TECHNICAL REPORT 124

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2019

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ISBN 978-0-7726-7323-7 – Print version
ISBN 978-0-7726-7324-4 – Digital version

Citation

de Montigny, L., P. Asante, S. Le Noble, and G. Nigh. 2019. The economic implications of pre-commercial thinning treatments in mixed western hemlock and amabilis fir stands in coastal British Columbia under varying cost and benefit assumptions and minimum harvest criteria (EP1211). Prov. B.C., Victoria, B.C. Tech. Rep. 124. www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr124.htm

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Victoria, BC V8W 9V7
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ABSTRACT

To meet the goal of economically valuable timber volume flow over time, silviculture programs apply silviculture treatments such as pre-commercial thinning (PCT) to concentrate growth on higher-value tree species and shorten the time to reach harvestable age. A study was established to examine growth and yield of a range of PCT treatments in a mixed western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and amabilis fir (*Abies amabilis* Dougl. ex Forbes) stand that had regenerated naturally, and at 18 years was characteristically clumpy with density ranging from 0 to 80 000 stems per hectare (sph). Using the results from the 15-year post-treatment measurement, future growth and yield of each PCT treatment was projected, and a financial analysis was conducted to compare the costs and benefits of PCT or no treatment. As expected, the results of the financial analysis showed that the site values increased for all the PCT treatments and the control under the scenarios with lower discount rate, lower harvesting costs, and higher log prices. Minimum harvest criteria that reduced harvest age reduced merchantable volumes and site value. In general, of the PCT treatments, the denser 1200 sph treatment provided the best merchantable volume and site value. This information can assist in decision-making regarding best treatments needed to achieve stand-level objectives. Continued monitoring of this experiment over time will provide better information about the longer-term effects on growth, yield, and economic returns of PCT in these mixed western hemlock and amabilis fir stands.

ACKNOWLEDGEMENTS

We thank the following staff of the British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development for their assistance in making this project possible: Dave Goldie for his dedication to the continued measurement and maintenance of the Managed Stand Field Experiments Program; Peter Ott for statistical advice; and Jeff Stone, Atmo Prasad, Mario Di Lucca, and Lorne Bedford for manuscript reviews. Thanks also to Tracey Hooper for the comprehensive English edit and to Dave McEwan (Ministry of Environment) for assistance in the preparation of this technical report. This research was supported by the Research Program of the British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development.

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In British Columbia, sustainable management has been defined as management that maintains and enhances the long-term health of forest ecosystems for the benefit of all living things, while providing environmental, economic, social, and cultural opportunities for present and future forest conditions of British Columbia's provincial forests (B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development 2017). A provincial goal is to "promote resilient and diverse forest ecosystems to provide a sustainable flow of economically valuable timber that generates public revenue, and supports robust communities and healthy economies for a vigorous, efficient and world-competitive timber processing industry" (B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development 2017). The British Columbia government determines the supply of timber through a timber supply review that considers the size of the timber harvesting land base, current and forecasted forest inventories, and important environmental, social, and economic factors.

To meet the provincial goal of achieving economically valuable timber volume flow over time, government-funded silviculture programs, such as Forests for Tomorrow, conduct silviculture activities, including pre-commercial thinning (PCT) treatments (also called "juvenile spacing," "spacing," and "juvenile thinning"). The Forests for Tomorrow program makes investments in PCT treatments to make stands merchantable sooner to address forest-level mid-term timber supply gaps or age class imbalance and to prepare stands for future treatments (e.g., fertilization, commercial thinning). Treatments may also provide other benefits in terms of long-term fuel reduction, wildlife habitat, managing tree species composition, and risk reduction from damaging agents (e.g., disease, insects, wind storms, snowpress).[1] Since 2010, Forests for Tomorrow has completed PCT treatments on more than 10 300 ha of dense stands across the province.

In coastal British Columbia, dense stands of mixed western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and amabilis fir (*Abies amabilis* Dougl. ex Forbes) dominate almost 1 million hectares of forest land (B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development 2018). After clearcut harvesting, natural regeneration results in dense stands of mixed western hemlock and amabilis fir that are characteristically clumpy (Klinka et al. 1992), with density ranging from 0 to 80 000 stems per hectare (sph) (de Montigny et al. 2018).

Western hemlock stands have been found to respond to PCT in a manner similar to other species; that is, as spacing between trees increases, total stand volume and basal area decrease, while mean stand diameter and crop tree volume and basal area increase (Griffith 1959; Hoyer and Swanzy 1986; Curtis 2008, 2013; Newton and Cole 2012; Reynolds and de Montigny 2015; de Montigny et al. 2018). Studies to determine the optimum post-thinning density in coastal western hemlock stands have resulted in recommended densities that vary greatly from as low as 740 sph (Dilworth 1980) to 1600 sph in mixed

1 B.C. Ministry of Forests, Lands and Natural Resource Operations. 2017. Backgrounder on the Forests for Tomorrow review of juvenile spacing investments. Resource Practices Branch, Forests for Tomorrow. www2.gov.bc.ca/assets/gov/environment/natural-resource-stewardship/land-based-investment/forests-for-tomorrow/timber-supply-mitigation/9fft_silviculture_note_js_sept_final_sept_25.pdf.

western hemlock and Sitka spruce (*Picea sitchensis*) stands with fertilization (Reynolds and de Montigny 2015). This wide range of recommended post-thinning densities depends in part on the management objectives for the stand but also indicates that decisions about treating these stands are complex and depend on many factors.

Despite the expected benefits of PCT, this early stand treatment is expensive (Can$1400, 2016 dollars), which suggests that low returns on investment may not justify the use of PCT in these stands. Economists suggest that monetary measures of costs and benefits are necessary and appropriate for evaluating any forestry investment, including intensive silviculture (Faustmann 1849; Pearse 1967; Samuleson 1976; McKenney 2000), and most recommend conducting a cost-benefit analysis to determine the relative efficiency of proposed treatments. Cost-benefit analysis of PCT usually concludes that juvenile spacing treatments are expensive and will provide a positive return on investment only for faster-growing, high-value species on productive sites and with short rotations. However, Reynolds and de Montigny (2015) found that moderate PCT of mixed western hemlock and Sitka spruce stands, in combination with fertilizer application, was projected to provide a positive net present value (NPV) and earlier harvest entry under specific minimum harvest criteria that favoured the tree sizes and volumes resulting from PCT. This indicates that more work should be done to determine if there are situations where PCT can add value while meeting management objectives for mixed hemlock stands.

There are a number of key elements for conducting a cost-benefit analysis of intensive silviculture treatments. Estimating changes in growth and yield due to intensive silviculture is important because of the long period from treatment application to harvest age. Yield forecasts are required to evaluate the potential yield of different treatment options and are typically obtained from stand growth models that have been calibrated using long-term response data from well-designed experiments. The choice of "discount" rate is also important in cost-benefit analysis because silviculture treatments require a relatively long period to achieve their outcomes, and this represents real opportunity costs; the choice of discount rate is therefore important for weighing the opportunity costs against the benefits of activities that occur through time (Heaps and Pratt 1989). Assumptions about silvicultural treatment costs, harvesting costs, and future market values will also affect the cost-benefit analysis outcomes; consequently, inputs require as much accuracy as possible. Given future uncertainty in any of these factors, sensitivity analyses can be used to examine the risks to outcomes of increases or decreases in the input assumption.

Harvest age is another important consideration of cost-benefit analysis. The question of what is the best age at which forests should be harvested is among the oldest problems in forestry, debated for more than 150 years (Faustmann 1849; Pearse 1967; Samuelson 1976; McKenney 2000), and is one of the most important (Pearse 1967). Timber supply management objectives vary for different forest estate owners, as can the choice of harvest age to meet those management objectives. The choice of optimum rotation age can be determined in different ways, such as biologically, based on timber volume (maximizing culmination of mean annual increment [MAI]), or economically, based on timber value (maximizing the NPV or site value [SV]), or by a combination of economic, environmental, and political considerations of the landowner (Curtis

1995). For example, rather than for timber objectives, the optimal age may be when stand attributes have reached a point required for environmental considerations, such as snow interception in an ungulate winter range; or for social considerations, such as to meet the wood flow required to sustain local mills and economies; or for safety, such as to protect private or public infrastructure from fire.

In British Columbia, harvest age criteria are expressed as minimum harvest criteria (MHC). They are used to set the stand development conditions that must be met in order for stands to be eligible for harvesting and to prevent the harvesting of young stands without consideration of the future. These MHC are used in timber supply analyses that are conducted at least once every 10 years for each of British Columbia's 37 Timber Supply Areas (TSAs) and 34 Tree Farm Licences (TFLs). The MHC are generally based on current practices observed in the TSA or TFL at the time of modelling. Minimum harvest criteria are most often based on minimum age, minimum volume of wood per hectare, minimum average stand diameter, or culmination of mean annual increment. However, there is no legal obligation to follow the MHC assumptions in the timber supply analysis, and there are no restrictions specific to harvesting below the MHC; this has led to concerns that harvesting young silviculturally treated stands may affect timber supply and is not consistent with good forest stewardship (Forest Practices Board 2018).

The objective of this study is thus to determine if there is an optimal PCT density that meets required management objectives while providing a positive return on investment under various assumptions of log prices, discount rates, and MHC. We use the 15-year results from Experimental Project (EP) 1211, a growth and yield field experiment that examines the effects of six residual PCT densities against an unthinned control (de Montigny et al. 2018). The growth of each plot is simulated up to age 100 by the Tree and Stand Simulator (TASS) (Mitchell 1975). Output from TASS is run through a suite of linked modules in the Silviculture Impacts on Yield, Lumber Value, and Economic Return (SYLVER) system to estimate log recovery and value (Di Lucca 1999). The economic evaluation of the different treatments uses the Financial Analysis of Silviculture Investment and Economic Return (FAN$IER) to estimate the expected flow of benefits and costs from the different treatment regimes, discounted to present values, to determine the SV of the regimes. The economic results of the different treatments are compared under the different MHC published in Timber Supply Reviews in coastal British Columbia. Finally, sensitivity analyses are compared using default harvesting costs and new equations developed by FPInnovations (FPI),[2] log prices that do or do not provide a premium for piece size, and two social discount rates.

