Natural Resources Canada
Ressources naturelles Canada

Shifting the focus from volume yield toward financial returns and harvest timing

Showcasing the TASS and FAN$IER models to project volumetric growth and yield and financial returns of lodgepole pine and white spruce after site preparation at three sites in north-central British Columbia

Antoine Lalumière, Jean Heineman, Jim Goudie, John McClarnon,
Ken Polsson, Mario Di Lucca, and Roger Whitehead

Information Report
FI-X-020

2019

Canadian Wood Fibre Centre
Working together to optimize wood fibre value – creating forest sector solutions with **FP**Innovations.

Canada

The Canadian Wood Fibre Centre, Ottawa, Ontario

Working together to optimize wood fibre value – creating forest sector solutions with FPInnovations.

Additional information on Natural Resources Canada, the Canadian Forest Service, and the Canadian Wood Fibre Centre research and publications is also available online at: **https://www.nrcan.gc.ca/science-and-data/research-centres-and-labs/forestry-research-centres/canadian-wood-fibre-centre/13457**. To download this publication, see our online bookstore at: **https://cfs.nrcan.gc.ca/publications**.

Natural Resources Canada	Ressources naturelles Canada

Shifting the focus from volume yield toward financial returns and harvest timing

Showcasing the TASS and FAN$IER models to project volumetric growth and yield and financial returns of lodgepole pine and white spruce after site preparation at three sites in north-central British Columbia

Antoine Lalumière, Jean Heineman, Jim Goudie, John McClarnon, Ken Polsson, Mario Di Lucca, and Roger Whitehead

Natural Resources Canada
Canadian Forest Service
Canadian Wood Fibre Centre

2019

Fo4-140/2019E-PDF (PDF)
ISBN (PDF): 978-0-660-32021-2

A pdf version of this publication is available through the Canadian Forest Service Publications website: http://cfs.nrcan.gc.ca/publications.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge assistance, comments, and insight from (in no particular order): the British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development, Lorne Bedford, Al Powelson, Mei-Ching Tsoi, Frank McAllister, Phil Comeau, Torsten Kaffanke, Fred Klassen, Dunkley Lumber Ltd., Doug Perdue, Brad Johnson, Jim Whybra, Richard Kyle, Steve Stearns-Smith, Jacob Boateng, George Harper, Amanda Linnell Nemec, Ian Cameron, Oscar Garcia, Sandy Allen, Dominique Lejour, Ross Koppenaal, John Vallentgoed, Steve Taylor, Randy Butcher, Francesco Cortini, and anyone else we may have forgotten to list here. We also acknowledge funding support for this work from the Sustainable Fibre Solutions Program of the Canadian Forest Service, Natural Resources Canada. We thank Jim Stewart for reviewing the manuscript.

ABSTRACT

We used components of the British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development's suite of decision support tools, SYLVER (which facilitates evaluation of the effects of Silviculture on Yield, Lumber Value and Economic Return), to model and compare predicted merchantable wood volume and financial outcomes of stands that developed following various site preparation or vegetation control treatments applied at experimental sites in north-central British Columbia. We used data collected over a 25-year period on lodgepole pine at the Bednesti and Stony Lake sites (Sub-boreal Spruce biogeoclimatic zone) and on white spruce at the Inga Lake site (Boreal White and Black Spruce biogeoclimatic zone) to model predicted future growth and yield using the TASS (Tree And Stand Simulator) model, and used the FAN$IER (Financial ANalysis of Silviculture Investment and Economic Return) modelling software to compare predicted financial outcomes. The magnitude and timing of maximum net present value (NPV), site value (SV), and internal rate of return (IRR) financial metrics were interpreted in comparison with the age at which predicted maximum mean annual increment (MAI), and an operational merchantable volume target of 250 m^3/ha, were projected to be attained.

In the lodgepole pine stands, best-case outcomes defined by maximum NPV, SV, and IRR were consistently predicted to occur between ages 35 and 55 years, which was earlier than the age at which maximum MAI was predicted. On average, across all treatments at the Bednesti and Stony Lake sites, maximum NPV, SV, and IRR were predicted in pine stands at ages 49, 46, and 38 years, respectively. At the Bednesti site, the shear and pile control treatment selected to approximate post-harvest conditions (and assumed to have no cost for this exercise) outperformed all other treatments. The commonly applied disc trenching treatment had only 87% as many trees as in the shear and pile control treatment at age 25, which likely contributed to the lower volume increase projected in the former. At the Stony Lake site, maximum NPV was predicted to be approximately equal in the most costly treatment (a combination of disc trenching and follow-up brushing that produced the best growth) and in the no-cost treatment (shear and pile).

In the white spruce stands, maximum NPV, SV, and IRR were predicted to occur between ages 40 and 70 years, which again was earlier than the age projected for maximum MAI. Across all treatments at the Inga Lake site, NPV and SV maxima were projected at age 58 years and maximum IRR was projected at age 45. A herbicide-based vegetation control treatment (with follow-up manual brushing) applied at the Inga Lake site consistently showed the highest predicted financial returns from white spruce because volume development at that site was highly dependent on the extent to which treatments controlled overtopping vegetation. The plow inverting and vegetation control treatments were approximately equally successful and showed very good predicted volumetric and financial outcomes. Disc trenching did not effectively control vegetation at this site, and resulted in very low volumetric and financial returns that were only marginally higher than those predicted in the shear and pile control treatment.

The FAN$IER model provides a means of evaluating the effects of harvesting at different ages on financial outcomes. Our projections for lodgepole pine suggest that NPV, SV, and IRR are maximized no later than age 50, and before the stands have attained 95% MAI culmination age, which is the current criterion used for timber supply planning in the Prince George TSA of central British Columbia. For both pine and spruce, the model runs indicated that NPV can increase or decrease steeply during individual 5-year periods between stand ages 40–65 years, which highlights the importance of careful determination of harvest age. Decisions regarding harvest age are based on many factors besides maximizing financial returns, however; under current model parameters, adhering strictly to that single objective would result in more frequent harvesting of young stands, which could potentially negatively impact other forest values, as well as reduce the landscape-level structural diversity of our forests and limit our ability to respond to future market changes.

CONTENTS

TABLES

FIGURES

1 INTRODUCTION

Silviculture research most often focusses on coniferous tree responses to treatment, and results are generally discussed and interpreted from biological and ecological perspectives. Long-term tree growth data from many silviculture experiments have contributed to the calibration of growth and yield modelling software programs such as TASS[1] (Tree And Stand Simulator) and TIPSY[2] (Table InterPolation for Stand Yields) that are used for timber supply planning in British Columbia (Mitchell 1975; Mitchell et al. 2007). However, when making decisions about the allocation of financial resources at any level, from individual site prescriptions to landscape-level management plans, policy makers and managers from both public and private sectors also require information about the long-term financial implications of their choices.

The FAN$IER[3] (Financial ANalysis of Silviculture Investment and Economic Return) analysis software program (which supersedes FAN$Y, which superseded the TIPSY Economist) was developed to facilitate informed decision-making regarding silviculture investment in British Columbia. It is one component of a suite of predictive software tools known as SYLVER[4] (Silviculture on Yield, Lumber Value and Economic Return) (Mitchell et al. 1989), and provides a user-friendly means of comparing treatment options. The FAN$IER model applies default or customized cost and product value inputs to TASS and TIPSY growth and yield simulations to compute financial projections. It produces a range of outputs that include net present value (NPV), site value (SV), and internal rate of return (IRR).

The FAN$IER model can be used to compare the costs and benefits of specific silviculture treatments such as the various site preparation techniques that are available in British Columbia (von der Gönna 1992). Site preparation is widely used in British Columbia to facilitate the establishment and improve the early growth of conifer seedlings following harvest. Between 1980 and 2013, site preparation was applied to approximately 60% of the area requiring reforestation following harvesting or wildfire[5] in the Sub-boreal Spruce (SBS) and Boreal White and Black Spruce (BWBS) biogeoclimatic zones (Meidinger and Pojar 1991). Recent analyses using long-term data indicate that growth responses to certain site preparation treatments may be large and persistent enough to reduce rotation length (e.g., Cortini et al. 2010; Whitehead et al. 2011). Preliminary analyses of the costs and benefits of site preparation treatments have suggested that the techniques may be cost-effective over the long term, and that they are underutilized (Hawkins et al. 2006).

In 1987, several long-term site preparation studies were installed in sub-boreal and boreal British Columbia to investigate lodgepole pine (*Pinus contorta* var. *latifolia*) and white spruce (*Picea glauca*) responses to a range of site preparation techniques. We have used the British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development's TASS and FAN$IER modelling software to project and compare volumetric and financial outcomes of a subset of treatments set up to investigate growth and yield of lodgepole pine at two sites in the SBS zone (Taylor et al. 1991; Whitehead et al. 2011; Boateng et al. 2012; McClarnon et al. 2016), and white spruce at one site in the BWBS zone (Boateng et al. 2009; Powelson et al. 2016). These trials have been measured periodically for 24–25 years. Treatments were selected to allow comparison of outcomes where no site preparation other than preliminary shearing and piling was applied with those resulting from the most and least effective site preparation treatments. The disc trenching treatment was also included because it is currently the most frequently used site preparation technique in the SBS zone,[6] and because it was common to all three studies.

