,a,z,c$$ (total area constraint)

(10) $$H_t = H_{t+1},\ \forall t$$ (even flow of harvest constraint)

(11) $x_{sabct} \geq 0\,,\ \forall s,a,z,c,t$ (non-negativity)

plus relations (2)–(6) and x^{0}_{sazc} given – the hectares of stand type *s*, *a*, *z*, *c* present in the initial period.

The harvest, sawlog and bio-energy feedstock flows determined from the optimization model are found in Figure 2, while the associated expected weighted average costs (bio-energy log costs and roadside residual costs) are found in Figure 3.

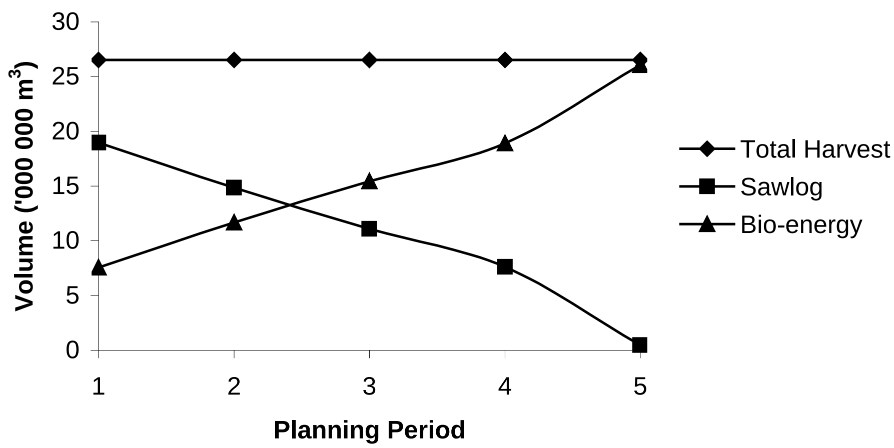

Figure 2: Maximum harvest flows (m^3) per period (5 year) under volume maximization

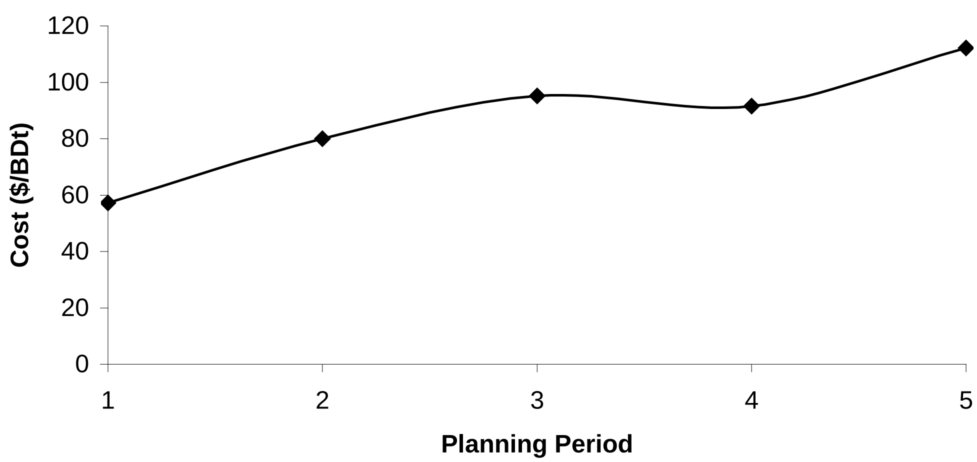

Figure 3: Average delivered bio-energy feedstock costs ($/BDt) under volume maximization

In this scenario, a harvest of about 26.5 million m^3 per five years (5.3 million m^3 per year) can be sustained throughout the planning horizon. However, the composition of the harvest changes significantly over time, with sawlog production taking a backseat to bio-energy feedstock production in period 3 and falling virtually to nothing in period 5. Further, average delivered bio-energy feedstock costs increase significantly from $57.24/BDt in the first period to $112.16/BDt in the final period. If we assume that 1 BDt of biomass feedstock can generate 1398 kWh of electricity (Stennes and McBeath 2006), the feedstock costs of producing electricity alone cost $0.041 per kWh in the early periods, but this rises to $0.080/kWh in the latter years of the planning horizon as more distant stands need to be accessed. To these costs must be added the costs of building, operating and maintaining a biomass generating facility.