METHODS

Site Description

Experiment Project 1211 and its analysis are described in detail in de Montigny et al. (2018). The site and treatments are discussed briefly here. This 20-ha study site is located in the Callaghan Valley near Whistler, B.C., approximately

2 FPInnovations is a Canadian not-for-profit forest products research organization: https://fpinnovations.ca.

90 km north of Vancouver, B.C. The site is in the Southern Moist Submaritime Coastal Western Hemlock biogeoclimatic variant (CWHms1) (Meidinger and Pojar 1991), and the site series is BaCw – Devil's club, with a soil moisture and nutrient regime of moist to very moist and rich to very rich, respectively. The site index at 50 years is 28 m for western hemlock.

The site was logged between 1977 and 1980, was spot burned in 1979, and then was allowed to regenerate naturally. In 1996, the resulting young stand of amabilis fir and western hemlock was identified as eligible for spacing using standard guidelines,[3] which included the following: the major crop tree species were western hemlock and amabilis fir, the average height of the leave trees after spacing was between 4 and 12 m, the average functional live crown ratio for the crop trees was ≥ 30%, the average height-to-diameter ratio was < 0.9, the total coniferous density was > 1500 sph, the site index for the target crop tree species in the stand was ≥ 20 m, and there were no identified forest health agents. The stand management prescription for the stand called for a target density of 800 (± 10%) sph.

Experimental Design

Six levels of thinning (including the non-treated controls) were used to examine the effects of PCT on the growth and yield of amabilis fir and western hemlock. The targeted densities included the prescribed treatment of 800 sph; a wider range of densities: 500, 1100, 1400, and 1800 sph; and an unthinned control. Four replicates were established for each level of thinning. The plot sizes ranged from 0.03 to 0.10 ha (Table 1) and were chosen to incorporate at least 50 trees and preferably 70 trees per plot after the thinning treatment, with a surrounding 10-m treated buffer. Figure 1 shows the relative size and proximity of the 24 plots, as well as the spacing treatment.

TABLE 1 *Target and actual density by treatment*

Treatment	Target density (sph)[a]	Target spacing (m)	Actual density (sph)	Plot size (ha)	Amabilis fir (%)	Western hemlock (%)
T550	500	4.5	565	0.10	59.0	41.0
T800	800	3.5	789	0.09	51.1	48.9
T950	1100	3.0	957	0.07	60.4	39.6
T1200	1400	2.7	1 180	0.05	53.4	46.6
T1600	1800	2.4	1 606	0.04	64.6	35.4
Control	n/a	n/a	22 008	0.03	30.5	69.5

a Stems per hectare.

Thinning Treatment

The criteria for the thinning treatments were to select trees based on (1) target spacing (Table 1), (2) target species composition of 60% amabilis fir and 40% western hemlock, and (3) leave trees with good form and vigour. Precommercial thinning operations were conducted during the fall of 1998 when the stand was 18 years old. The plots were measured immediately following treatment and 2, 4, and 15 years post-treatment. Densities of the four plots of each treatment were summarized after spacing and were found to be off from

3 B.C. Ministry Forest Lands and Natural Resource Operations. 2017. Silviculture Funding Criteria: 2017/18 to 2020/21. www2.gov.bc.ca/assets/gov/environment/natural-resource-stewardship/land-based-investment/forests-for-tomorrow/201718_lbis_silviculture_funding_criteria_-_july_final.pdf.

Callaghan Valley Spacing Trial Plot Layout

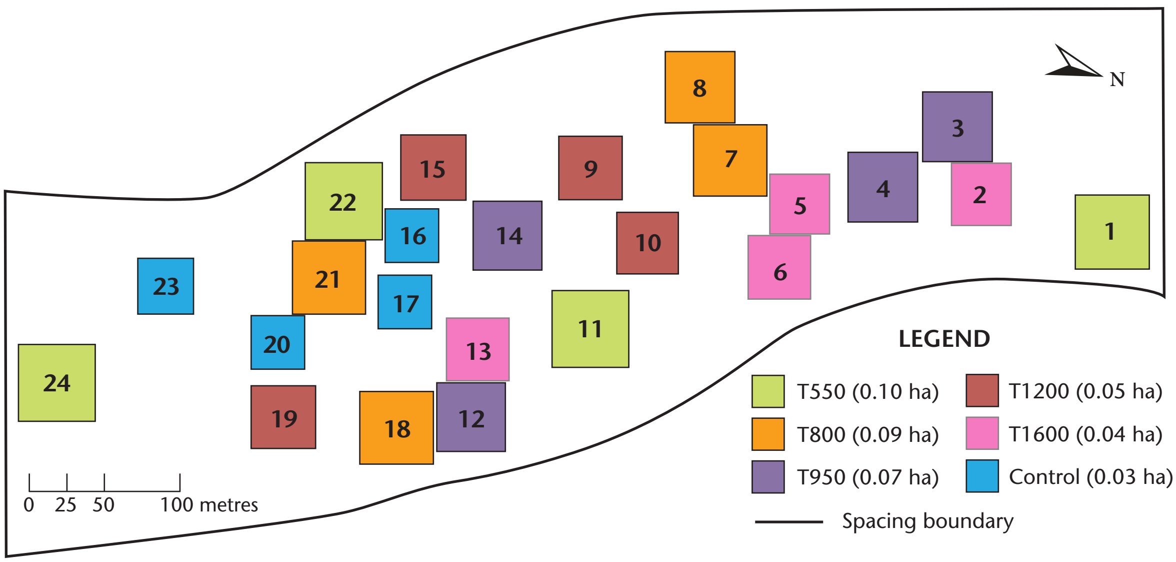

FIGURE 1 *Distribution of plots by treatment.*

the target densities. To better reflect the actual spacing treatment, the treatments were renamed based on the average post-treatment density of the four original replications per treatment rounded to an even 50 (i.e., T550, T800, T950, T1200, T1600, and control).

Growth and Yield Projections

The Tree and Stand Simulator (TASS) simulated the growth of each plot in steps of 1 year up to age 100. TASS is an individual-tree model that predicts the growth and yield of even-aged, single-species stands (Mitchell 1975). Site index and the spacing treatment at age 18 were used in the simulation runs, and natural regeneration was assumed. Initial density was adjusted so that the density and volume predicted by TASS at age 33 was approximately the same as the observed density and volume at the last measurement. Merchantable volume was the variable of interest and was calculated using a minimum diameter at breast height (dbh) of 12.50 cm, a top diameter of 10 cm, and a stump height of 30 cm. TASS is calibrated for western hemlock but not for amabilis fir. However, Oliver and Larson (1996) found that the two species are similar in shade tolerance and height growth patterns in the first 100 years, and Mitchell and Polsson (1988) found that site index curves for second-growth coastal western hemlock and amabilis fir were virtually identical until at least 50 years. Therefore, because these mixed stands behave much like single-species stands, all trees were assumed to be western hemlock for modelling purposes.

Output from TASS was run through a suite of linked modules in the SYLVER system to estimate product recovery and value (Di Lucca 1999). The Buck program optimally bucks trees grown by TASS into logs to maximize log value. The Grade program classifies logs according to their quality (Di Lucca 1999). The grading criteria for logs were set by minimum length, average small-end diameter, and wood quality, including maximum knot diameter and minimum number of annual growth rings per 2 cm (Di Lucca 1999).

Economic Analysis

FAN$IER is an economic evaluation module designed to give British Columbia forest managers a convenient tool to undertake stand-level economic analysis of silviculture treatments on Crown (public) or private land (B.C. Ministry of Forests, Lands and Natural Resource Operations 2013). We used FAN$IER to estimate the expected flow of benefits and costs from the different treatment regimes, discounted to present values to determine the SV of the regimes.

Financial analyses must weigh the cost of initial treatment against potential future returns. A financial decision criterion called net present value (NPV) is often used to determine returns and select between mutually exclusive projects. Net present value is defined as the present value of expected future returns minus the present value of expected future costs plus initial costs discounted with the appropriate interest rate or required rate of return (Gunter and Haney 1984). For any project or activity, a positive NPV indicates that the project will earn more than the selected interest rate.

Net present value is a good tool for ranking silvicultural investments and for helping determine which investments or projects should be funded. However, if the rotation lengths are different between competing management regimes, then using SV is a more appropriate way of ranking silviculture investments because it accounts for an infinite timeline, while the NPV computation stops at the end of the first rotation. Another case against using NPV computations to compare competing management regimes is that they ignore the opportunity to reinvest revenues. Pre-commercial thinning is often prescribed to reduce rotation lengths; therefore, SV is the better measure for comparing treatments that may have different rotation lengths.

Site value is the NPV of an infinite series of identical, even-aged forest rotations and represents the maximum amount that someone would be willing to pay for bare land if the land were devoted to producing an infinite series of rotations of identical growing regimes (Faustmann 1849). Like NPV, any project or activity with a positive SV will indicate that the project will earn more than the selected discount rate, and projects with the highest SV are most desirable. Site value is the same as soil expectation value and land expectation value; however, the purchase price of the land and the revenue generated from ultimately selling the land are not included in the calculation.

Site value can therefore be said to be a special case of NPV. It is calculated by estimating all costs and revenues for the first rotation of timber, compounding these to the end of the first rotation, and assuming that the net present value will be repeated as a perpetual periodic series. The formulation is as follows:

$$\mathrm{SV} = \left[\frac{\mathrm{NPV}\,(1+i)^R}{(1+i)^R - 1} \right]$$

where SV = site value or soil expectation value or land expectation value, NPV = net present value of the investment, i = discount rate, and R = length of rotation.

Cost and Benefit Assumptions

Assumptions were made about the silviculture, harvesting, road, and infrastructure costs (Table 2) and benefits derived from all log products (Table 3). We used the FAN$IER default values for silviculture costs that were based on 10-year averages derived from the BC Timber Pricing Branch in 2006 for the Chilliwack District and the Coast Region (B.C. Ministry of Forests, Lands and

TABLE 2 *Silviculture and harvesting costs used in the economic analysis. All values are in 2006 Canadian dollars using a discount rate of 4%.*

Item	Costs ($/ha)
Silviculture	
Survey and prescription	29.00
Spacing	1200.00
Harvesting costs	
Tree-to-truck[a] functions:	FAN$IER default or FPI[b] test
Hauling	17.21
Harvesting overhead	8119.00
Road maintenance	1154.00
Road and infrastructure costs	8492.00

a See the Methods section for details about the tree-to-truck functions.

b FPInnovations.