2 METHODS

2.1 Site Characteristics

The Bednesti study site is located approximately 50 km west of Prince George, B.C., in the Stuart variant of the dry warm Sub-Boreal Spruce subzone (SBSdw3) (Delong et al. 1993). The site was strip harvested in 1963–1964, with remaining strips removed in 1971. By 1986, the site was insufficiently stocked with juvenile conifers growing amongst a relatively non-competitive low shrub-herb community. Standing juvenile trees were sheared and piled into windrows in winter 1986/87 in preparation for the research study, and windrows were burned in fall 1988.

---

[1] https://www.for.gov.bc.ca/hts/growth/tass/tass_overview.html#

[2] https://www.for.gov.bc.ca/hts/growth/tipsy/tipsy_description.html

[3] https://www.for.gov.bc.ca/hts/growth/fanier/fanier_description.html

[4] https://www.for.gov.bc.ca/hts/growth/sylver/sylver_description.html

[5] From the B.C. Ministry of Forests, Lands, and Natural Resources RESULTS (Reporting Silviculture Updates and Landstatus Tracking System) database (May 2014).

[6] Ibid.

The Stony Lake study site is located approximately 90 km southeast of Prince George, B.C., in the Willow variant of the wet cool SBS subzone (SBSwk1) (Delong 2003). The site was selectively logged from 1968 to 1970, and by 1986 scattered residual conifers and a dense layer of competitive shrubs and herbs, including black twinberry (*Lonicera involucrata*), thimbleberry (*Rubus parviflorus*), and fireweed (*Epilobium angustifolium*), occupied the site. Treatment plots used for modelling in the present study were sheared with a brush blade in summer 1987. Slash was piled into windrows outside the plot boundaries and burned in fall 1987.

The Inga Lake study site is located approximately 85 km northwest of Fort St. John, B.C., in the Peace variant of the moist warm BWBS subzone (BWBSmw) (Delong et al. 2011). The site is of fire origin, and has no harvest history, but was periodically burned until the 1950s to improve livestock forage. As a result, in 1986, it had a well-developed tall shrub community that was dominated by willow (*Salix* spp.). The site was mechanically sheared and piled into windrows in preparation for the study in winter 1986/87, and windrows were burned in fall 1987. Site and climate characteristics for all three sites are provided in Table 1.

Table 1. Site and climate characteristics

	Bednesti	Stony Lake	Inga Lake
Site characteristics			
Latitude/longitude	53°52' N/123°29' W	53°27' N/121°54' W	56°37' N/121°38' W
BEC unit/site series	SBSdw3/05 (01)	SBSwk1/01	BWBSmw/01
Elevation	850 m	960 m	890 m
Soil moisture regime	Mesic	Mesic	Mesic to subhygric
Soil nutrient regime	Poor	Medium to good	Medium
Slope	0–15%	0–10%	0–15%
Aspect	Variable rolling terrain	Level to West	Variable rolling terrain
Soil texture	Silty clay loam to sandy loam	Loam	Fine to coarse loam
Coarse fragment content	10–65%	15–20%	15–25%
Effective rooting depth	10–50 cm	30–50 cm	5–25 cm
Climate characteristics[a]			
Mean annual temperature (°C)	3.3	3.3	1.5
Mean annual precipitation (mm)	597	847	483
Precipitation as snow (mm)	235	327	143
Average frost-free period (days)	106	92	99

[a] From Climate BC (updated July 5, 2015) using normals 1981–2010. Wang et al. (2012). Accessed Feb. 11, 2016.

2.2 Experimental Design and Treatments

The results presented in this report were projected from growth data of selected treatments from the three research sites (Table 2). A randomized complete block design that included five blocks was implemented in each of the Bednesti and Inga Lake studies. Plot shape, size (range of 0.24–0.52 ha), and the spacing of planted trees varied at these sites due to the different site preparation configurations and machinery dimensions; as a result, planting density per hectare varied among treatments (Table 2). The Stony Lake study was set up as a split-split plot design with regularly shaped rectangular 0.10-ha plots, resulting in consistent planting density among treatments. In the three studies, site preparation treatments were performed in fall 1987, and planting was carried out in spring 1988. The Bednesti and Stony Lake sites were planted with PSB 211 1+0 lodgepole pine, and the Inga Lake site with PSB 313 2+0 white spruce. Full descriptions of experimental designs and treatments have been published previously for the Bednesti (McClarnon et al. 2016), Stony Lake (Taylor et al. 1991; Whitehead et al. 2011), and Inga Lake (Powelson et al. 2016) studies.

2.3 Measurements

Lodgepole pine and white spruce height (± 5 cm) and diameter (± 0.1 cm) were measured at intervals up to year 25 at the Bednesti site as described by McClarnon et al. (2016) and up to year 25 at the Inga Lake site as described by Powelson et al. (2016). At the Stony Lake site, measurements were taken in years 1 (1988), 2, 3, 4, 5, 12, 20, and 25 (Whitehead et al. 2011). Diameter was measured at ground level until years 9, 12, and 10 at the Bednesti, Stony Lake, and Inga Lake sites, respectively, and at breast height of 1.3 m (dbh) thereafter.

Table 2. Summary of the treatments modelled from the Bednesti, Stony Lake, and Inga Lake long-term research sites

Site	Treatment	Site preparation machinery used (after shear and piling)	Average planting density (stems/ha)[a]	Treatment cost ($/ha)[b]	Description
Bednesti	Shear & pile control (SPC)	None	1280	$0	Entire cutblock was sheared and piled using a flat-bladed D8 Caterpillar working on snowpack in winter 1986/87. The result approximated newly harvested conditions with no mineral soil exposure. There was no further site preparation. Seedlings were planted into boot screefs.
	Plow inverting (PI)	Double-bottom agricultural breaking plow pulled by D7 crawler tractor	1891	$379	Plow inverting was applied in late summer 1987 (after shearing and piling). Furrow slices were laid down in somewhat irregular berms separated by gaps. Material was loose even after over-winter settling. Soil exposure was 100%. Seedlings were planted deeply into the loose berm material.
	Disc trench hinge (DTH)	TTS Delta disc trencher pulled by a rubber-tired skidder	1142	$214	Disc trenching was done in late summer 1987 (after shearing and piling). Continuous, shallow, linear furrows with loosely mixed berms that were spaced 3 m apart. Soil exposure averaged 48%. Seedlings were planted at the hinge of the berm and furrow.
	Disc trench furrow (DTF)	As above for DTH	1193	$214	Disc trenching was done in late summer 1987 (after shearing and piling). Continuous, shallow, linear furrows with loosely mixed berms that were spaced 3 m apart. Soil exposure averaged 48%. Seedlings were planted in the exposed mineral soil at the bottom of the trench.
Stony Lake	Shear & pile control (SPC)	None	1111	$0	Treatment area was sheared and piled in June 1987 with a brush blade mounted on an International TD-15C crawler tractor. Seedlings were planted into boot screefs.
	Disc trench hinge (DTH)	TTS Delta disc trencher pulled by a rubber-tired skidder	1111	$214	Disc trenching was done October 1987 (after shearing and piling). Treatment characteristics were approximately the same as described above for the DTH treatment at the Bednesti site. Seedlings are assumed to have been planted at the hinge of the berm and furrow.
	Post-planting vegetation control (VC)	None	1111	$261	No site preparation except shearing and piling in June 1987. Seedlings were planted into boot screefs. After three growing seasons (August 1990), glyphosate (Vision®) was broadcast applied at a rate of 1.8 kg ae/ha.
	Disc trench hinge + post-planting vegetation control (DTH+VC)	As described above for DTH	1111	$475	Disc trenches were installed as described for the Bednesti site. After three growing seasons (in August 1990), glyphosate (Vision®) was broadcast applied at a rate of 1.8 kg ae/ha. Seedlings are assumed to have been planted at the hinge of the berm and furrow.
Inga Lake	Shear & pile control (SPC)	None	1421	$0	Shearing and piling was done in winter 1986/87 as described above for the Bednesti site. Seedlings were planted to the root collar without screefing.
	Plow inverting (PI)	3-bottom breaking plow	1664	$379	Plow inverting was applied in late summer 1987 (after shearing and piling), as described for the Bednesti site. Seedlings were planted deeply into the loose berm material.
	Disc trench hinge (DTH)	As described above for DTH at the Bednesti site	1097	$214	Disc trenching was done in late summer 1987 (after shearing and piling), as described above for the Bednesti site. Seedlings were planted at the hinge of the berm and furrow.
	Post-planting vegetation control (VC)	None	1437	$261	No site preparation except the shearing and piling that was done in winter 1986/87 and no mineral soil exposure. Seedlings were planted into boot screefs. After three growing seasons, glyphosate (Vision®) was broadcast applied at a rate of 2.14 kg ae/ha, but failed to control willow, which had been defoliated by insects that year. Manual cutting treatments were subsequently applied 4, 6, 8, 9, 11, and 14 years after planting.

a Planting densities were calculated from TASS input files as described in Section 2.4.

b Treatment costs are 2006 Canadian dollar values.