Even Flow of Bio-energy Feedstock

The biggest drawback associated with volume maximization is the volatility of the feedstock supply, despite the imposition of an even-flow of harvest constraint. In Figure 2, the supply of bio-energy fiber increases over the planning horizon, which would then be subject to a steep decline once pine is liquidated. Given the capital intensive nature of many bio-energy facilities and that biomass-fired generators function best if they do not ramp up and down too frequently, remaining near their optimal generating capacity, a steady flow of fiber will be required. Pellet plants with a shorter payback period and greater mobility might be an exception. To meet this requirement, the even-harvest flow requirement of the volume maximization scenario (10) is replaced with the following constraint:

(12) $BH_t = BH_{t+1},\ \forall t$ (bio-energy fiber flow constraints)

Harvest flows for this scenario are provided in Figure 4, and the associated expected delivered costs are shown in Figure 5.

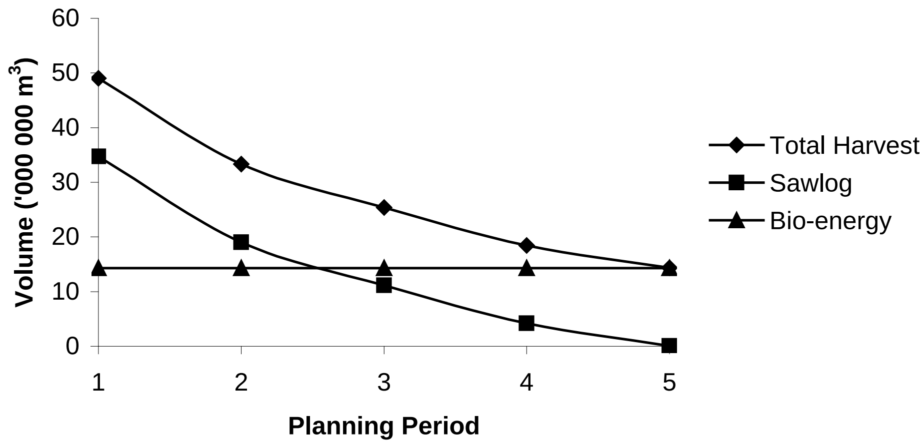

Figure 4: Maximum harvest with even bio-energy flow.

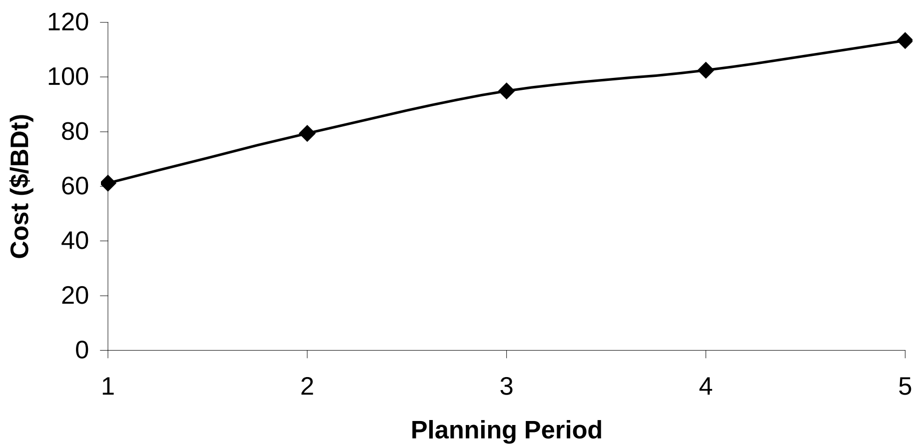

Figure 5: Average delivered bio-energy feedstock costs ($/BDt)

In this scenario, an even flow of 14.3 million m^3 of biomass for energy is available in each five-year period (2.86 million m^3 annually). Once again, the costs of delivering this material increase significantly through time from $61.12/BDt ($0.044/kWh) in the first period to \$113.31/BDt (\$0.081/kWh) in the final period. Furthermore, sawlog production is significantly higher than under volume maximization in the first period, but it decays more rapidly over time.