TABLE 3 *Log values used in the economic analysis. Default values are in 2006 Canadian dollars, except industrial values are 2016 values not discounted.[a]*

Log grade[b]	Minimum top diameter (cm)	Minimum length (m)	Minimum no. rings per 2 cm	Maximum knot size[c] (cm)	Default value[d] ($/m)	Industrial value[a] ($/m^3)
H	38	5.0	5	4–5	115	70
I	38	3.8		8–10	90	70
J	16	5.0		4–6	71	60
U	10, 16	5.0		4–14	53	50
X	10	3.8		4–14	50	50
Y					48	30

a Industrial values were based on industrial log sorts as suggested in Blackwell, B.A. & Associates Ltd. (2017).[4] If values had been discounted, 2006 values would be $57, $57, $49, $41, $41, and $25 per cubic metre of log grade H, I, J, U, X, and Y, respectively. This was considered too low for the purposes of the sensitivity analysis.

b Log quality declines from grade H to X. Better-quality logs are larger with more clear wood. Grade Y is pulp-quality logs.

c Maximum knot size varies by top diameter.

d More information about default values and log grading in British Columbia can be found in B.C. Ministry of Forests, Lands and Natural Resource Operations (2015): www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/forestry/timber-pricing/timber-scaling/ch10_amendment_3.pdf.

Natural Resource Operations 2013). Other silvicultural treatment costs and end-product values are described in Mitchell et al. (1989) and in the FAN$IER online help documentation.

Default log prices in FAN$IER are based on 10-year market price averages for the coast region of British Columbia, derived from log transactions on the Vancouver Log Market.[5] Logs on this market are sold by major forest companies to other major forest companies by grade, reflecting the value of the

4 Blackwell, B.A. and Associates. Ltd. 2017. Forests for Tomorrow review of juvenile spacing investments. Contract report submitted to B.C. Min. For., Lands and Nat. Resource Ops, Resource Pract. Br., Victoria, B.C.

5 Details about the derivation of FAN$IER log prices are available in the Help tabs of the model: www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/forest-inventory/growth-and-yield-modelling/financial-analysis-of-silviculture-investment-economic-returns-fansier.

timber contained in the logs. Log grades are based on the physical factors that affect the potential for the manufacture of lumber and veneer products, including log length, size of knots, and growth rate (ring count). Log grades were assigned to one of two groups: sawlogs (grades H, I, and J) and pulp logs (grades U, X, and Y). Although the U and X grades produce some lumber, most of their log volume is used for pulp. These default prices essentially provide a premium price for larger log sizes (Table 3). For sensitivity analysis, we also considered log prices that did not have a premium for larger sizes (Table 3), as suggested in Blackwell, B.A. & Associates Ltd. (2017).[6]

Harvesting costs can vary depending on equipment type, terrain, season, and stand characteristics, such as harvestable volume and distribution of piece sizes. In FAN$IER, tree-to-truck costs are harvesting costs, including expenses for landing and skid trail construction, felling, skidding, bucking, loading, crew transportation, and any contractor overhead and profit. We used FAN$IER's ground-based tree-to-truck (TTT) default cost function that considers merchantable volume/hectare and average tree size, and adjusts costs for small trees < 0.34 m^3/ha, as follows:

$$\text{TTT FAN\$IER Default } (\$/m^3) = 16.09 + 9.42 \times \text{SLOPE}/100 - 4.79 \times \text{VPH}/1000 + 7.63 \times \text{STD} - 22.03 \times \text{STVOL} + 1.49 \times \text{DIST200}/100 + \text{BECADDITIVE} + 10.91 \times \text{CE} + 6.81 \times 1.06 \times \text{HE}$$

where:

SLOPE = average side slope (%);

VPH = average net merchantable volume per hectare (m^3/ha);

STD = small tree dummy (STD) variable (0, 1) such that if average net merchantable volume (m^3) per tree is < 0.34, then STD = 1; otherwise STD = 0;

STVOL = small tree volume is the average net merchantable volume per tree (m^3) if the tree is < 0.34 m^3/tree. If ≥ 0.34 m^3/tree, STVOL = 0;

DIST200: if DS is ≤ 100 km, DIST200 = DS – 100; or if DS is > 100 km and ≤ 200 km, DIST200 = DS – 100; or if DS is > 200 km, DIST200 = 100;

BECADDITIVE = 0 for the Coastal Western Hemlock BEC zone;

CE = species western redcedar (%); and

HE = species hemlock and amabilis fir (%).

For sensitivity analysis, we used a test equation developed by FPI that is based solely on merchantable volume/tree (B.C. Ministry of Forests, Lands and Natural Resource Operations 2013), which results in lower harvesting costs for a larger log size. FPInnovations' test function is as follows:

$$\text{TTT FPI test function } (\$/m^3) = 11.826 \times \text{VPT}^{-0.588}$$

where VPT is merchantable volume per tree (m^3).

This test function, as used in this analysis, assumes current cost values and not the 10-year averages. In the future, this function should be calibrated to use 10-year averages for all costs and prices. This will require further research.

6 Blackwell, B.A. and Associates Ltd. 2017. p. 7.

Discount Rate Assumptions

The discount rate is the most critical component in understanding economic rotation ages and SV. The discount rate is the rate at which future values are discounted to the present; the higher the discount rate, the lower the SV of the stand. The discount rate also plays an important role in determining the optimal rotation age. For example, the overall shape of a forest stand yield curve is described as sigmoid, which means that the growth rate (the slope, or first derivative, of the yield curve) increases initially, reaches a maximum, and then declines as the stand ages. As a general rule, to maximize the financial rotation, a rational investor will choose to harvest the stand when the growth in timber value is equal to the chosen discount rate. If the investor harvests earlier, when the timber value is growing faster than the discount rate, returns on the investment will not be maximized because the investor would be earning more by leaving the stand than by an alternative investment. Conversely, if the growth in timber value is lower than the discount rate, the investor is better off harvesting the stand and investing the returns in an alternative investment. Therefore, a lower discount rate will result in a later harvest, while a higher discount rate will result in an earlier harvest (a lower economic rotation age).

The appropriate discount rate for comparing silvicultural scenarios has long been a topic of debate. Rates of 3–5% may approximate what is termed the social discount rate, or a government's time preference for achieving public policy objectives (Klemperer et al. 1994; Hawkins et al. 2006). FAN$IER's default discount rate is 4%, which is based on Heaps and Pratt (1989), who examined the social opportunity cost of public sector investments in Canada, and argued that the appropriate range for silviculture investments is between 3 and 5%. We used 4% as our default discount rate. For sensitivity analysis, we used a discount rate of 2%, which is recommended for the Forests for Tomorrow Program to "balance the economic return of silviculture investments with future timber supply and other resource values and objectives."[7]

Minimum Harvest Criteria Assumptions

Harvest age was based on the minimum harvestable ages from timber supply reviews in areas of British Columbia where western hemlock/amabilis fir stands were within the timber harvesting land base. These included the following:

- minimum harvestable volume of 350 m^3/ha, as used in the Soo TSA in southwestern British Columbia for hemlock/amabilis fir stands on good sites (site index ≥ 25 m) for conventional land-based logging (B.C. Ministry of Forests, Lands and Natural Resource Operations 2011), and in the Arrowsmith TSA on southern Vancouver Island for coniferous ground/cable harvesting (B.C. Ministry of Forests, Lands and Natural Resource Operations and Rural Development 2018);
- minimum average stand diameter of 25 cm, with a minimum top height ≥ 19.5 m and stand volume ≥ 250 m^3/ha, as used in the Kalum TSA in northwestern British Columbia (B.C. Ministry of Forests, Mines and Lands 2011). The minimum average diameter criterion is based on Howard and Temesgen (1997);
- 95% culmination of MAI and a minimum volume of 350 m^3/ha, as used in the Fraser TSA in southwestern British Columbia (B.C. Ministry of Forests, Lands and Natural Resource Operations 2016);

7 B.C. Ministry of Forest Lands and Natural Resource Operations. 2017. Silviculture Funding Criteria, p.4.

- minimum stand age of 50 years and requiring a minimum volume of 350 m^3/ha for combinations of three site productivity classes and two species groups, as used in TFL 19. Both the minimum volume and minimum age requirements had to be met before a stand was assumed to be harvestable in the model (B.C. Ministry of Forests and Range 2010).

We also examined the harvest age at which the stand's SV is maximized, known as the economic rotation age.

RESULTS

Tree and Stand Simulator Projections

The custom TASS projections that simulated the treatments were compared with actual values from EP1211 at age 33. T1600 was not included in further analyses because densities were higher than what would be achieved in operational spacing, and growth and yield were always less than that of other treatments. Predicted mean density for each treatment at age 33 varied from actual measured density by 1.8% (T1200) to −10.8% (T550) for spaced treatments, which was deemed acceptable. However, in the unthinned control, the model predicted density to be 45.5% greater than actual (10 830 sph versus 5900 sph, respectively) due to a lower predicted mortality. To compensate for this difference, modelled density in the control was reduced to 5536 sph at age 34, which resulted in an acceptable difference in density from predicted to actual of 6.2%.

The resulting predicted quadratic mean diameter (QMD) estimates at age 33 were very similar to the measured values (Figure 2). The volume estimates over this period were also similar (data not shown). This provides confidence that TASS was able to accurately simulate the growth of tree and stand parameters in the individual plots that were then "grown" by the model until age 100.