2.4 Data Manipulation and Modelling

Growth data from the long-term research installations at the three sites were used as in Whitehead et al. (2011), to generate input files for TASS growth modelling using customized runs. Due to unequal planting density among block replicates of the treatments at the Bednesti and Inga Lake sites (Figure 1), each block replicate (each plot) was modelled separately using plot-level values to generate input files. At the Stony Lake site, equal planting density among block replicates (Figure 1) allowed treatment averages to be used as by Whitehead et al. (2011). Input parameters were localized using permanent sample plot data to describe the spatial tree distribution, initial planting density, individual tree vigour (based on height growth), mortality, site index, and height-age curves to year 25 at the Bednesti and Stony Lake sites, and year 24 at the Inga Lake site (in all three cases this is 26 years of growth in total from seeding). We estimated effective site index (SIE) from current growth, using the growth-intercept method (Nigh 1997, 2004).

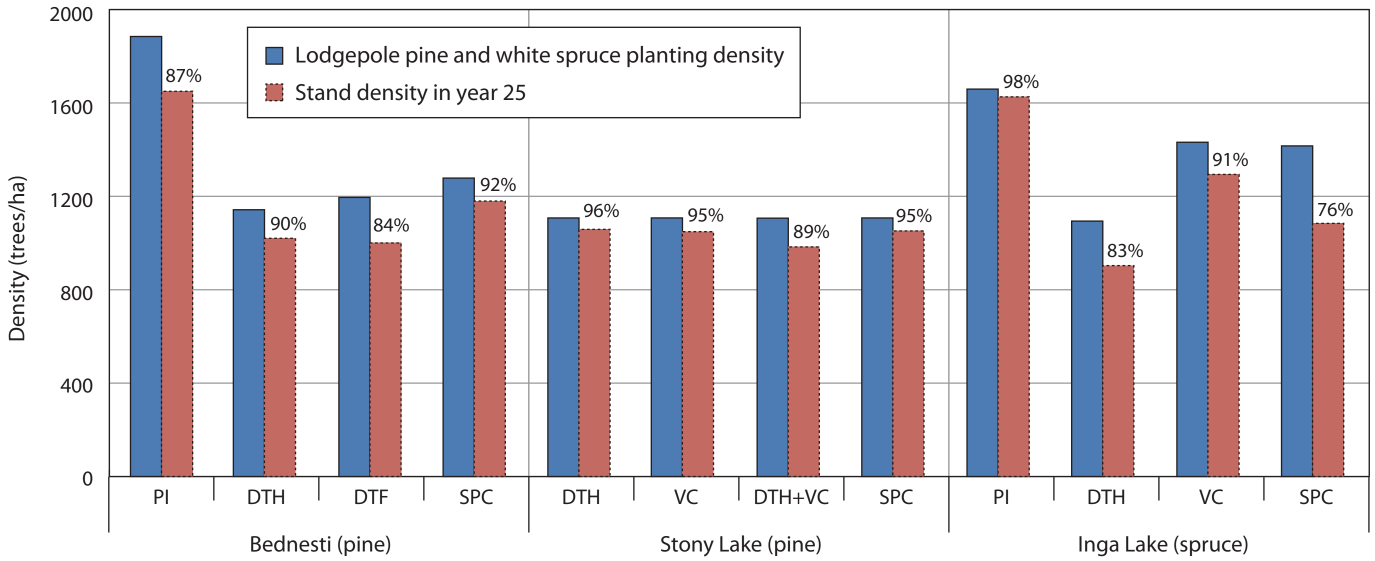


Figure 1. Lodgepole pine and white spruce planting density (dark bars with solid outline) and stand density in year 25 site (pale bars with dashed outline) in selected treatments at the Bednesti and Stony Lake sites and year 24 at Inga Lake. Values above the pale bars are year 24 or 25 percentage survival of the planted trees. PI is plow inverting; DTH is disc trench hinge; DTF is disc trench furrow; SPC is shear and pile control; VC is vegetation control; DTH+VC is disc trench hinge + vegetation control in year 3.

Whereas site index estimates are intended to express site potential based on the growth of undamaged trees under unimpeded conditions (Stearns-Smith 2001), SIE characterizes growth under conditions (e.g., the presence of overtopping vegetation) that may have impacted potential growth, an important consideration at the Inga Lake site where overtopping vegetation had a severe impact on spruce growth after the dominant trees had reached breast height. For each treatment at the Stony Lake site, block replicate (plot) areas and planting locations were replicated and positioned randomly to generate the necessary areas for TASS (yielding one area per treatment), and for treatment-level FAN$IER projections. Because of the irregularly shaped plots at the Bednesti and Inga Lake sites that had different planting densities, each plot was replicated individually as few times as possible to generate an area for TASS modelling measuring at least one hectare.[7]

To generate treatment-level results from the Inga Lake and Bednesti sites, FAN$IER plot-level projections were then averaged at the treatment level. Quadratic mean dbh values generated by TASS at the last sampling age were compared with measured values to verify the predictive accuracy of the model (not presented). Operational Adjustment Factor (OAF) values were turned off in TASS (OAFs 1 and 2 both set to 1.0) because mortality was explicitly modelled to age 25. This may result in a slight underestimation of the mortality likely to occur beyond age 25 that is normally accounted for with the OAFs; however, using default OAFs in the TASS runs would have double-counted mortality to age 25, thus artificially inflating it to a much greater extent than the potential underestimation caused by not including the OAFs. The FAN$IER model runs were conducted using TASS-generated "regime" output files. With the exception of site preparation treatment costs, we used 2006 default costs for sites regenerated with lodgepole pine or white spruce in the

---

[7] Values for planting density per hectare that were generated using this approach differed slightly from those reported by McClarnon et al. (2016) and Powelson et al. (2016).

Northern Interior Forest Region, and a discount rate of 4%. Representative site preparation treatment costs (Table 2) were determined by averaging cost estimates from two to six sources per treatment ranging from 1987 to 2012, and an interest rate of 2% was used to discount the costs to 2006 Canadian dollar values. Default planting costs based on B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development District averages were used in the FAN$IER model. We present standing merchantable volume projected by the TASS model (MERCHVOLST, m^3/ha) at the site preparation treatment level. Standing merchantable volume is calculated using minimum dbh of 12.5 cm, top diameter inside bark (DIB) of 10.0 cm, and stump height of 0.3 m. Because operational managers have indicated that they are mainly interested in projections of stand volume, with less concern for juvenile wood, we present corresponding financial projections of graded lumber generated by the FAN$IER model (FAN$IER product category "Lumber & Mill Residues (Pre Adjustments)." This output lumber category includes Residual, Clear, Select Structural, #1, #2, #3, and #4 grades, and takes knots into account, but does not include degrade due to juvenile wood.[8] The earliest occurring maxima of the treatment-average net present value (NPV, $/ha), site value (SV, $/ha), and mean annual increment of merchantable volume (MAI, m^3/yr) over time were determined, and the timing and magnitude of the maximum NPV and MAI values were plotted as insets on graphs of MERCHVOLST and SV over time. This allows the financial and biological rotation ages to be easily seen on the graphs, along with the magnitude of these metrics. We also present dimensional lumber product (2 × 4, 2 × 6, 2 × 8, 2 × 10) spectra of Clear, Select Structural, #1, #2, #3, and #4 lumber grades (regime file output lumber category "Lumber & Chips") projected by the SAWSIM module of the SYLVER suite of models, for individual treatments at each site.

3 RESULTS AND DISCUSSION

3.1 Merchantable Volume and Mean Annual Increment

Bednesti

At the Bednesti site, MERCHVOLST development, as modelled by TASS, was similar among the three most successful treatments (disc trench hinge, plow inverting, and shear and pile control) until approximately age 30 (Figure 2), with maximal difference around 35 m^3/ha. Beyond age 35, however, TASS projections showed that MERCHVOLST development in the shear and pile control treatment was projected to increasingly exceed that projected in the disc trench hinge and plow inverting treatments. There were only 87% as many trees in the disc trench hinge treatment as in the shear and pile control treatment at age 25 (Figure 1), which likely contributed to the lower volume increase projected in the former. Volume was also projected to accumulate more slowly in the plow inverting treatment than the shear and pile control treatment, despite density being 40% higher at age 25 in the former. The fourth treatment at the Bednesti site (disc trench with seedlings planted in the furrow) was projected to have considerably lower MERCHVOLST than the other treatments for at least 95 years (Figure 2). This trend was evident as early as age 20 years, and is attributed primarily to the planting position in the bottom of the trench furrow providing inhospitable conditions for seedling establishment, which resulted in worse survival and early growth than in the other treatments (Boateng et al. 2010; McClarnon et al. 2016).

The greater rate of accumulation of merchantable volume projected after age 30 in the shear and pile control stand (SIE 20.7 m) than in the disc trench hinge and plow inverting treatments (SIE 20.8 m and 21.2 m, respectively) is interesting in that it differs from trends anticipated based on the ordering of SIE that we describe, and the ordering of year 25 gross stand volume reported by McClarnon et al. (2016). McClarnon et al. reported no significant differences in gross stand volume or gross stand volume increment (determined from the sum of individual calculated tree volumes or volume increments) between these three treatments at age 25, and mean growth rates did not suggest that the ordering of gross volume observed at that age (plow inverting > disc trench hinge > shear and pile control) was likely to change.