Cost Minimization

The previous scenarios maximized volume subject to various constraints, with the costs of meeting a biomass energy target as a secondary output of the model. Delivered bio-energy feedstock costs can be lowered if operators are given sufficient flexibility to meet a given volume target. Furthermore, the previous scenarios assumed bio-energy production could begin immediately. In reality, for a large bio-energy facility, it may take upwards of five years for the necessary environmental planning and construction before production can begin. To allow for this in this scenario, the objective is to minimize the discounted cost (discount rate i = 5%) of producing the current AAC (5.28 million m^3 log volume) in the first period and an annual flow of 2.8 million m^3 of bio-energy feedstock throughout the rest of the planning horizon (as determined from the previous optimization). The cost minimization model is as follows:

(13) $$\min_{x_{sazct}} \sum_{t=1}^{T} \frac{C_t}{(1+i)^t}$$

Subject to:

(14) BH_t = 14 million m^3, t = 2, 3, 4, 5 (Biomass for energy harvest target)

(15) $\sum_{s\in S}\sum_{a\in A}\sum_{z\in Z}\sum_{c\in C} v_{sazct}^{\log} x_{sazct}$ = 26.4 million m^3, t = 1 (Current AAC target)

and equations (2)–(7), (9) and (11), and x^0_{sazc} given. For this scenario, Figure 6 illustrates that expected delivered average costs increase throughout the planning horizon from \$54.60/BDt

($0.039/kWh) to $116.14/BDt ($0.083/kWh), while the marginal costs for period 2 are provided in Figure 7. The spatial pattern of harvesting for this scenario is provided in Appendix C.