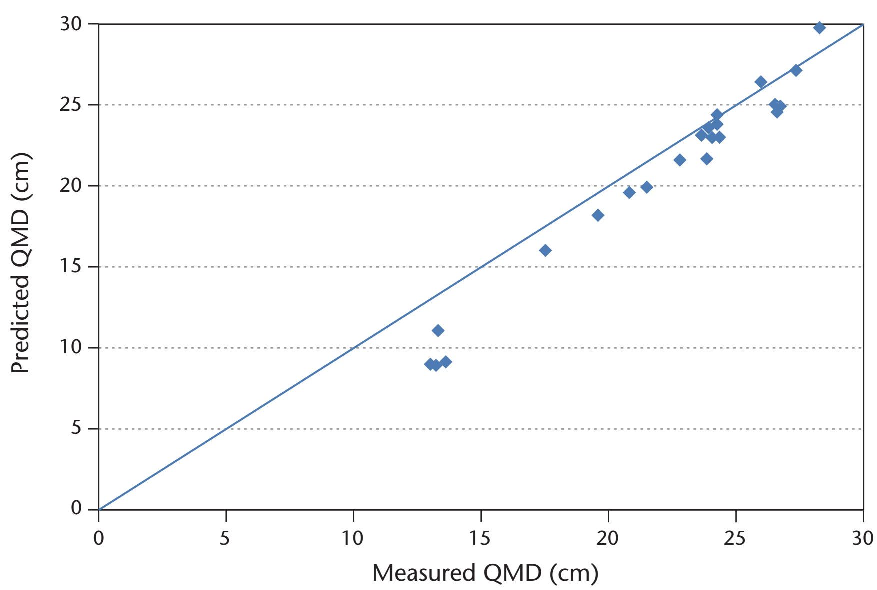

FIGURE 2 *Comparison between measured values of quadratic mean diameter (QMD) and Tree and Stand Simulator predicted values of QMD for each plot at age 33 years (measurement 4).*

Projections of QMD up to 100 years post–stand establishment indicated considerable differences between treatments, with a general trend of increasing QMD as stand density decreased (Figure 3). Predicted standing merchantable volume (MV) by treatment is shown in Figure 4; note that the reduction in volume of the control at age 34 appears as a thinning, but this volume reduction was to align predicted densities with actual densities at age 33, and there are no costs for this in FAN$IER. Merchantable volume was projected to be highest for the unthinned control from age 17 onward until about age 60, when T1200 appeared to converge with MV of the unthinned control. After spacing, treatment T550 had the lowest merchantable volume over the 100-year period.

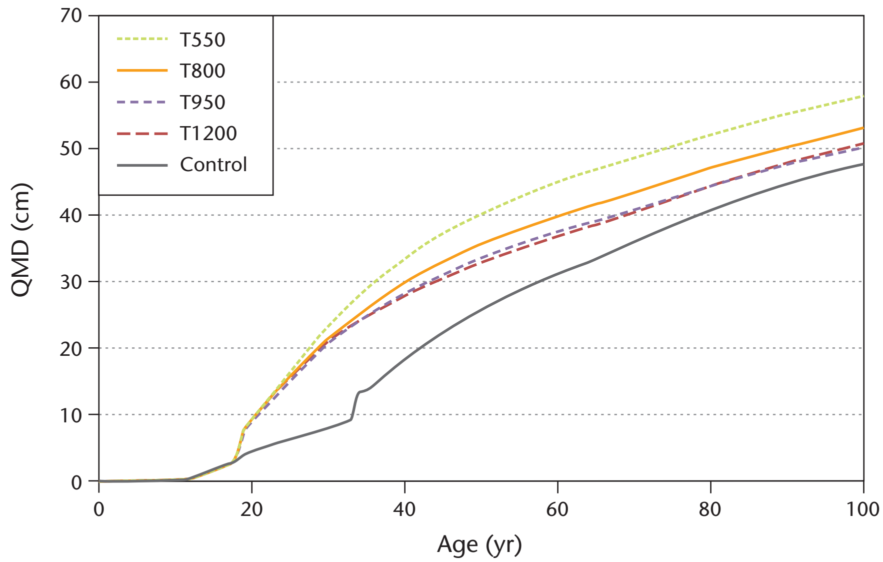

FIGURE 3 *Quadratic mean diameter (QMD) predicted over time for each treatment.*

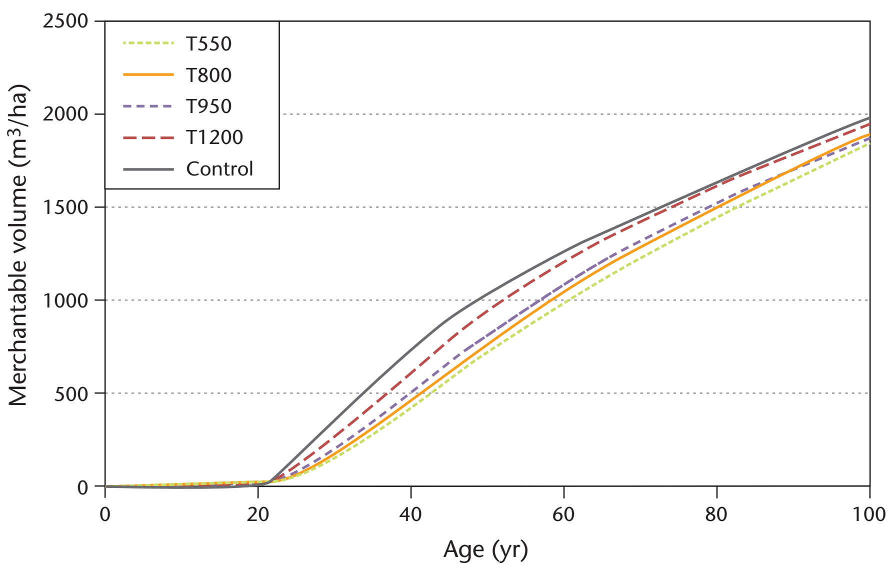

FIGURE 4 *Standing merchantable volume predicted by the Tree and Stand Simulator for each treatment.*

The maximum MAI for merchantable volume increased with increasing density, while the age at maximum MAI decreased with increasing density as follows: 18.4 m^3/ha/yr at age 91 for T550; 19.0 m^3/ha/yr at age 88 and age 75 for T800 and T950, respectively; 20.4 m^3/ha/yr at age 65 for T1200; and 21.0 m^3/ha/yr at age 54 for the control.

TASS projections of growth for each plot were then run through the SYLVER model to obtain projected merchantable volume by log grade. This was summarized by treatment and is shown for stand ages 50, 70, and 90 years in Figure 5. As expected, the percentage of total standing volume in each log grade changed over time, which reflected that as the trees grew, the increasing size of the boles produced logs with higher grades:

- Log grade J contributed most of the merchantable volume until age 51 years for T550, 62 years for T800, 70 years for both T950 and T1200, and 93 years for the control, at which point log grade I surpassed the volume of J.
- Log grade I, the next larger log grade, became available after age 35 years for all treatments, and the available volume increased until about age 80 years, at which point tree stem volume grew large enough that the resulting logs could be graded to the higher log grade H. The volume of log grade I was greater for treatments with wider spacings. For example, by age 50 years, the T550 treatment was predicted to have 329 m^3/ha in log grade I compared to 157 m^3/ha in the control.
- Log grade H, the highest log grade, did not develop until after age 60 years. By age 90 years, the volume of log grade H ranged from 497 to 587 m^3/ha among the control and PCT treatments T800, T950, and T1200 but was much lower for T550 (298 m^3/ha). At a density of 500 sph, negative wood quality attributes of larger knot size, taper, and wood density (as measured by rings per centimetre) had offset the positive attribute of the larger log sizes of log grade H; consequently, although T550 had the highest volume

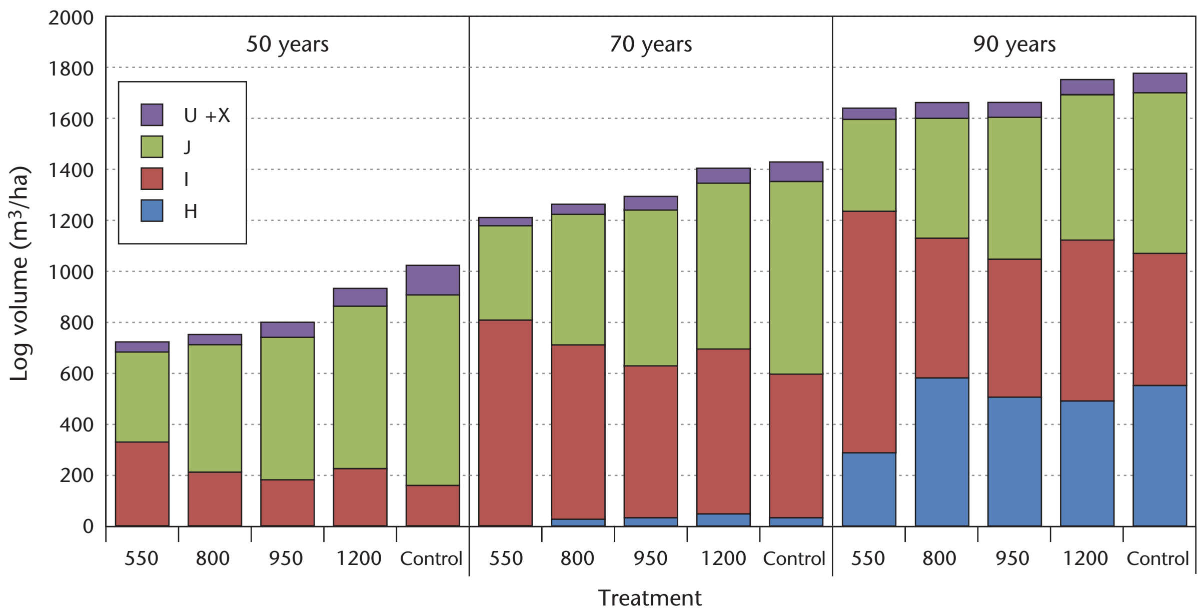

FIGURE 5 *Projected log merchantable volume at 50, 70, and 90 years since disturbance by log grade and treatment. Descriptions of log classes are provided in Table 3.*

of log grade I, it had the lowest volume of log grade H throughout the 100-year projection (Figure 5).

- Log grades U and X contributed a relatively small proportion of the total merchantable volume for all treatments. Volume of U and X increased as treatment density increased, with most available in the unthinned control. The largest proportion was produced relatively early, between 20 and 50 years.

Harvesting Costs

Harvesting costs in FAN$IER were calculated using an equation that considered, among other factors, the harvest method used. We used the default ground equation that depended in part on volume; therefore, harvesting costs/hectare increased over time as volume/hectare increased. The default equation also depended on tree size. Harvesting costs were higher in young stands until tree sizes reached 0.34 m^3/tree, after which harvesting costs decreased as piece size increased. Using the default equation, T550 had lower overall harvesting costs per hectare over time compared to the control (Figure 6a). The difference in harvesting costs between the treatments was greatest when the stands were young, and then costs began to converge as the stands aged. Maximum difference in costs per hectare ($13 822/ha) occurred at age 38. The age at which average piece size in the stand reached > 0.34 m^3 was 32 years for T550 and 43 years for the unthinned control. When harvesting costs per cubic metre were compared (Figure 6b), the T550 had lower costs until age 42, after which the control had slightly lower costs because there was less volume to be harvested in T550 than in the control.