Despite our ordering of SIE corroborating the results observed by McClarnon et al. (2016), TASS projections suggest that the treatment ordering will change as the stands age. We attribute the higher merchantable volume projected in the shear and pile control to a combination of favourable planting density (1280 stems/ha) and high survival (92% at age 25), which resulted in a stand density of 1180 stems/ha at age 25 (Figure 1). The disc trench hinge treatment was projected to accumulate less merchantable volume over time than the shear and pile control treatment due to lower initial planting density (1142 stems/ha) and density at age 25 (1029 stems/ha) despite similar percentage survival by age 25 (90%) (Figure 1). In contrast, projected merchantable volume accumulation in the plow inverting treatment may be lower than that in the shear and pile control treatment due to a combination of high planting density (1891 stems/

---

[8] Refer to: www.for.gov.bc.ca/hts/growth/fanier/fanier_news.html#

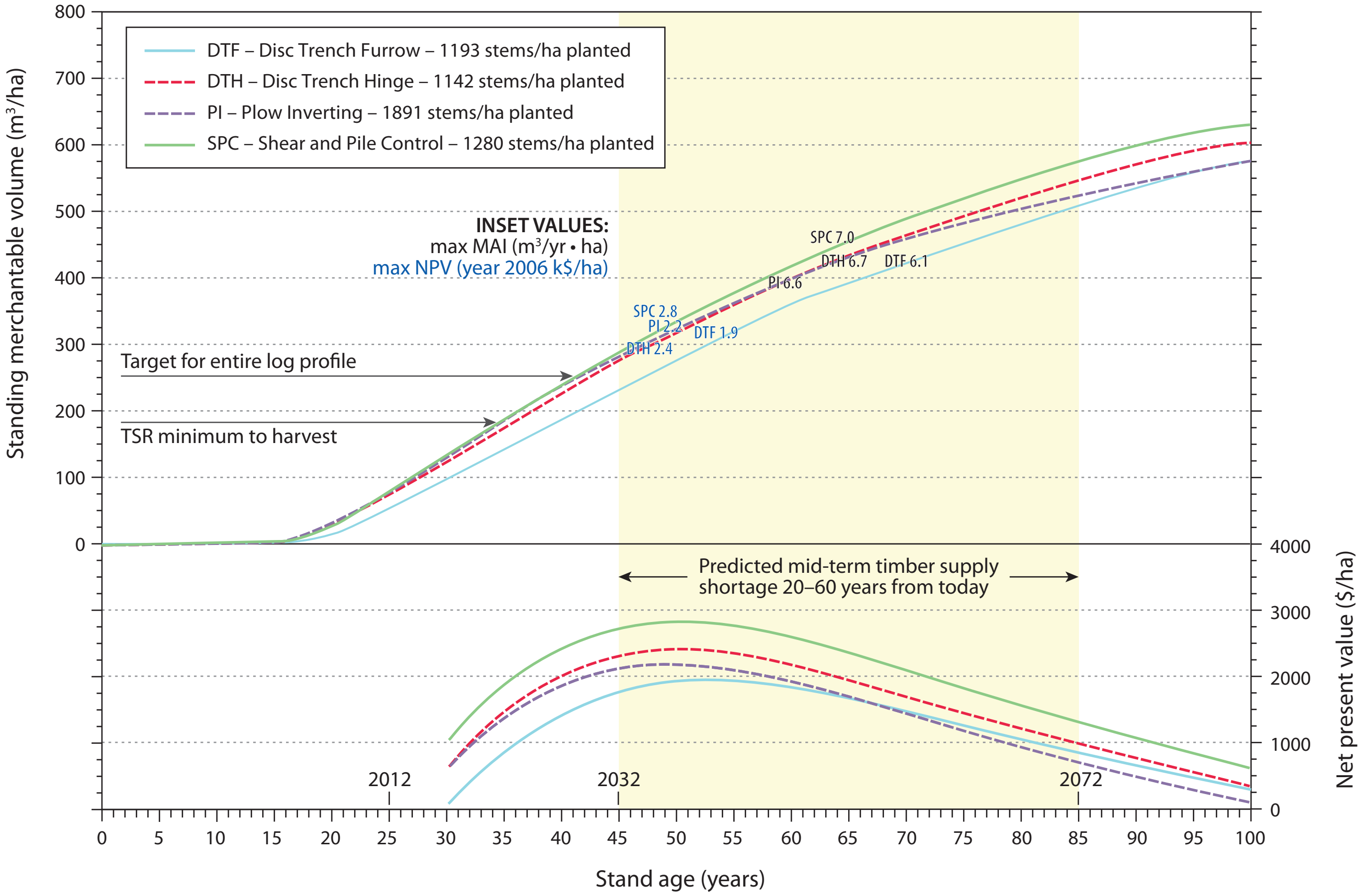


Figure 2. Merchantable volume estimates (predicted by TASS) and net present value estimates (predicted by FAN$IER) for lodgepole pine in the disc trench furrow (DTF), disc trench hinge (DTH), plow inverting (PI), and shear and pile control (SPC) treatments at the Bednesti long-term research site.

ha) and survival (87%), which resulted in a density of 1652 stems/ha at age 25 that may have been higher than optimal for maximizing merchantable volume accumulation at the Bednesti site. Until approximately age 65, TASS projected similar merchantable volume accumulation in the disc trench hinge and plow inverting treatments, despite the fact that the disc trench hinge had only 62% as many trees at age 25. Beyond age 65, however, the lower-density disc trench hinge treatment was projected to be more productive. The TASS projections suggest that planting density, which was not controlled in the Bednesti experiment, may have had a greater effect on long-term merchantable volume development than the type of site preparation treatment, or than SIE; this hypothesis is worthy of further investigation through an observational or theoretical (TASS) study that controls planting density.

Maximization of MAI was predicted at age 60 in the plow inverting treatment, age 65 in the disc trench hinge and shear and pile control treatments, and age 70 in the disc trench furrow treatment (Table 3, Figure 2). Higher planting density in the plow inverting treatment likely contributed to earlier predicted maximization of MAI in that treatment than in others. Harvesting at MAI culmination age is a common forest management strategy (Smith 1986), and from that perspective, the plow inverting treatment stand could be harvested at age 60, 5 years before the disc trench hinge or the shear and pile control treatment stands, albeit at lower merchantable volume. At the Bednesti site, the plow inverting treatment stand was also predicted to reach the industry target[9] merchantable volume of 250 m^3/ha 1 year earlier than the disc trench hinge treatment stand and less than 1 year after the shear and pile control treatment stand (Table 4, Figure 2). The shear and pile control, plow inverting, and disc trench hinge treatments were all predicted to reach this industry target merchantable stand volume between 41 and 42 years after planting, while the disc trench furrow treatment was not predicted to attain this target until 46 years after planting (Table 4, Figure 2).

---

[9] Based on information provided by Dunkley Lumber Ltd. (2014).

Table 3. Age at which mean annual increment of volume (MAI), net present value (NPV), site value (SV), and internal rate of return (IRR) are projected to be maximized in the site preparation trials examined at the Bednesti, Stony Lake, and Inga Lake long-term research sites

			MAI		NPV		SV		IRR	
Species	**Site**	**Treatment**[a]	**Maximum (m^3/yr·ha)**	**Age at maximum (years)**	**Maximum (\$/ha)**[b]	**Age at maximum (years)**	**Maximum (\$/ha)**[b]	**Age at maximum (years)**	**Maximum (%)**	**Age at maximum (years)**
Lodgepole pine	Bednesti	PI	6.64	60	\$2175	50	\$2547	45	6.9	40
		DTH	6.68	65	\$2401	50	\$2777	50	7.4	40
		DTF	6.11	70	\$1934	55	\$2225	50	6.8	45
		SPC	7.00	65	\$2817	50	\$3266	45	8.4	40
	Stony Lake	DTH	7.22	60	\$2985	45	\$3573	45	8.3	35
		VC	6.88	60	\$2682	50	\$3163	45	7.7	35
		DTH+VC	7.77	60	\$3161	45	\$3784	45	7.7	35
		SPC	7.07	60	\$3036	50	\$3618	45	9.1	35
White spruce	Inga Lake	PI	8.70	55	\$3111	50	\$3577	50	6.9	45
		DTH	4.44	90	\$732	60	\$803	60	5.7	45
		VC	9.53	55	\$3895	50	\$4478	50	7.8	40
		SPC	3.57	100	\$283	70	\$301	70	4.7	50

a PI is plow inverting; DTH is disc trench hinge; DTF is disc trench furrow; SPC is shear and pile control; VC is vegetation control; DTH+VC is disc trench hinge + vegetation control in year 3.

b Canadian dollar value in 2006.

Table 4. Effective site index[a] and time[b] required to attain the industry target standing merchantable volume[c] of 250 m^3/ha, and the associated differences in that timing relative to the shear and pile control treatment in site preparation treatments examined at the Bednesti, Stony Lake, and Inga Lake long-term research sites

	Lodgepole pine						White spruce		
	Bednesti			Stony Lake			Inga Lake		
		Time to 250 m^3/ha			Time to 250 m^3/ha			Time to 250 m^3/ha	
Treatment[d]	**Effective site index (m)**	**Age (years)**	**Difference relative to SPC (years)**[e]	**Effective site index (m)**	**Age (years)**	**Difference relative to SPC (years)**	**Effective site index (m)**	**Age (years)**	**Difference relative to SPC (years)**
PI	21.2	41.4	+0.4	–	–	–	22.9	37.6	−38.9
DTH	20.8	42.4	+1.4	24.0	38.5	−0.8	18.1	62.7	−13.8
DTF	19.8	46.2	+5.2	–	–	–	–	–	–
VC	–	–	–	22.8	40.4	+1.1	23.5	36.3	−40.2
DTH+VC	–	–	–	23.4	36.9	−2.4	–	–	–
SPC	20.7	41.0	–	23.2	39.3	–	18.5	76.5	–

a Effective site index was estimated using current growth data to year 25 (Bednesti and Stony Lake) or year 24 (Inga Lake).

b Time determined by interpolation of values generated by TASS at 5-year intervals.

c Target merchantable volume based on information provided by Dunkley Lumber Ltd. (2014).

d PI is plow inverting; DTH is disc trench hinge; DTF is disc trench furrow; SPC is shear and pile control; VC is vegetation control; DTH+VC is disc trench hinge + vegetation control in year 3.

e Negative and positive values indicate, respectively, reductions and increases in the time required to reach the 250 m^3/ha merchantable volume target relative to the shear and pile control treatment.