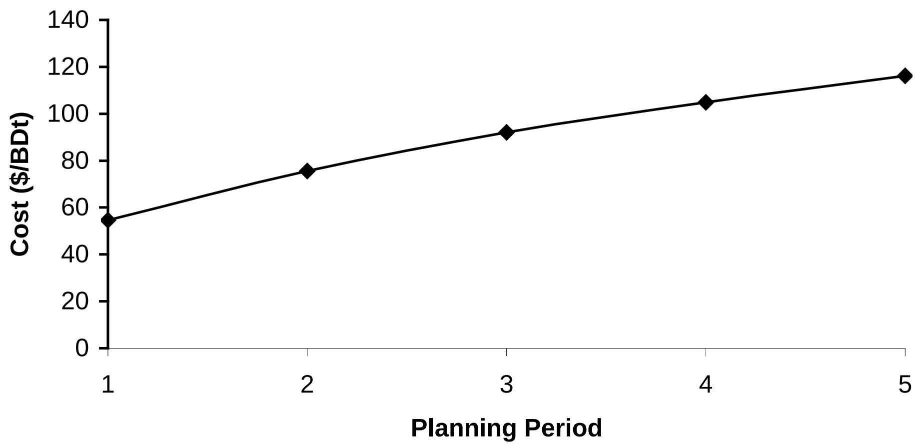

Figure 6: Average delivered bio-energy costs ($/BDt) under cost minimization

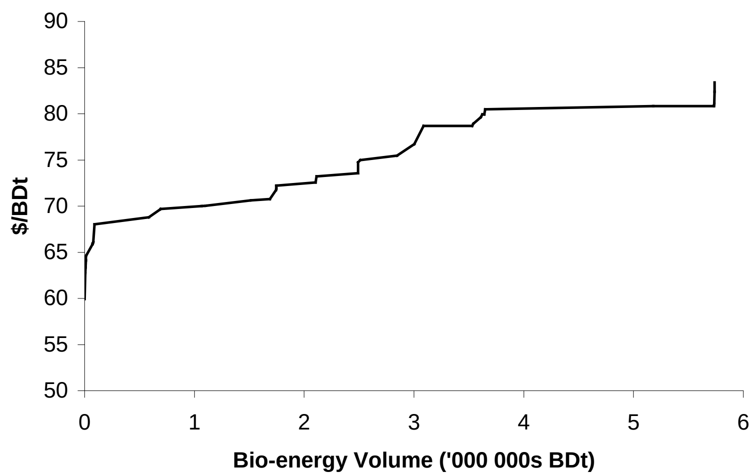

Figure 7: Marginal delivered bio-energy costs ($/BDt) in period 2

Discussion

While earlier studies neglected spatial and temporal considerations in bio-energy feasibility studies, these turn out to be crucial in evaluating the feasibility of biomass feedstock derived from forests. Our results indicate that, in the context of feedstock derived from stands infested by the MPB, average delivered feedstock costs can be expected to increase significantly over the life of a generating facility. Although costs could be stabilized temporally by spreading production equally across different stand locations and qualities, such a strategy will increase the already high discounted costs of producing feedstock for energy production. Power producers require the flexibility to source the cheapest feedstock throughout time; for example, tailoring extraction methods to the proportion of bio-energy volume in the stand could also reduce costs (McDonald 2006). This was not considered in the analysis and could slightly flatten the cost curves in Figures 3, 5 and 6.

The results from the Quesnel TSA are somewhat unique due to the very high proportion of MPB-killed pine. Part of the reason for the high costs in later periods is due to the falling proportion of roadside residuals in the mix, as well as having to move further afield. If the bio-energy facility is located near a large forest products manufacturing centre, there may well be a supply of low-cost mill residuals as well. Indeed, in a different TSA a higher proportion of non-affected timber and proximity to processing residuals could serve to flatten the cost curve of woody feedstock to a bio-energy facility.

Ultimately, the creation of new energy capacity in BC from biomass will depend on what BC Hydro is willing to pay for 'green' power. In the absence of carbon subsidies for clean energy, the market prices of electricity should be a guide. In our models, we simply assumed that wood biomass would be available to produce electricity, and on this basis our analysis suggests that a power plant with a capacity of about 187 MW could be supported. However, given that costs of feedstock alone are estimated to rise from \$0.044/kWh in the first period to \$0.081/kWh in the final period, and even more so in periods beyond when the power facility will need to compete with other claimants on the forest resource (sawmills, pulp mills), substantial subsidies might be required to encourage construction of a biomass-fired power plant.

A major justification for subsidies is the claim that bio-energy production is carbon neutral (Kumar et al. 2008). However, a biomass generator will emit CO2 just as any other fossil fuel burning facility. It is only when trees are planted and growing, thereby sequestering carbon from the atmosphere, that CO_2 offset credits are earned, and these must be used to offset the debits from the biomass burning facility. By permitting bio-energy production to claim a credit or exemption up front implies that, implicitly, physical carbon does not get discounted – that it makes no difference when CO_2 emissions are reduced, now or eighty years from now. If carbon was properly priced, carbon taxes would occur at the time of harvesting and carbon subsidies would accrue each year according to the growth of the stand (van Kooten et al. 1995). Given that salvaging MPB will result in harvest levels that are dramatically greater than growth levels, this suggests that bio-energy production would be a significant net carbon liability rather than a benefit. Bio-energy proponents may argue that the decay of MPB stands leads to significant carbon emissions anyway and that a prudent strategy is to salvage stands as quickly as possible to get stands growing again (Kurz et al. 2008). But recent research has also shown that in most cases advanced understory regeneration in MPB infested stands is abundant (Nigh et al. 2008). In order to establish an accurate baseline, research on the expected growth of this advanced regeneration is needed. Once this is done, the additional carbon costs and benefits associated with bio-energy projects can be properly assessed.

Finally, another benefit of bio-energy production that is used to justify subsidies is the mitigation of forest sector job losses in regions heavily dependent on the forest industry. For instance, 45 percent of the income generated in the Quesnel forest district is attributed to the forest sector (BC MoFR 2008b). Although bio-energy production may offset job losses or lead to positive employment benefits for the local economy, it is important to understand that the costs of providing such regional socio-economic benefits might be distorting. From the standpoint of the provincial economy, wages and capital expenditures in bio-energy production should be treated as costs rather than benefits, and the opportunity cost of supporting jobs in one region might well be higher job losses elsewhere in the economy (see Stabler et al. 1988).