The FPI test equation that depended only on merchantable volume per tree resulted in lower overall harvesting costs per hectare than the default ground equation (Figure 6a); average harvesting costs ($/ha) over the 100-year period were 14% less for the FPI test equation than by using the default equation, and differences increased over time (Figure 6a). When using the FPI test equation, the maximum difference in harvesting costs per hectare between T550 and the unthinned control stands was $12 086/ha at age 41. When harvesting costs per cubic metre were compared (Figure 6b), the T550 costs were always lower than those for the control.

Using the FPI test as a sensitivity analysis resulted in lower overall harvesting costs. However, further research is needed to ensure that the cost of current harvest practices is accurately reflected in the harvesting cost functions in FAN$IER.

Site Value

The log outputs of the different treatment scenarios derived from SYLVER were run through FAN$IER to calculate SV. Using the default discount rate (4%), log prices, and harvesting costs, the maximum SV was highest for the control at age 60 ($3051/ha) and ranged from $1874 to $2380/ha at age 64–73 for PCT treatments T550–T1200, respectively (Table 4; Figure 7). Treatment T1200 gave the highest SV of the PCT-treated stands ($2380/ha), which was 22% less than that for the control. In comparison to the PCT treatments, the control treatment reached a positive SV by age 40 years or 3–7 years earlier than the PCT treatments (Table 4). The results show that the control (unthinned) treatment had the highest SV, largely because it had no thinning costs and SV was maximized earlier. For thinning to be economically justified, the additional costs incurred by thinning must be recovered by higher returns or by savings elsewhere in the rotation. The results of the economic analyses also revealed that all the thinning treatments had a lower maximum SV than the control treatment (Table 4).

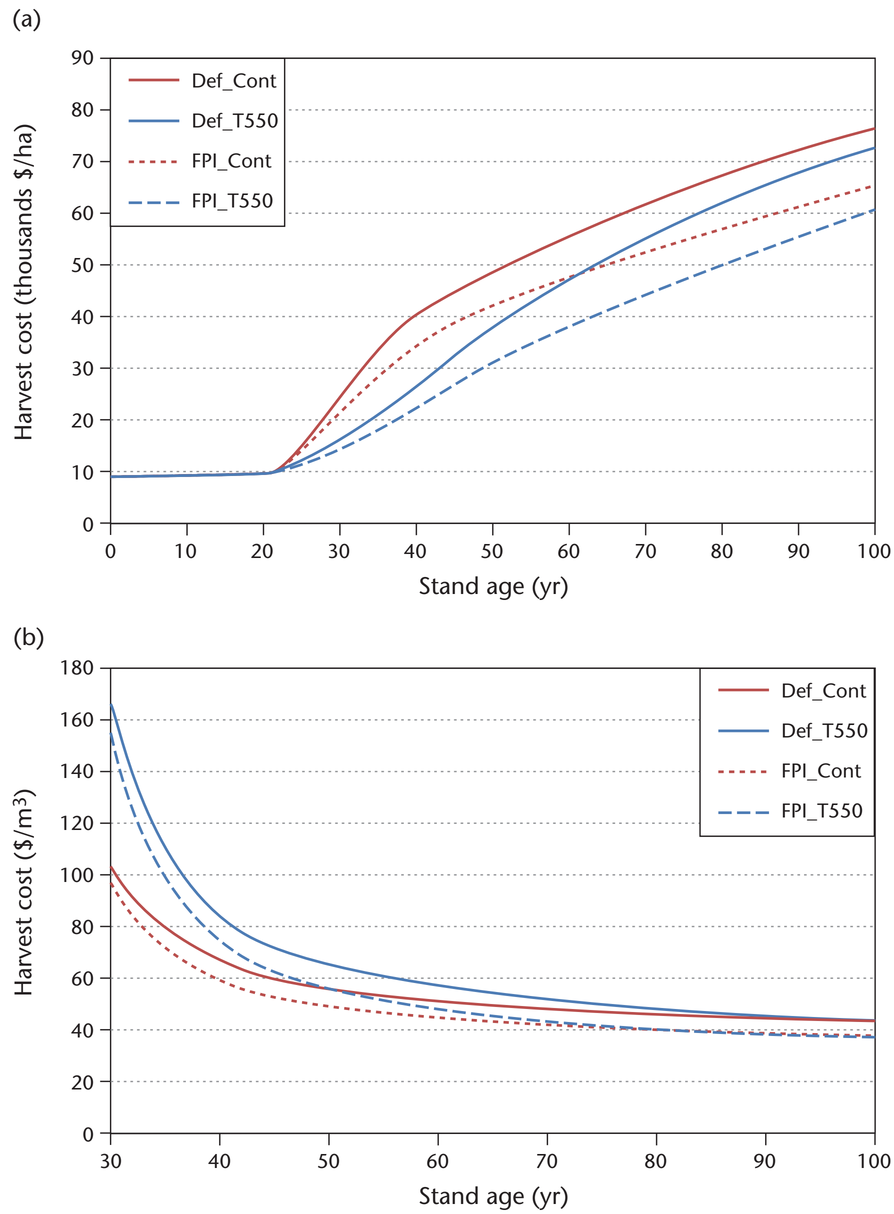

FIGURE 6 *Harvesting costs (a) per hectare and (b) per cubic metre over time for unthinned control (Cont) stands and spaced stands (T550) using the default (Def) ground equation (solid line) and the FPInnovations (FPI) test equation (hatched line). The FPI test equation always resulted in lower harvesting costs compared to the FAN$IER default.*

Sensitivity analyses were run using a discount rate of 2%, industrial log prices that did not have a premium for large piece size, and lower harvesting costs using the FPI equation. For all sensitivity analyses, the maximum SV was always highest for the control, and of the PCT-treated stands, T1200 was always highest (Table 4). The discount rate had a much greater effect on SV than did the log prices or harvesting costs. The financial advantage of improved merchantable volumes and sawlog volumes stemming from PCT decreases

TABLE 4 *Site value (SV), including stand age when SV > 0, stand age at maximum SV, and maximum SV by treatment, and assumptions of log prices, discount rates, and harvesting costs by treatment regime (PCT: pre-commercial thinning; FPI: FPInnovations)*

Assumptions			Treatment means				All PCT treatment means[a]		
Discount rate	Log price[b]	Harvesting cost[c]	Treatment	Stand age when SV > 0	Stand age at max. SV	Max. SV ($/ha)	Stand age where SV > 0	Stand age at max. SV	Max SV ($/ha)
4%	Default	Default	T550	47	67	1 874	46	68	2 028
			T800	47	73	1 947			
			T950	47	67	1 912			
			T1200	43	64	2 380			
			Control	40	60	3 051			
		FPI	T550	43	61	2 760	42	62	2 876
			T800	43	63	2 720			
			T950	42	63	2 702			
			T1200	39	59	3 321			
			Control	37	58	3 928			
	Industrial	Default	T550	59	75	462	57	74	558
			T800	59	74	518			
			T950	58	75	498			
			T1200	53	70	755			
			Control	46	68	1 456			
		FPI	T550	45	63	1 954	45	64	2 066
			T800	46	66	1 952			
			T950	45	65	1 941			
			T1200	42	60	2 418			
			Control	39	59	3 060			
2%	Default	Default	T550	45	93	13 231	45	92	14 370
			T800	46	93	15 005			
			T950	45	94	14 160			
			T1200	42	87	15 085			
			Control	40	92	16 580			
		FPI	T550	42	89	15 536	41	87	16 696
			T800	42	90	17 270			
			T950	41	87	16 402			
			T1200	39	83	17 576			
			Control	37	85	18 815			
	Industrial	Default	T550	54	91	5 748	53	88	5 985
			T800	55	91	5 940			
			T950	54	88	5 695			
			T1200	50	82	6 556			
			Control	46	85	7 718			
		FPI	T550	47	83	8 369	47	79	8 641
			T800	48	79	8 516			
			T950	47	79	8 290			
			T1200	44	76	9 387			
			Control	41	77	10 359			

a The mean of the four PCT treatments but not including the unthinned control.

b Default prices pay a premium for larger log sizes; industrial log prices do not (see Table 3).

c Default costs use FAN$IER's ground-based default function that considers merchantable volume/hectare and average tree size, and adjusts costs for small trees < 0.34 m^3/ha. FPI costs are based solely on merchantable volume/tree, which results in lower harvesting costs for a larger log size.

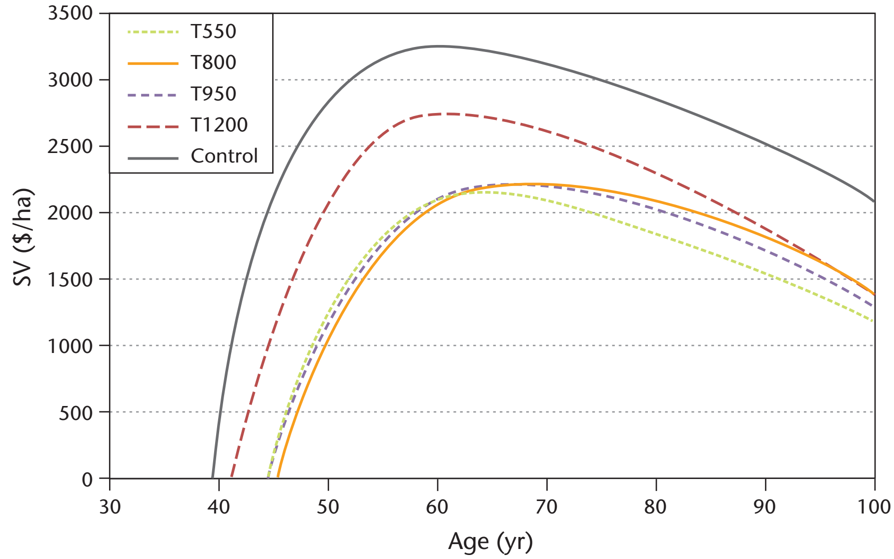

FIGURE 7 *Site value (SV) predicted by FAN$IER from the age at which site value is 0 until age 100 for each treatment, using default assumptions for discount rate, log prices, and harvesting costs.*

dramatically as discount rate is increased. For example (see Table 5), using default log prices and harvesting costs, reducing the discount rate assumption from 4 to 2% increased the maximum SV for the control from $3051 to $18 815/ha (517%), and for the PCT treatments (averaged), from $2028 to $14 370/ha (609%). In contrast, at a 4% discount rate, changing the log price assumptions from the default that provides a premium price for larger logs sizes to the industrial log sort prices that do not reduced the maximum SV for the control from $3051 to $1456/ha (−52%), and for PCT treatments, an average of $2028 to $558/ha (−72%). Similarly, at a 4% discount rate and using default log prices, reducing the harvesting cost assumptions (from default to FPI) increased the maximum SV for the control from $3051 to $3928/ha (29%), and for PCT treatments (averaged), from $2028 to $2876/ha (42%). However, reducing the harvesting cost (from default to FPI) with default assumptions of a 4% discount rate and industrial log prices resulted in a larger SV where maximum SV increased 110% for the control and 270% for the PCT stands. This indicates that where both log prices and discount rate assumptions are high, harvesting cost reductions can have a large effect on SV.