Stony Lake

Planting density was consistent across the experimental plots at the Stony Lake site (1111 stems/ha), and age 25 survival was consistently high, ranging from 89% in the disc trench hinge + vegetation control treatment, to 95% in the shear and pile control and vegetation control treatments, and 96% in the disc trench hinge treatment. This resulted in year 25 densities of 994 stems/ha in the disc trench hinge + vegetation control treatment, 1052 stems/ha in the shear and pile control treatment, 1053 stems/ha in the vegetation control treatment, and 1064 stems/ha in the disc trench hinge treatment (Figure 1). Predicted MERCHVOLST development over time was similar among the shear and pile control, vegetation control, and disc trench hinge treatments with maximal difference only around 20 m^3/ha (Figure 3). Among these three treatments, the ranking of predicted MERCHVOLST, from highest to lowest, was disc trench hinge > shear and pile control > vegetation control (where only herbicide was used after windrowing), with these differences predicted to persist until approximately age 90. Predicted MERCHVOLST development over time was higher in the disc trench hinge + vegetation control treatment than in the other three less intensive treatments. The disc trench hinge + vegetation control treatment diverged from the others as early as age 15, and was predicted to reach the industry target merchantable volume of 250 m^3/ha slightly more than 2 years before the shear and pile control treatment stand (Table 4). In all treatments at the Stony Lake site, maximum MAI was predicted to occur at age 60 (Table 3, Figure 3).

The Stony Lake site is more productive than the Bednesti site (effective site index of 22.8–24.0 m versus 19.8–21.2 m, respectively), which resulted in predictions that the Stony Lake shear and pile control and disc trench hinge stands would reach the 250 m^3/ha benchmark approximately 2–4 years earlier than their counterpart treatments at the Bednesti site. In the shear and pile control treatments, the benchmark volume was predicted to occur earlier at the Stony Lake site than at the Bednesti site, despite higher tree density at the Bednesti site at all ages (Table 4, Figure 1). In

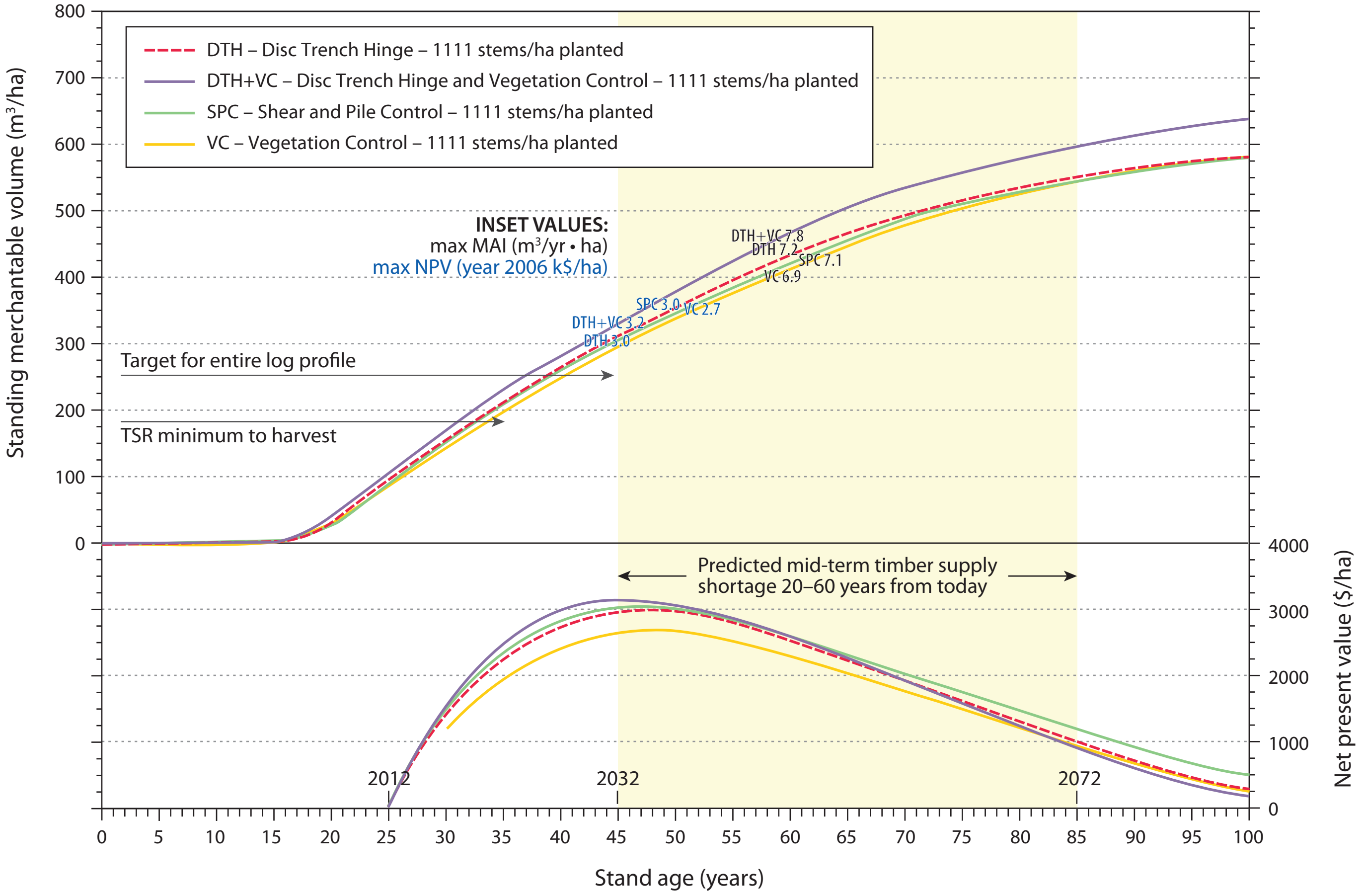


Figure 3. Merchantable volume estimates (predicted by TASS) and net present value estimates (predicted by FAN$IER) for lodgepole pine in the disc trench hinge (DTH), disc trench hinge + vegetation control (DTH+VC), shear and pile control (SPC), and vegetation control (VC) treatments at the Stony Lake long-term research site.

the disc trench hinge treatments at both the Stony Lake and Bednesti sites, tree densities at planting and at age 25 were similar, pointing to SIE as a driver of the greater volume growth at the Stony Lake site.

The Stony Lake and Bednesti sites also supported different vegetation communities; a vegetation control treatment was not carried out at the Bednesti site because, as is typical of the SBSdw3 (DeLong et al. 1993), the site was occupied by a shrub-herb community having low stature and low competitive ability (Boateng et al. 2012). In contrast, the Stony Lake site supported a competitive herb-shrub community (Taylor et al. 1991), and lodgepole pine clearly benefitted from follow-up chemical brushing (Table 2) in addition to disc trenching. Independently, neither disc trenching nor vegetation control resulted in appreciable increases in predicted MERCHVOLST over the shear and pile control at the Stony Lake site, which suggests that the combination of both was necessary to substantially improve lodgepole pine growth. Vegetation control on its own may have been more effective if it had been applied before year 3; lodgepole pine is shade-intolerant (Klinka et al. 2000), and vegetation control in other pine species has the most positive effect on growth if applied 1–2 years after planting (Wagner et al. 1999). Other studies have also reported that lodgepole pine growth responses to mechanical site preparation combined with follow-up chemical brushing exceed responses to the treatments applied individually (Newsome et al. 2016). Over the long term, studies in the SBSwk (Bedford et al. 2017) and the BWBSmw (Powelson et al. 2016) have also demonstrated that disc trenching on its own exerts little control over aggressive, well-established tall shrub–dominated vegetation.