Acknowledgements: Research support from the British Columbia Ministry of Forests and Range, and from the Social Sciences and Humanities Council of Canada (SSHRC Grant 410-2006-007), is greatly appreciated. However, the views expressed in the paper do not necessarily reflect those of the BC Government or Government of Canada.

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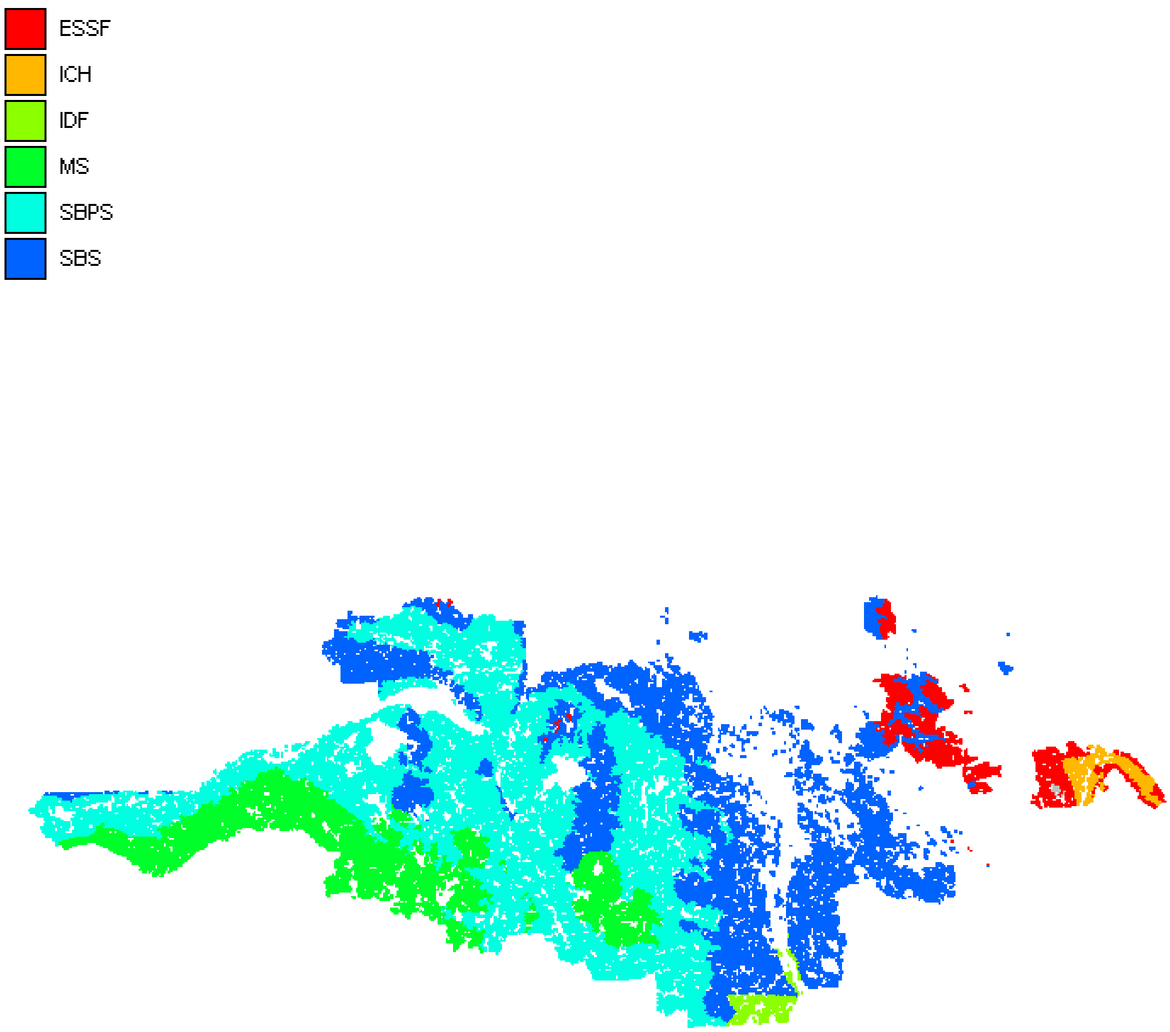
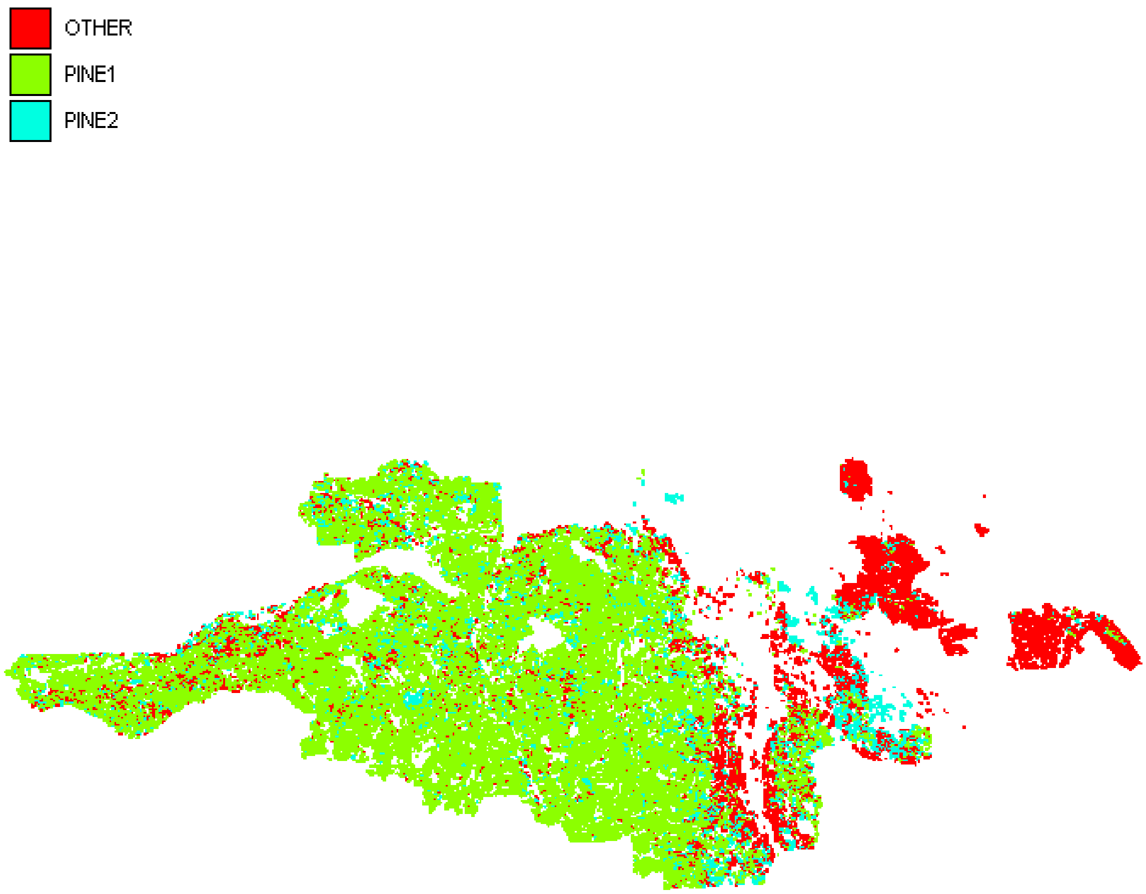
Appendix A: Stand Types in the Quesnel Forest District