Minimum Harvest Criteria

The minimum harvest criteria greatly affected the age of harvest, the merchantable log volume available for harvest, and the SV of the stand at the corresponding age. Using the default assumptions of a 4% discount rate and default log prices and harvesting costs, results of the economic analysis (Tables 6–8) indicated the stand characteristics when the harvest criteria were reached, including harvest age, merchantable log volume, and SV.

The Kalum TSA harvest criteria required that three minimum criteria be met: average stand diameter > 25 cm, merchantable volume > 250 m^3/ha, and top height > 19.5 m. In our study, for treatments T550, T800, T950, T1200, and control, mean dbh of 25 cm was met by age 33, 35, 37, 37, and 52 years,

TABLE 5 *Difference in site value (%) for all treatments, pre-commercial thinning (PCT) treatments only, and control treatment only, between using a 2–4% discount rate and between using the default and industrial log prices (FPI: FPInnovations)*

	Cost-benefit assumptions			Unspaced control means			All PCT treatment means[a]		
				Site value ($/ha)			Site value ($/ha)		
Comparison	Discount rate (%)	Log price[b]	Harvesting cost[c]	Using default assumption	Using new assumption	Site value difference (%)	Using default assumption	Using new assumption	Site value difference (%)
Discount rate: 4–2%	n/a	Default	Default	3051	16580	443	2028	14370	609
	n/a	Default	FPI	3928	18815	379	2876	16696	481
	n/a	Industrial	Default	1456	7718	430	558	5985	972
	n/a	Industrial	FPI	3060	10359	239	2066	8641	318
Log price[b]: default to industrial	4	n/a	Default	3051	1456	−52	2028	558	−72
	4	n/a	FPI	3928	3060	−22	2876	2066	−28
	2	n/a	Default	16580	7718	−53	14370	5985	−58
	2	n/a	FPI	18815	10359	−45	16696	8641	−48
Harvesting cost[c]: default to FPI	4	Default	n/a	3051	3928	29	2028	2876	42
	4	Industrial	n/a	1456	3060	110	558	2066	270
	2	Default	n/a	16580	18815	13	14370	16696	16
	2	Industrial	n/a	7718	10359	34	5985	8641	44

a The mean of the four PCT treatments but not including the unthinned control.

b Default prices pay a premium for larger log sizes; industrial log prices do not (Table 3).

c Default costs use FAN$IER's ground-based default function that considers merchantable volume/hectare and average tree size, and adjusts costs for small trees < 0.34 m^3/ha. FPI costs are based solely on merchantable volume/tree, which results in lower harvesting costs for a larger log size.

respectively; merchantable volume > 250 m^3/ha was met by age 34, 33, 32, 30, and 28 years, respectively; and top height > 19.5 m was met by age 37, 37, 37, 35, and 35 years, respectively (Table 6). As a result, for T550, T800, and T950, the limiting factor was top height (reached at age 37), and for T1200, it was mean dbh (reached at age 37). Merchantable volume for the PCT treatments increased with increasing density from 332 to 504 m^3/ha, and for all PCT treatments, the SV was negative. For the control, the limiting factor was a mean dbh of 25 cm, reached at age 52, an additional 15 years over that of the PCT, which resulted in a correspondingly greater MV of 1072 m^3/ha and a positive SV. For comparison, if the control was harvested at age 37, the same age as the PCT stands, MV would be 609 m^3/ha, and the SV would be approximately −$1500 (Table 6).

When the minimum harvest age criterion was for a minimum harvest volume of 350 m^3/ha, as with the Soo TSA, the criterion was met as early as age 31 for the control and from 35 to 38 years for treatments T1200 to T550, respectively (Table 6). Harvesting such low volumes at this early age resulted in negative SV for all treatments, including the control.

The minimum harvest age criteria for TFL 19 required both MV > 350 m^3/ha and a minimum harvest age of 50 years. For all treatments, the 50-year age criterion was the limiting factor (Table 7). At age 50, MV for T550 to T1200 ranged from 722 to 932 m^3/ha, respectively, and SV was positive, while for the control, the MV (1024 m^3/ha) and SV were greater than those for the PCT-treated stands.

TABLE 6 *Effects of harvest age criteria on harvest age, merchantable log volume, and site value for the Kalum and Soo Timber Supply Areas. Highlighted cells indicate a positive site value (FPI: FPInnovations).*

Minimum harvesting age criteria		Economic assumptions: Discount rate	Log prices[a]	Harvesting costs[b]	Treatment: 500	800	950	1200	Control	Control[c]
Kalum Timber Supply Area criteria: dbh >25 cm; MV[f] > 250 m³/ha; TopHt[g] > 19.5 m	MHA[d] (years)				37	37	37	37	52	37
	MLV[e] (m³/ha) at MHA				332	370	407	504	1 072	609
	Site value ($/ha)	4%	Default	Default	−3 427	−3 309	−3 049	−2 147	2 779	−1 498
				FPI	−2 413	−2 260	−1 957	−844	3 827	162
			Industrial	Default	−4 566	−4 469	−4 305	−3 718	888	−3 240
				FPI	−3 552	−3 419	−3 213	−2 414	1 936	−1 580
		2%	Default	Default	−9 517	−9 162	−8 375	−5 647	10 319	−4 530
				FPI	−6 450	−5 988	−5 072	−1 704	14 214	490
			Industrial	Default	−12 963	−12 668	−12 173	−10 396	3 295	−9 798
				FPI	−9 896	−9 495	−8 870	−6 453	7 190	−4 778
Soo Timber Supply Area criteria: MV > 350 m³/ha	MHA (years)				38	37	36	33	31	
	MLV (m³/ha) at MHA				362	370	375	363	371	
	Site value ($/ha)	4%	Default	Default	−2 940	−3 309	−3 537	−4 388	−5 406	
				FPI	−1 882	−2 260	−2 485	−3 183	−4 354	
			Industrial	Default	−4 159	−4 469	−4 724	−5 666	−6 582	
				FPI	−3 101	−3 419	−3 673	−4 460	−5 529	
		2%	Default	Default	−8 125	−9 162	−9 750	−11 908	−15 136	
				FPI	−4 882	−5 988	−6 610	−8 447	−12 190	
			Industrial	Default	−11 860	−12 668	−13 294	−15 576	−18 428	
				FPI	−8 618	−9 495	−10 154	−12 115	−15 482	

a Default prices pay a premium for larger log sizes; industrial log prices do not (Table 2).

b Default costs use FAN$IER's ground-based default function that considers merchantable volume/hectare and average tree size, and adjusts costs for small trees < 0.34 m³/ha. FPI costs are based solely on merchantable volume/tree, which results in lower harvesting costs for a larger log size.

c Site value of the control treatment if harvested at age 37, the same age as the pre-commercial thinning treated stands.

d Minimum harvest age (MHA) is the age of the stand when the minimum harvest criteria are met.

e Merchantable log volume (MLV) at the age when the minimum harvest criteria are met.

f Merchantable volume.

g Top height.

When the MHC specified that the stand must reach 95% of the culmination of mean annual increment, as for the Fraser TSA, the minimum harvest age for the control was 46 years, and minimum harvest age increased as stand density from PCT treatments decreased to a maximum of 70 years for T550 (Table 7). Site value was positive for all treatments, and the SV of T1200 was slightly higher than that of the control.

When the MHC was to maximize SV (the economic rotation age), SV was always greatest for the untreated control under all economic assumptions (Table 8). For PCT-treated stands, SV was always greatest for T1200 under all economic assumptions.

TABLE 7 *Effects of harvest age criteria on harvest age, merchantable log volume, and site value for Tree Farm Licence 19 and the Fraser Timber Supply Area. Highlighted cells indicate a positive site value (FPI: FPInnovations).*

Minimum harvesting age criteria		Economic assumptions			Treatment				
		Discount rate	Log prices[a]	Harvesting costs[b]	500	800	950	1200	Control
Tree Farm Licence 19 criteria: MV[e] > 350 m³/ha MHA = 50 years	MHA[c] (years)				50	50	50	50	50
	MLV[d] (m³/ha) at MHA				722	759	810	932	1 024
	Site value ($/ha)	4%	Default	Default	828	650	788	1 626	2 602
				FPI	2 000	1 800	1 939	2 863	3 693
			Industrial	Default	−908	−978	−858	−295	681
				FPI	264	173	293	942	1 773
		2%	Default	Default	4 337	3694	4 194	7 220	681
				FPI	8 568	7 847	8 348	11 686	13 334
			Industrial	Default	−1 927	−2 180	−1 748	283	1 024
				FPI	2 303	1 974	2 406	4 750	6 401
Fraser Timber Supply Area criteria: 95% of maximum MAI	MHA (years)				70	66	60	54	46
	MLV (m³/ha) at MHA				1 220	1 186	1 078	1 045	915
	Site value ($/ha)	4%	Default	Default	1 841	1 910	1 753	2 073	2 052
				FPI	2 569	2 707	2 675	3 197	3 195
			Industrial	Default	432	401	165	175	109
				FPI	1 160	1 198	1 087	1 300	1 252
		2%	Default	Default	11 233	10 802	9 100	9 438	7 004
				FPI	14 772	14 442	12 946	13 736	10 905
			Industrial	Default	4 388	3 909	2 472	2 186	371
				FPI	7 927	7 549	6 319	6 483	4 272

a Default prices pay a premium for larger log sizes; industrial log prices do not (Table 2).

b Default costs use FAN$IER's ground-based default function that considers merchantable volume/hectare and average tree size, and adjusts costs for small trees < 0.34 m³/ha. FPI costs are based solely on merchantable volume/tree, which results in lower harvesting costs for a larger log size.

c Minimum harvest age (MHA) is the age of the stand when the minimum harvest criteria are met.

d Merchantable log volume (MLV) at the age when the minimum harvest criteria are met.

e Merchantable volume.