Inga Lake

In white spruce stands at the Inga Lake site, two clear groupings of predicted MERCHVOLST were evident by age 20 (Figure 4). The vegetation control and plow inverting stands were growing at effective site indices of 23.5 m and 22.9 m, respectively (Table 4), and both had a predicted MAI culmination stand age of 55 years (Table 3, Figure 4). The TASS projections indicated that the vegetation control and plow inverting stands could achieve the industry target merchantable volume of 250 m^3/ha at stand ages of 36 and 38 years, respectively (Table 4). The favourable growth of white spruce in these treatments has been attributed to successful long-term control of overtopping vegetation (mainly willow) (Boateng et al. 2009; Powelson et al. 2016). In contrast, a large proportion of white spruce in both the disc trench hinge and shear and pile control treatments were still overtopped in year 24, and hence were growing at considerably lower effective site indices of 18.1 m and 18.5 m, respectively (Table 4), with maximal difference (at age 70) of around 426 m^3/ha between the vegetation control and the shear and pile control treatments. More trees also died under the overtopped conditions, with 76% and 83% surviving to age 24 in the shear and pile control and disc trench hinge treatments, respectively, compared with 91% in the vegetation control treatment and 98% in the plow inverting treatment (Figure 1). The two underperforming stands were also predicted to achieve stand development benchmarks later; MAI culmination was expected to occur at age 90 in the disc trench hinge stand, and at age 100 or later (since the age to which FAN$IER could make projections was limited by the 100-year rotation length) in the shear and pile control stand (Table 3, Figure 4). The benchmark spruce volume of 250 m^3/ha was predicted in these treatments at ages 63 and 77 years, respectively (Table 4). The low initial planting densities in the disc trench hinge and shear and pile control treatments, in combination with higher mortality to age 24 and overtopping vegetation, dramatically constrained stand volume increase. At age 24, there were 912 stems/ha in the disc trench hinge treatment and 1087 stems/ha in the shear and pile control treatment compared with 1301 stems/ha in the vegetation control treatment and 1637 stems/ha in the plow inverting treatment (Figure 1). Nevertheless, ongoing crop tree suppression at the Inga Lake site was judged by Powelson et al. (2016) to be the largest contributor to poor volume accumulation in the disc trench hinge and shear and pile control treatments. Assuming that the overtopped white spruce in the shear and pile control and disc trench hinge treatments at the Inga Lake site maintain adequate vigour, they are expected to gradually achieve growth rates that reflect site potential when they eventually grow through the dense willow canopy. The time required for this to occur is unknown and cannot be predicted using TASS version 2, which is not set up to model conifer growth when overtopped by early successional broadleaf competition. At age 25, Powelson et al. (2016) reported that the willow canopy was still approximately 3 m taller than the average white spruce tree, although the high variability in spruce height suggested that at least some trees were in the process of breaking through the canopy. The disc trench treatment reduced overtopping only slightly, and Powelson et al. (2016) concluded that it was not an effective treatment for BWBSmw sites with vigorous vegetation development. It should be noted, however, that vegetation development at the Inga Lake site, which was repeatedly burned prior to the start of the study to promote willow as a forage species, is not typical of zonal sites (site series 01) in the BWBSmw, especially those that are managed according to current practices.

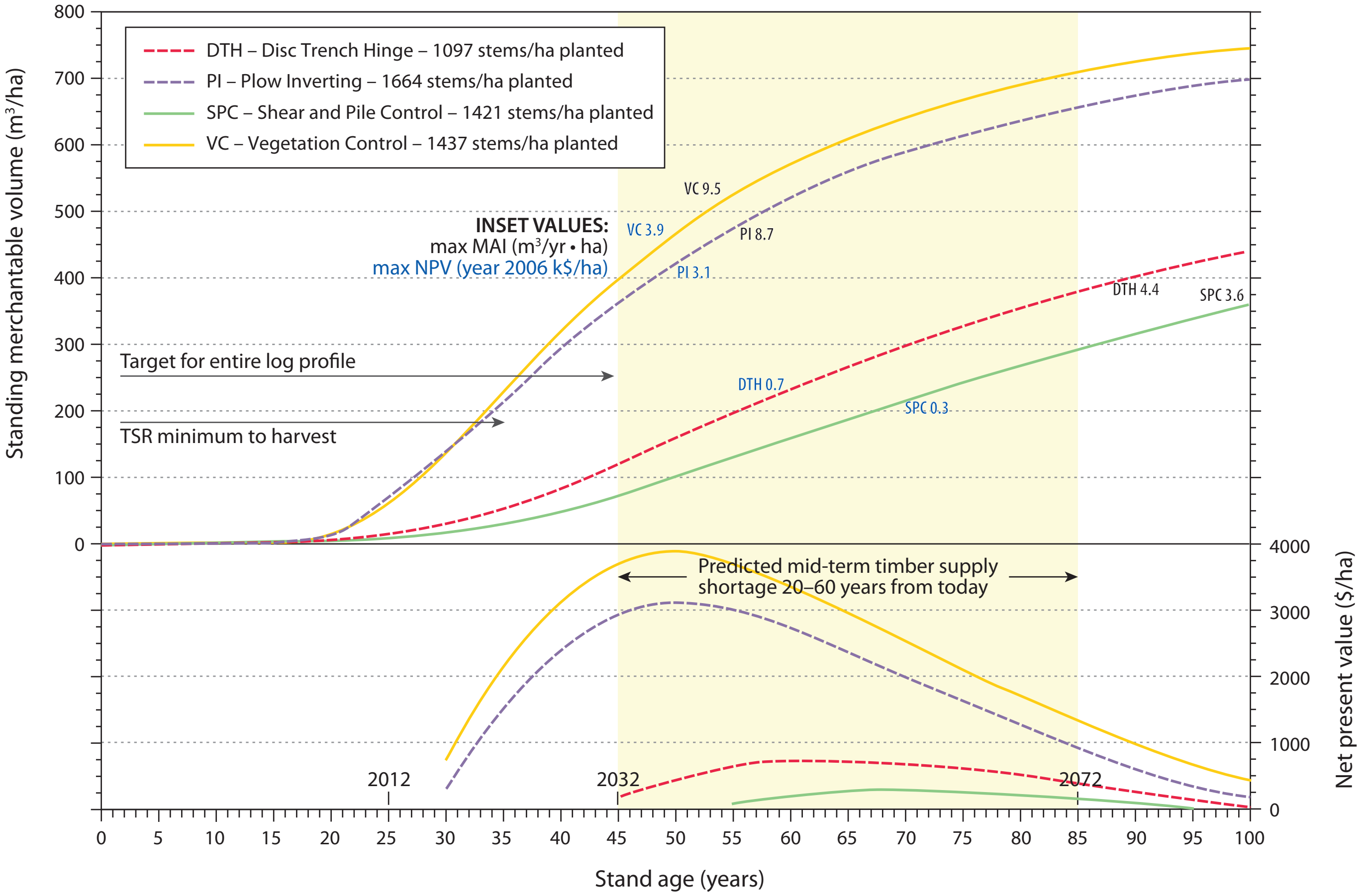


Figure 4. Merchantable volume estimates (predicted by TASS) and net present value estimates (predicted by FAN$IER) for white spruce in the disc trench hinge (DTH), plow inverting (PI), shear and pile control (SPC), and vegetation control (VC) treatments at the Inga Lake long-term research site.

3.2 Financial Variables

3.2.1 Net present value (NPV) Net present value is based on the summation of discounted benefits (e.g., harvest revenue) and discounted costs (e.g., silviculture, road, harvest, and manufacturing) and is used to express costs and benefits occurring at different points in time in present-day terms.

Bednesti

At the Bednesti site, predicted maximum NPV was highest in the shear and pile control ($2817/ha) treatment, intermediate in the disc trench hinge ($2401/ha) treatment, and lowest in the plow inverting ($2175/ha) and disc trench furrow ($1934/ha) treatments (Table 3, Figure 2). Net present value was predicted to be maximized at age 50 in the shear and pile control, disc trench hinge, and plow inverting treatments, and at age 55 in the disc trench furrow treatment (Table 3, Figure 2). At the earliest NPV maximization age of 50, the shear and pile control treatment had the highest predicted MERCHVOLST and NPV, while the disc trench hinge treatment had higher predicted maximum NPV but only very slightly lower volume than the plow inverting treatment (Figure 2). Despite having vastly dissimilar initial planting densities, the plow inverting (1891 stems/ha) and disc trench hinge (1142 stems/ha) stands were projected to have fairly similar MERCHVOLST development until age 65 (Figure 2). However, due to higher planting and treatment costs, the plow inverting treatment was predicted to underperform financially compared to the more cost-effective disc trench hinge treatment, which cost only 56% as much as the plow inverting treatment and was planted with only 60% as many trees. The high planting density and survival observed in the plow inverting treatment also resulted in volumetrically and proportionally more smaller-dimension lumber projected over time than in the other treatments, which were more sparsely planted (see section 3.3). Despite this, during a field visit, industry representatives subjectively deemed that the high density in the plow inverting treatment had improved the stem, crown form, and branch diameter of trees over that in other treatments. The high planting density may also represent a built-in buffer in the face of climate change, pest, and disease uncertainties, thereby potentially reducing overall risk. Due to no associated site preparation treatment costs, the shear and pile control stand was predicted to reach a higher maximum NPV than those predicted in the disc trench hinge and plow inverting treatments (Table 3, Figure 2). The impressive volume and NPV returns predicted in the least costly shear and pile control treatment were based on good survival and an intermediate planting density of 1280 stems/ha that was slightly higher than the disc trench hinge treatment planting density of 1142 stems/ha, but much lower than that in the plow inverting treatment (1891 stems/ha). The lowest predicted maximum NPV also occurred the latest, at age 55 in the disc trench furrow treatment due to lower predicted MERCHVOLST than in the other treatments (Figure 2). For all treatments at the Bednesti site, maximum NPV was predicted to occur 8–9 years after volume reached 250 m^3/ha (Tables 3 and 4, Figure 2). At the ages the stands were projected to attain 250 m^3/ha, NPV ranged from $1808/ha to $2523/ha, which was $126–$294/ha below the maximum values projected (Table 5).