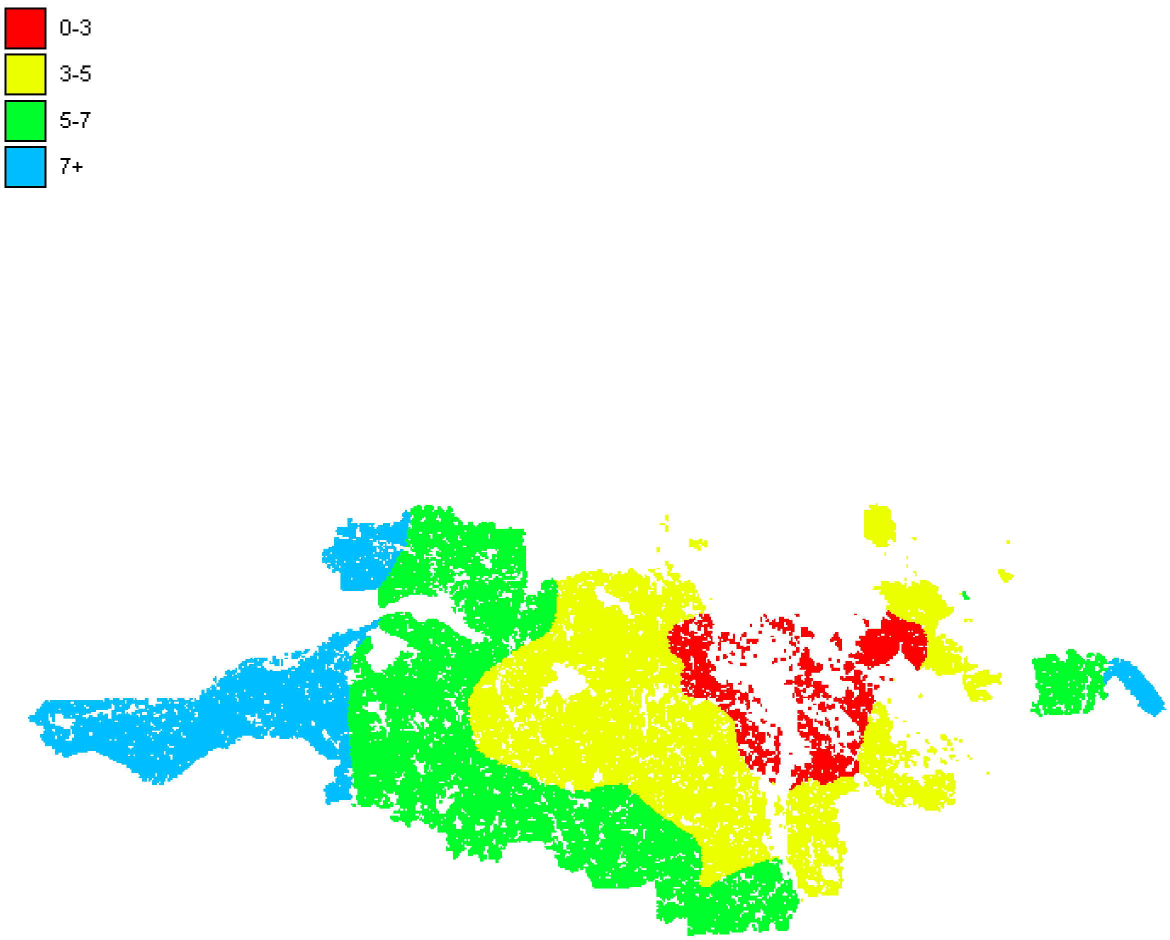
BEC zones in Quesnel Forest District



SPECIES groups in Quesnel Forest District



Cycle time zones in Quesnel District



Appendix B: Summary of Landscape Level Model Parameters

Table B1: MPB caused decay in merchantable proportion over planning horizon

		Planning Period				
BEC	**SPECIES**	**1**	**2**	**3**	**4**	**5**
ESSF	Pine1	1	0.85	0.7	0.5	0.3
	Pine2	1	0.9	0.8	0.65	0.5
ICH	Pine1	1	0.8	0.6	0.4	0.3
	Pine2	1	0.9	0.8	0.65	0.5
IDF	Pine1	1	0.9	0.75	0.55	0.4
	Pine2	1	0.95	0.8	0.75	0.6
MS	Pine1	1	0.95	0.9	0.8	0.7
	Pine2	1	1	0.95	0.85	0.8
SBPS	Pine1	1	0.95	0.8	0.7	0.6
	Pine2	1	1	0.95	0.85	0.7
SBS	Pine1	1	0.9	0.7	0.55	0.4
	Pine2	1	0.95	0.8	0.75	0.6