TABLE 8 *Effects of harvest age criteria on harvest age, merchantable log volume, and site value to maximize site value. Highlighted cells indicate a positive site value (FPI: FPInnovations).*

Minimum harvesting age criteria		Discount rate	Log prices[a]	Harvesting costs[b]	500	800	950	1200	Control[c]
		Economic assumptions			**Treatment**				
Economic rotation: maximum site value	MHA[d] (years)	4%	Default	Default	67	73	67	64	60
				FPI	61	63	63	59	58
			Industrial	Default	75	74	75	70	68
				FPI	63	66	65	60	59
		2%	Default	Default	93	93	94	87	92
				FPI	89	90	87	83	85
			Industrial	Default	91	91	88	82	85
				FPI	83	79	79	76	77
	MLV[e] (m^3/ha) at MHA	4%	Default	Default	1 152	1 353	1 246	1 293	1 250
				FPI	1 010	1 111	1 153	1 175	1 208
			Industrial	Default	1 333	1 375	1 416	1 423	1 406
				FPI	1 058	1 186	1 201	1 199	1 229
		2%	Default	Default	1 705	1 758	1 764	1 731	1 842
				FPI	1 627	1 703	1 643	1 668	1 719
			Industrial	Default	1 667	1 721	1 661	1 650	1 719
				FPI	1 502	1 478	1 497	1 539	1 574
	Site value ($/ha)	4%	Default	Default	1 874	1 947	1 912	2 380	3 051
				FPI	2 760	2 720	2 702	3 321	3 928
			Industrial	Default	462	518	498	755	1 456
				FPI	1 954	1 952	1 941	2 418	3 060
		2%	Default	Default	13 231	15 005	14 160	15 085	16 580
				FPI	15 536	17 270	16 402	17 576	18 815
			Industrial	Default	5 748	5 940	5 695	6 556	7 718
				FPI	8 369	8 516	8 290	9 387	10 359

a Default prices pay a premium for larger log sizes; industrial log prices do not (Table 2).

b Default costs use FAN$IER's ground-based default function that considers merchantable volume/hectare and average tree size, and adjusts costs for small trees < 0.34 m^3/ha. FPI costs are based solely on merchantable volume/tree, which results in lower harvesting costs for a larger log size.

c Site value of the control treatment if harvested at age 37, the same age as the pre-commercial thinning treated stands.

d Minimum harvest age (MHA) is the age of the stand when the minimum harvest criteria are met.

e Merchantable log volume (MLV) at the age when the minimum harvest criteria are met.

The goal for timber management in British Columbia is to "…provide a sustainable flow of economically valuable timber that generates public revenue…" (B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development 2017). Silviculture treatments provide investment opportunities that, when applied correctly, can improve timber volume and/or timber value and consequently, improve public revenue. With more than one million hectares of mixed western hemlock and amabilis fir stands available for harvest on the coast, and knowing that harvested stands can readily regenerate naturally to dense mixed-species stands, can investment in pre-commercial thinning treatments in these naturally regenerated stands help achieve British Columbia's timber management goal? Will PCT meet Forests for Tomorrow objectives to make stands merchantable sooner to address forest-level mid-term timber supply gaps or age class imbalance and to prepare stands for future treatments (e.g., fertilization, commercial thinning)?

Did Pre-commercial Thinning Concentrate Growth on Higher-value Tree Species?

One advantage of a PCT treatment is that it can be used to influence stand composition (Smith et al. 1997). At the time of spacing in 1996, amabilis fir was thought to be the more valuable species, and the PCT prescription was written to favour amabilis fir over western hemlock. Pre-commercial thinning treatments did increase the relative amount of amabilis fir over hemlock from 40% in the unthinned control to 100–180% in the PCT-treated stands (Table 1), but as of 2018, western hemlock and amabilis fir are commonly sold and shipped together under the name Hem-Fir (also often referred to as Hem-Bal). Consequently, because there is no difference in value between amabilis fir and western hemlock, we cannot say that PCT concentrated growth on higher-value tree species. This is a good example of how assumptions made at the time of silviculture investments may prove wrong decades later, and this supports the need to test assumptions using sensitivity analyses.

Will Pre-commercial Thinning Result in Greater Merchantable Volume Compared to the Unthinned Stands?

Pre-commercial thinning treatments did not generate greater merchantable volume compared to the unthinned stands. At age 32 years, 15 years after PCT treatments, the treated stands had significantly less volume than the unthinned stands (de Montigny et al. 2018). TASS projections of MV by treatment to 100 years showed that the unthinned control stands continued to have greater MV compared to PCT stands (Figure 4), although the T1200 treatment was within 5% of the control by age 60 and within 1% by age 70. Similarly, the maximum mean annual increment was highest for the control and decreased with decreasing density over the 100-year projection period. This is because the reduction in density to allow greater growing space for residual trees results in a reduction in full site occupancy and therefore, a reduction in the productive capacity of the site; this continues until crown closure is reached. Both MV and MAI were lowest in the T550 treatment, even after 100 years, indicating that PCT to this low density was extreme. T800 and T950 appeared to be on track for convergence with T1200 and the control but not within the 100-year projection period. Consequently, PCT to 1200 sph provided the best opportunity for focussing growth on fewer trees without greatly reducing total MV or MAI compared to the unthinned control over a 100-year period.

Will Pre-commercial Thinning Result in a Greater Quantity of Larger Log Sizes at an Earlier Age?

Pre-commercial thinning treatments, as expected, removed many small-diameter trees and focussed growth on fewer stems compared to the unthinned control. For example, 15 years after spacing, the proportion of trees larger than 25 cm decreased as density increased: 0.92, 0.87, 0.79, and 0.80 for T550, T800, T950, and T1200, respectively, compared to 0.25 for the control (de Montigny et al. 2018). This chainsaw effect is well documented.

However, a more uniform piece size did not necessarily result in a larger quantity of merchantable log volume in larger piece sizes. Most of the merchantable volume in the first 50 years for all PCT and control treatments came from log grade J, and the control treatment had more volume in this log grade than did PCT treatments (Figure 5). Pre-commercial thinning did increase the volume of log grade I, and in general, lower-density PCT treatments resulted in higher volumes of log grade I; however, the higher volume of log grade I was at the expense of a much higher volume in log grade J. The highest log grade available over the 100-year period (log grade H) did not develop until after age 60 years (Figure 5), and the volume of this log grade did not vary greatly among control or PCT treatments, with the exception of T550, which had much lower volume between age 60 and 100 years than other treatments. This is because log grades are affected by density not only through piece size but also through knot size, taper, and wood density, as measured by rings per centimetre. Minimum top diameter for log grade H and I are both 38 cm, but log grade H requires a minimum ring width of five growth rings per 2 cm of wood thickness and a maximum knot size of 4 cm compared to no ring width minimum and maximum knot size of 8 cm for log grade I (Table 2). At 550 sph, the wide spacing allowed these negative wood qualities to offset the potential value of the larger log size. Consequently, although T550 produced the highest volume of log grade I, it had the lowest volume of log grade H over the 100-year projection. In other words, thinning to low densities to produce larger log sizes will not necessarily result in higher log value if log quality is reduced.

Will Pre-commercial Thinning Lead to Reduced Harvesting Costs?

An assumption that is often used to justify PCT treatments is that larger tree size will reduce harvesting costs and will therefore result in better returns on investment. To test this assumption, we used two harvesting cost functions: FAN$IER's ground-based default function that considers merchantable volume/hectare and average tree size and adjusts costs for small trees < 0.34 m³/ha, and a test equation developed by FPI that is based solely on merchantable volume/tree and results in lower harvesting costs for a larger log size. Both equations resulted in lower overall harvesting costs in the PCT treatments than in the untreated control (see the example in Figure 6), and the FPI cost function resulted in lower harvesting costs than the FAN$IER's default. Harvesting cost projections in both cases indicated that harvesting costs in the untreated control tended to converge with those of the PCT treatment as the stand aged and tree size increased. Despite the higher harvesting costs for the control relative to the PCT treatments, SV tended to be higher for the untreated control. As harvesting technology improves, harvesting costs will undoubtedly decrease; further harvesting cost research is needed to ensure that harvesting functions accurately represent reality.

What Are the Effects of Pre-commercial Thinning on Biological Rotation Age?

Biological rotation age occurs at the culmination of MAI (CMAI). When the stand-level objective was to achieve 95% of CMAI, the age where this occurred was 46 years for the control but 70, 66, 60, and 54 years for PCT treatments T550–T1200, respectively, with the more heavily PCT treatments achieving the objective at a later age (Table 7). The age to reach 95% CMAI is much earlier than the age to achieve 100% CMAI, which would be 56 years for the control and 97, 90, 79, and 70 years for PCT treatments T550 to T1200, respectively (data not shown); this reflects the relatively flat asymptote of the volume-over-age curve.

Pre-commercial thinning treated stands have longer projected biological rotations than unthinned stands because the residual trees maintain faster growth rates over a longer period when there are fewer competitors (Curtis 1995). In our study, the control achieved 95% CMAI at a much younger age than the PCT-treated stands, but MV at this young age (46 years) was only 915 m^3/ha for the control compared to 1045–1220 m^3/ha for the PCT treatments (Table 7). Consequently, depending on economic assumptions, PCT-treated stands can have higher SV than untreated stands. For example, using a discount rate of 4% and default assumptions, T1200 had an SV ($2073/ha) that surpassed that of the control ($2052/ha) at 95% CMAI, but when the discount rate was reduced to 2%, the SV of all PCT treatments exceeded that of the control at 95% CMAI (Table 7). These findings are consistent with other financial analyses of silvicultural investment (Hawkins et al. 2006), which show that SV is highly influenced by the discount rate used in the calculation. At 2% discount rate (compared to 4%), the financial advantage of improved merchantable volumes and sawlog volumes stemming from PCT treatments increases dramatically, which more than compensates for the high silviculture cost associated with PCT treatments. This explains why at 2%, all PCT treatments exceeded the control using default log prices and harvest costs (Table 7). Also, at a 4% discount rate, only T1200 had a higher SV than the control because the gain in value (diameter growth) was high enough to offset the expense of carrying the treatment costs to rotation age (Table 7). The results also suggest that T550 had the highest SV because the volume produced at 95% CMAI (70 years) was greater at that age than for the other treatments at younger ages (46–66 years).