At the Bednesti site, the large differences in planting density likely affected NPV, which makes it difficult to accurately determine the most profitable site preparation treatment choice. In the three treatments where maximum NPV was achieved at age 50, the value (at the planting densities examined) decreased in the following order: shear and pile control > disc trench hinge > plow inverting. The disc trench furrow treatment had the lowest predicted maximum NPV and it was achieved 5 years later than in the other treatments. The most cost-effective shear and pile control treatment may offer the most compelling trade-off between volume and value returns while potentially reducing risk; however, the disc trench hinge treatment showed high predicted NPV. Planting density, survival, piece size, and lumber recovery are so intimately linked that it is impossible to know the extent to which the variable planting densities at the Bednesti site contributed to the projected financial outcomes; however, it is possible that, with a lower initial planting density, predicted maximum NPV in the plow inverting treatment could have been greater due to effects on piece size and the potential to mill larger dimensional lumber. The differences observed among treatments in timing and magnitude of projected maximum NPV and MERCHVOLST suggest that a low-cost treatment with intermediate planting density could be most profitable, returning a high value early and with a satisfactorily high volume. Lumber quality

Table 5. Net present value (NPV), site value (SV), and internal rate of return (IRR) at the age when stands at the Bednesti, Stony Lake, and Inga Lake long-term research sites are projected to attain the industry target[a] standing merchantable volume of 250 m^3/ha, and the difference[b] from maximum values for these financial metrics (shaded rows)

	Lodgepole pine						White spruce		
	Bednesti			Stony Lake			Inga Lake		
Treatment[c]	NPV ($/ha)[d]	SV ($/ha)[d]	IRR (%)	NPV ($/ha)	SV ($/ha)	IRR (%)	NPV ($/ha)	SV ($/ha)	IRR (%)
PI	$1984	$2449	6.8	–	–	–	$1976	$2495	6.7
	–$191	–$98	–0.1	–	–	–	–$1135	–$1082	–0.2
DTH	$2165	$2649	7.3	$2657	$3372	8.1	$732	$793	5.3
	–$236	–$128	–0.1	–$328	–$201	–0.2	$0	–$10	–0.4
DTF	$1808	$2145	6.8	–	–	–	–	–	–
	–$126	–$80	0.0	–	–	–	–	–	–
VC	–	–	–	$2463	$3067	7.7	$2373	$3044	7.5
	–	–	–	–$219	–$96	0.0	–$1522	–$1434	–0.3
DTH+VC	–	–	–	$2650	$3425	7.7	–	–	–
	–	–	–	–$511	–$359	0.0	–	–	–
SPC	$2523	$3127	8.3	$2776	$3496	8.9	$247	$259	4.3
	–$294	–$139	–0.1	–$260	–$122	–0.2	–$36	–$42	+0.4

[a] Target merchantable volume based on information provided by Dunkley Lumber Ltd. (2014).

[b] Differences relative to maxima (refer to Table 3) were determined by interpolation of values generated by the FAN$IER model at 5-year intervals.

[c] PI is plow inverting; DTH is disc trench hinge; DTF is disc trench furrow; SPC is shear and pile control; VC is vegetation control; DTH+VC is disc trench hinge + vegetation control in year 3.

[d] Canadian dollar value in 2006.

must be maintained however, and if it cannot, this could affect management decisions. Efforts are underway to link the Optitek[10] lumber milling model to SYLVER to assess effects on lumber quality. An observational or theoretical (TASS + FAN$IER) study designed to explore this idea would have to control for planting density.

Stony Lake

The Stony Lake experimental site, with equal planting density across treatments, demonstrates the predicted impacts of site preparation on financial outcomes more clearly than the projections based on the Bednesti and Inga Lake experiments. In the Stony Lake lodgepole pine stands, maximum NPV was projected at age 45 in the disc trench hinge + vegetation control and disc trench hinge treatments, and at age 50 in the shear and pile control and vegetation control treatments (Table 3, Figure 3). The treatment predicted to provide the earliest and highest NPV maximization was the high-cost, double-entry approach of disc trenching followed by chemical brushing, which resulted in a projected maximum NPV of $3161/ha (Table 3, Figure 3). A maximum NPV of $3036/ha (only $125/ha or 4% lower) was projected 5 years later at age 50 in the zero-site preparation cost, chemical-free, shear and pile treatment that was selected from the backlog sites used in this study to approximate newly harvested conditions (similar to conditions on sites being managed according to current practice) (Table 3, Figure 3). The disc trench hinge treatment had a similar predicted maximum NPV of $2985/ha at age 45, while the vegetation control treatment had the lowest value of $2682/ha, at age 50 (Table 3, Figure 3). The least costly shear and pile control treatment had a slightly higher ($51/ha, or 1.7%) predicted maximum NPV than the disc trench hinge treatment, and it was predicted to occur 5 years later and with 36 m^3/ha greater volume than that predicted in the disc trench hinge treatment (Table 3, Figure 3). The lowest predicted maximum NPV achieved at age 50 in the vegetation control treatment was $303/ha lower than the second-lowest maximum NPV predicted in the disc trench hinge treatment at age 45 (Table 3, Figure 3). Treatments examined at the Stony Lake site were predicted to surpass the merchantable volume target of 250 m^3/ha by age 37–40 years, which is 7–11 years sooner than they were projected to reach maximum NPV (Tables 3 and 4, Figure 3). At the ages the stands were projected to attain 250 m^3/ha, NPV ranged from $2463/ha to $2776/ha, which was $219–$511/ha less than the maximum values projected (Table 5).

Inga Lake

In white spruce stands at the Inga Lake site, maximum NPV varied greatly among treatments; it was projected to be highest in the vegetation control treatment and second highest in the plow inverting treatment, with both projected to reach this financial rotation benchmark at age 50 (Table 3, Figure 4). These two treatments had dissimilar planting densities however, and for interpretive purposes it is more appropriate to compare predicted outcomes of the vegetation control and the shear and pile control treatments, which had similar planting densities (1437 and 1421 stems/ha, respectively). The vegetation control treatment was highly successful at the Inga Lake site, with spruce MERCHVOLST of approximately 467 m^3/ha projected at age 50 when maximum NPV was predicted to occur (Figure 4). In the shear and pile control treatment, where overtopping vegetation developed rapidly following shearing in 1987, spruce MERCHVOLST and maximum NPV were both only projected to reach very low values of around 215 m^3/ha and $283/ha, respectively, at age 70 (Figure 4). The MERCHVOLST increases and financial returns projected in the vegetation control treatment at the Inga Lake site may be somewhat higher than could be operationally realized due to the manual brushing treatments that were repeatedly applied to ensure lasting reduction of overtopping vegetation (see treatment description in Table 1). Projected maximum NPV in the disc trench hinge treatment at the Inga Lake site was also low ($732/ha) and was not projected to occur until age 60 (Table 3, Figure 4). The plow inverting and vegetation control treatments at the Inga Lake site were predicted to surpass the merchantable volume target of 250 m^3/ha by ages 38 and 36 years, respectively, which is 12–14 years earlier than they were projected to reach maximum NPV (Tables 3 and 4, Figure 4,). The projected NPVs of these stands at ages 36 and 38 years were $2373/ha and $1976/ha, which was $1522/ha and $1135/ha lower, respectively, than the projected maximum values (Table 5). In contrast, NPV of the disc trench hinge and shear and pile control stands was predicted to be maximized at ages 60 and 70 years, approximately 3–7 years earlier, respectively, than they were predicted to attain a merchantable volume of 250 m^3/ha (Tables 3 and 4, Figure 4). The differences between maximum NPV and NPV at the 250 m^3/ha technical rotation target were small ($0–$36/ha) for these two treatments (Table 5). These projections indicate that where extremely vigorous tall shrub–dominated vegetation is expected to develop, aggressive approaches to vegetation control, either through high-severity site preparation or chemical brushing, are cost-effective.

---

[10] The Optitek software program is a tool developed by FPInnovations that allows the simulation of softwood lumber industry processes. https://fpinnovations.ca/products-and-services/technologies/pages/default.aspx.

3.2.2 Site value (SV) Site value is similar to NPV in being a measure of discounted (to year 2006 Canadian dollar values) net financial return, except that it characterizes the value of an infinite series of rotations of the same length, taking into account the summation of discounted benefits and costs. While NPV is more useful for examining the value of current stands, SV allows for the comparison of various treatment and rotation length scenarios that could be applied in the future – it is a measure of soil rent, bare land value, soil expectation value, or variations on these. Site value outcomes at all three long-term research sites mirrored those of NPV, but the magnitude of the values was consistently slightly higher, and, in some cases, projected maximal SV timing was 5 years earlier (Table 3, Figures 5–7). As was the case for NPV, maximum SV was consistently projected at older stand ages than was attainment of the merchantable volume target of 250 m³/ha (Tables 3 and 4). Site value was consistently higher than NPV at the ages when stands attained 250 m³/ha; however, the difference from maximum values was nearly always smaller for SV than for NPV (Table 5).