Table B2: MPB caused decay in sawlog proportion over planning horizon

		Planning Period				
BEC	**SPECIES**	**1**	**2**	**3**	**4**	**5**
ESSF	Pine1	0.85	0.7	0.5	0.2	0.0
	Pine2	0.85	0.8	0.7	0.5	0.4
ICH	Pine1	0.85	0.7	0.5	0.2	0.0
	Pine2	0.85	0.8	0.7	0.5	0.4
IDF	Pine1	0.9	0.7	0.5	0.2	0.0
	Pine2	0.9	0.8	0.65	0.5	0.4
MS	Pine1	0.85	0.7	0.5	0.2	0.0
	Pine2	0.9	0.8	0.65	0.5	0.4
SBPS	Pine1	0.85	0.7	0.5	0.2	0.0
	Pine2	0.9	0.8	0.65	0.5	0.4
SBS	Pine1	0.9	0.7	0.5	0.2	0.0
	Pine2	0.9	0.8	0.65	0.5	0.4

Table B3: Logging rates per m^3

	Biogeoclimatic zone					
Age	ESSF	ICH	IDF	MS	SBPS	SBS
60-64	$ 27.30	$ 22.16	$ 26.16	$ 30.20	$ 27.30	$ 24.28
65-69	$ 24.28	$ 20.58	$ 25.16	$ 30.20	$ 26.16	$ 23.50
70-74	$ 23.50	$ 20.14	$ 23.50	$ 26.30	$ 25.16	$ 22.80
75-79	$ 23.50	$ 20.14	$ 23.50	$ 26.30	$ 25.16	$ 22.16
80-84	$ 21.59	$ 18.99	$ 22.80	$ 27.30	$ 24.28	$ 21.59
85-89	$ 19.73	$ 17.53	$ 22.16	$ 26.16	$ 22.80	$ 20.58
90-94	$ 19.35	$ 16.64	$ 21.59	$ 26.16	$ 22.80	$ 19.73
95-99	$ 18.66	$ 16.25	$ 20.58	$ 25.16	$ 21.59	$ 18.66
100-104	$ 18.66	$ 15.74	$ 19.35	$ 24.28	$ 20.58	$ 17.79
105-109	$ 17.79	$ 15.30	$ 18.66	$ 23.50	$ 20.14	$ 17.29
110-114	$ 17.53	$ 14.90	$ 17.79	$ 22.80	$ 20.14	$ 16.84
115-119	$ 17.06	$ 14.66	$ 17.06	$ 22.16	$ 19.35	$ 16.25
120-124	$ 16.64	$ 14.44	$ 16.64	$ 21.59	$ 18.66	$ 15.74
125-129	$ 16.44	$ 14.33	$ 16.25	$ 20.58	$ 18.35	$ 15.30
130-134	$ 16.08	$ 14.04	$ 16.08	$ 19.73	$ 17.53	$ 14.90
135-139	$ 15.74	$ 13.86	$ 15.74	$ 19.35	$ 17.06	$ 14.78
140+	$ 15.74	$ 13.86	$ 15.74	$ 19.35	$ 17.06	$ 14.78

Table B4: Roadside residual chipping costs per BDt

VPH (m^3)	Cost ($/BDt)
<150	$ 21.56
150 to 250	$ 17.25
>250	$ 14.28

Table B5: Hauling Costs per m^3

Cycle time (hrs)	Cost ($/m^3)
0 to 3	$ 4.44
3 to 5	$ 8.88
5 to 7	$ 13.32
7+	$ 17.76

Table B6: Silviculture costs per ha by biogeoclimatic zone

ESSF	ICH	IDF	MS	SBPS	SBS
$ 1,605	$ 1,522	$ 1,007	$ 880	$ 778	$ 1,122

Appendix C: Spatial Harvest Pattern by Period for Cost Minimization Scenario