How Do Pre-commercial Thinning Treatments Affect Financial Rotation Age (Site Value)?

Financial rotation is defined as the harvest age where SV is maximized, and in our study, SV varied with different cost-benefit assumptions (Tables 4 and 8). Under all assumptions, the unthinned control had the largest maximum SV, the earliest age at SV > 0, and the earliest stand age at maximum SV compared to any of the PCT treatments. The unthinned control treatment had the highest maximum SV, largely because it had the shortest rotation length and no thinning costs. For PCT to be economically justified, the additional costs incurred by thinning must be far less than the marginal gain in revenue as a result of stem growth. Among the PCT treatments, T1200 had the largest maximum SV, the earliest age at SV > 0, and the earliest stand age at maximum SV.

Comparing the effects of the cost-benefit assumptions (Table 5), SV was most greatly affected by the choice of discount rate, with a smaller discount rate resulting in higher SV. These findings are consistent with other financial analyses of silvicultural investment (Hawkins et al. 2006). For example, choosing a discount rate of 2% compared to 4% increased the SV of the untreated control by 239–443%, depending on which assumptions were chosen for log price and harvesting cost, and for the PCT treatments, by an average of 318–972%; the largest difference occurred with lower log price and higher harvest cost assumptions. The higher the discount rate, the lower the present value of the future stand. This can be explained by the fact that by increasing the discount rate, we are simply discounting future net revenues and costs to the present at a higher rate, and therefore reducing the SV.

Reducing the harvesting costs from the FAN$IER default equation to the FPI test function also increased SV but at a more modest level compared to reducing the discount rate. For example, for the unthinned control, using the lower log harvesting cost assumption increased the SV by as little as 13% and as much as 110%; for the PCT treatments, it increased the SV by as little as 13% to as much as 270%. The higher SVs for the control and PCT treatments occurred where the discount rate was 4% and industrial log prices were used. Finally, reducing the log prices reduced the SV by 22–52% for the untreated control, and by 28–72% for the PCT treatments. The lowest SV occurred using default harvesting costs at a 4% discount rate.

Will Pre-commercial Thinning Treatments Result in an Earlier Harvest Age?

Pre-commercial thinning treatments resulted in an earlier harvest age only when the minimum harvest criterion was average stand diameter but not when the criterion was minimum merchantable volume (250 or 350 m^3/ha), 95% MAI, or maximum SV (Tables 6–8). This is because PCT removes small trees, and as a consequence, the resulting stand will always have a larger average stand diameter than an untreated stand in the early years after treatment (the chainsaw effect). For example, using the Kalum criteria that required an average stand diameter > 25 cm, the PCT treatments T550 to T1200 were ready to harvest at about 15–19 years after treatment, or age 33–37, and considering other required criteria, including MV > 250 m^3/ha and top height > 19.5 m, the earliest harvest age for all the PCT treatments was 37 years (Table 6). However, the SV at age 37 for PCT treatments was negative for all economic assumptions; for the control, the SV at age 37 was negative for all economic assumptions, except under the FPI harvesting cost assumption (Table 6).

The age at which SV became positive always occurred earlier for the control than the PCT-treated stands; among the PCT treatments, T1200 was always earlier than other PCT treatments (Table 4). Reducing the discount rate to 2% had little effect on the age when SV became positive, but when lower log prices were used, the stand age when SV became positive increased by 6 years for the control and by 10–17 years for PCT-treated stands (Table 4).

When comparing the maximum SV (economic rotation age) using default assumptions, the age when SV was at its maximum occurred earlier for the control (60 years) than for the PCT-treated stands (up to 76 years), but treatment T1200 was closest (64 years) and provided a similar return (Table 4). The economic rotation age is established by comparing the annual growth in timber value against the cost of holding the timber for an extra year; it considers the marginal benefits and marginal costs of growing the forest one additional year. In this case, the marginal benefit of holding the timber for an additional year is higher than the cost of doing so; hence, it is better to delay the rotation age. This explains why PCT-treated stands under these scenarios have a longer economic rotation age.

Should Average Stand Diameter Be Used as a Minimum Harvest Criterion?

Using average stand diameter as the minimum harvest criterion provides a very narrow view of the stand, which can be misleading for making sound decisions. In addition to the fact that average diameter fails to show the range in tree size in both thinned and unthinned stands, average stand diameter also fails to indicate that a more heavily thinned stand will always have a larger average stand diameter than a lightly thinned stand (the chainsaw effect). For example, when average stand diameter of 25 cm is met (age 35–37 for all PCT treatments), if we were to harvest at age 37 when average stand diameter is > 25 cm (and other criteria are met), the MV of logs would be 332, 370, 407, and 504 m³/ha for treatments T550, T800, T950, and T1200, respectively (Table 6). In this case, the higher post-PCT density of 1200 sph would provide about 50–65% more MV than the more widely spaced stands. Furthermore, the SV for the spacing treatments was always negative regardless of interest rate, log prices, or harvesting cost. In comparison, if the untreated control stands were to be harvested at age 37, the same age as when the PCT stands reach > 25 cm, the MV would be 609 m³/ha, which is 105 m³/ha more than the T1200 treatment, and SV would be positive under assumptions of either a 4% discount rate, default log prices, and FPI logging costs or a 2% discount rate, default log prices, and FPI logging costs (Table 6).

Average stand dbh of 25 cm is used as a minimum harvest criterion in the Kalum TSA. This criterion arises from the results of Howard and Temesgen (1997), who found that the marginal tree size that made no contribution to covering fixed costs or profits for three harvesting system scenarios was between approximately 24 and 28 cm; therefore, they recommended that for profits to be maximized, no trees smaller than this threshold diameter should be handled. However, this marginal tree size should not be interpreted as a minimum harvest criterion because all PCT treatments harvested at the age when average stand diameter reached 25 cm, under all economic assumptions, led to negative SV. Consequently, because average stand diameter does not adequately assess response to density management, it should not be used as the minimum harvest criterion.

Was There an Optimum Spacing Density?

Finding an optimum spacing will depend on the management objectives of the stand. If the objectives were to simply maximize log size or average stand diameter or to reach a low minimum merchantable volume (such as 350 m³/ha), then heavy PCT treatments achieved these objectives earliest but resulted in lower volumes of the highest log quality and significantly lower total and merchantable volume (Table 6; Figure 4). If the stand-level objectives were to maximize SV or MV, then when the default assumptions were used, the unthinned option resulted in higher SV (Figure 7) and MV (Figure 4) than any PCT treatment; T1200 was the best of the PCT treatments, and MV for T1200 was within 5% of that of the control by age 60 and within 1% by age 70.

Other management objectives that PCT could help achieve, such as enhancing non-timber forest values, enhancing wildlife habitat, managing tree species for climate change adaptation/mitigation, and reducing future fuel loads for wildfire prevention could become increasingly important in the near future.

Continued remeasurement of this experiment and use of the data for testing different scenarios with TASS could provide much needed information for decision-makers. Further research is also needed to ensure that harvesting costs reflect current practices.

Financial analysis is an important tool for evaluating forestry investments because the costs and benefits of the initial treatment costs are weighed against their potential future financial returns; this information can help decision-makers choose between mutually exclusive projects. Although net present value is often used for financial analysis, site value (SV) is the better measure for comparing silviculture treatments, such as PCT, that may have different rotation lengths. As a general rule, to maximize the financial rotation, a rational investor will choose to harvest the stand when the growth in timber value is equal to the chosen discount rate. Harvesting when timber is growing faster than the discount rate will not maximize returns or maximize SV because the investor will still be earning more than alternative investments. When the growth in timber value is lower than the discount rate, the investor will be better off to harvest the stand early and invest the returns in an alternative investment.

The choice of discount rate is the most critical component in determining effects of silviculture treatments on SV. The higher the discount rate, the lower the SV of the forest and the less attractive silviculture investments will be. In this study, although the 2% discount rate made PCT investments more attractive than did the 4% rate, the higher rate is a better alternative because it approximates what is termed the social discount rate or a government's time preference for achieving public policy objectives. The discount rate also plays an important role in determining the optimal rotation age. In our study, increasing the discount rate from 2 to 4% resulted in a lower optimal rotation age, and the financial advantage of improved merchantable volumes and sawlog volumes stemming from PCT decreased dramatically.

The criteria used to determine the minimum harvest age (i.e., MHC) profoundly affected not just the rotation age but also MV and SV. In comparison to a minimum harvest criterion that maximized SV, a criterion that set the harvest age when average stand diameter was 25 cm favoured widely spaced PCT treatments (a result of the chainsaw effect) and resulted in very young rotation ages with low harvestable MV and very negative SV. A criterion that set the harvest age when a minimum MV of 350 m^3/ha was reached favoured the unthinned control for minimum harvest age, but all treatments, including the control, had low MV and negative SV. The minimum harvest criterion that maximized MAI, also called the biological rotation age, favoured the control for minimum harvest age, MV, and SV, and all treatments provided positive SV.

Assumptions made at the time of investment introduce risk because they may prove wrong decades later. Risks can be examined using sensitivity analyses to test an assumption, and this is useful to help weigh the risks during decision-making. In this study, higher discount rates, lower log prices, and higher harvesting costs made PCT investments less financially viable than the untreated control.

Other risks to long-term silviculture investments include negative effects on growth and yield from climate change and associated increases in pests and diseases. To mitigate these risks, PCT treatments should encourage species diversity and err on the side of higher densities. In our study, except where minimum average diameters were the MHC, the denser treatment T1200 typically resulted in higher MV and SV than lower-density treatments. However, if sites are prone to drought and wildfire, more widely spaced PCT treatments might be favoured, but this will have an associated lower MV and SV.

CONCLUSIONS

Despite the higher volume of larger logs and lower harvesting costs resulting from PCT treatments, the unharvested control tended to have higher site value. Sensitivity analyses indicated that lower discount rate, lower harvesting costs, and higher log prices increased the site value of all treatments. Minimum harvest criteria that reduced harvest age reduced merchantable volumes and site value. In general, the denser 1200 sph treatment provided the best merchantable volume and site value of the PCT treatments. Continued monitoring of this experiment over time will provide better information about the longer-term effects on growth, yield, and economic returns of PCT in these mixed western hemlock and amabilis fir stands.

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