3.2.3 Internal rate of return (IRR) Internal rate of return (IRR) is a metric used to examine return on investment (ROI) – the annualized rate of return on an investment. It is the discount rate at which NPV is 0 (i.e., the discount rate at which the NPV of costs equals the NPV of benefits). The higher the IRR, the more efficiently a treatment converts costs into benefits. In lodgepole pine stands at the Bednesti and Stony Lake sites, projections of maximum IRR were

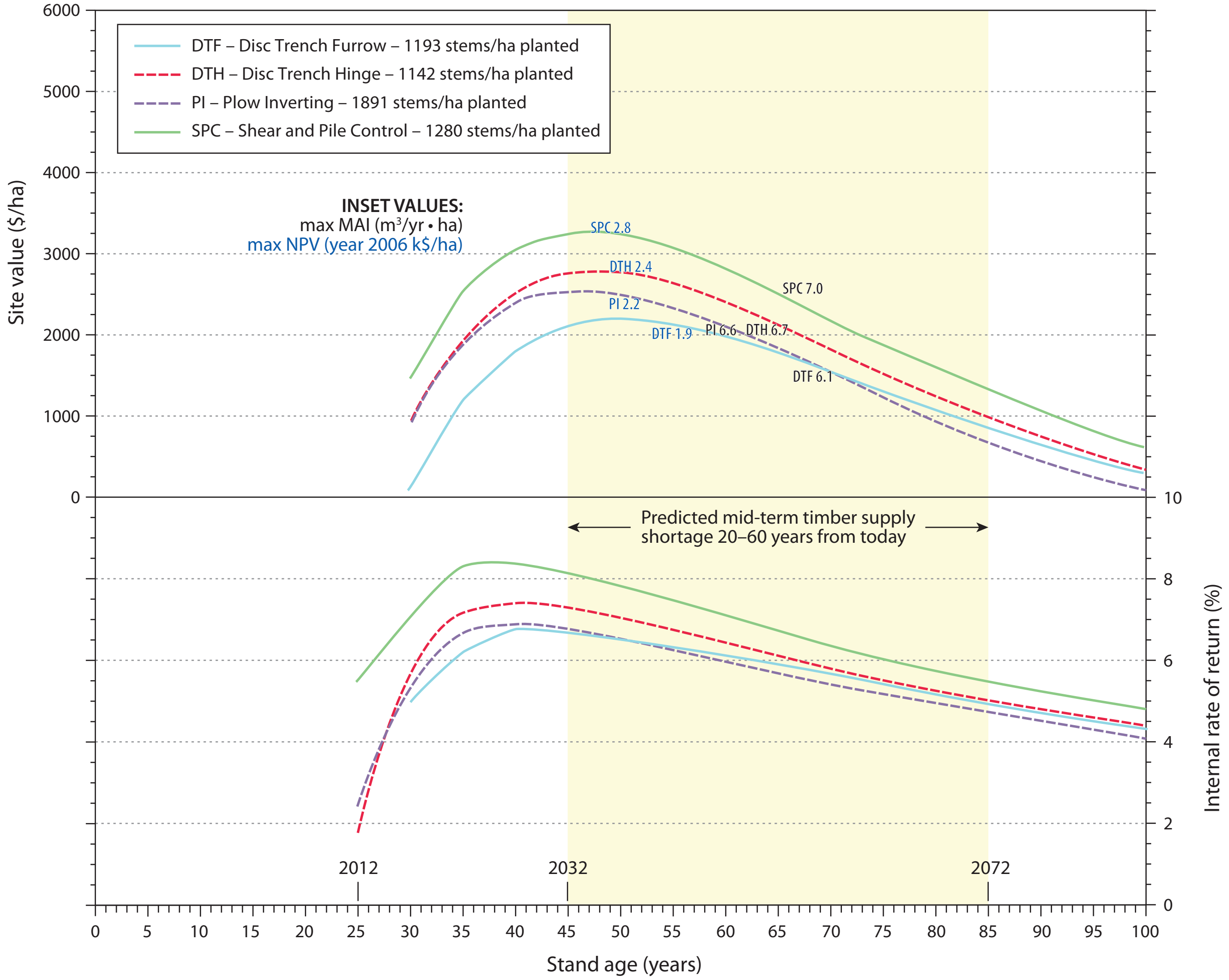


Figure 5. Site value and internal rate of return estimates (predicted by FAN$IER) for lodgepole pine in the disc trench furrow (DTF), disc trench hinge (DTH), plow inverting (PI), and shear and pile control (SPC) treatments at the Bednesti long-term research site.

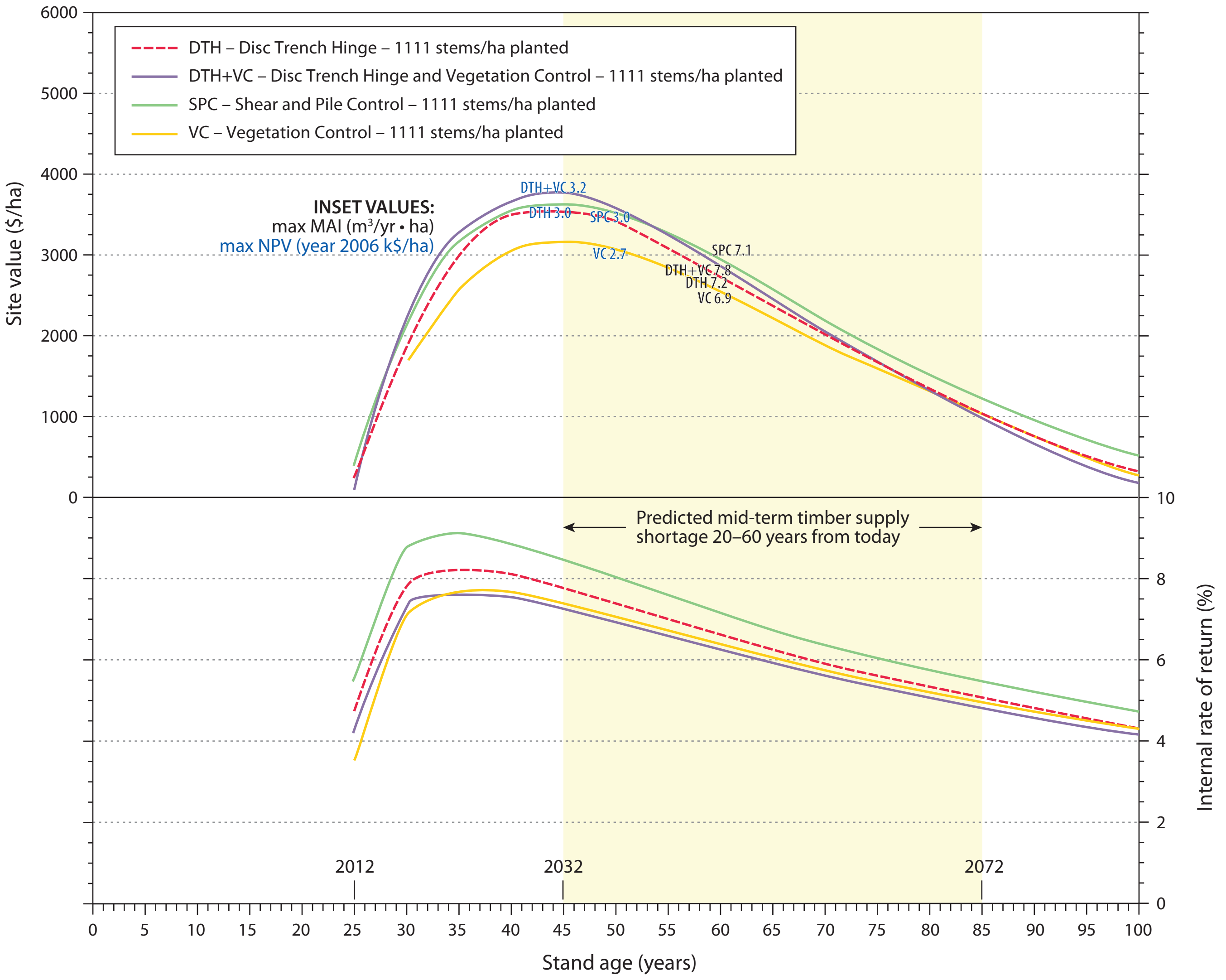


Figure 6. Site value and internal rate of return estimates (predicted by FAN$IER) for lodgepole pine in the disc trench hinge (DTH), disc trench hinge + vegetation control (DTH+VC), shear and pile control (SPC), and vegetation control (VC) treatments at the Stony Lake long-term research site.

higher in the shear and pile control treatment than in the other treatments (Table 3, Figures 5 and 6). This suggests that from the perspective of return on investment, the do-nothing approach (aside from shearing and piling, which was assumed for this exercise to have no cost) was the best choice for those sites. This was not the case in white spruce stands at the Inga Lake site, where the lowest maximum IRR was projected for the do-nothing approach than in the other treatments (Table 3, Figure 7). At that site, spruce productivity was severely impacted by the overtopping vegetation, and vegetation control was a good investment.

Our projections indicated that IRR would be consistently maximized at younger stand ages than NPV or SV. However, this does not indicate that harvest timing should be determined strictly from timing of maximum IRR, as IRR is simply a metric of investment efficiency and therefore differs from NPV or SV in its applicability (Lutz 2011). In the Bednesti and Stony Lake lodgepole pine stands, IRR was maximized 5–15 years earlier than NPV or SV (Table 3, Figures 5 and 6), while maximum IRR in the Inga Lake white spruce stands was projected between 5 and 20 years earlier than projected maxima of NPV or SV (Table 3, Figure 7). At the age when the merchantable volume target of 250 m^3/ha was projected, IRR was equal to or below the maximum values in all treatments investigated in this study, except in the shear and pile control treatment at the Inga Lake Site (Table 5).

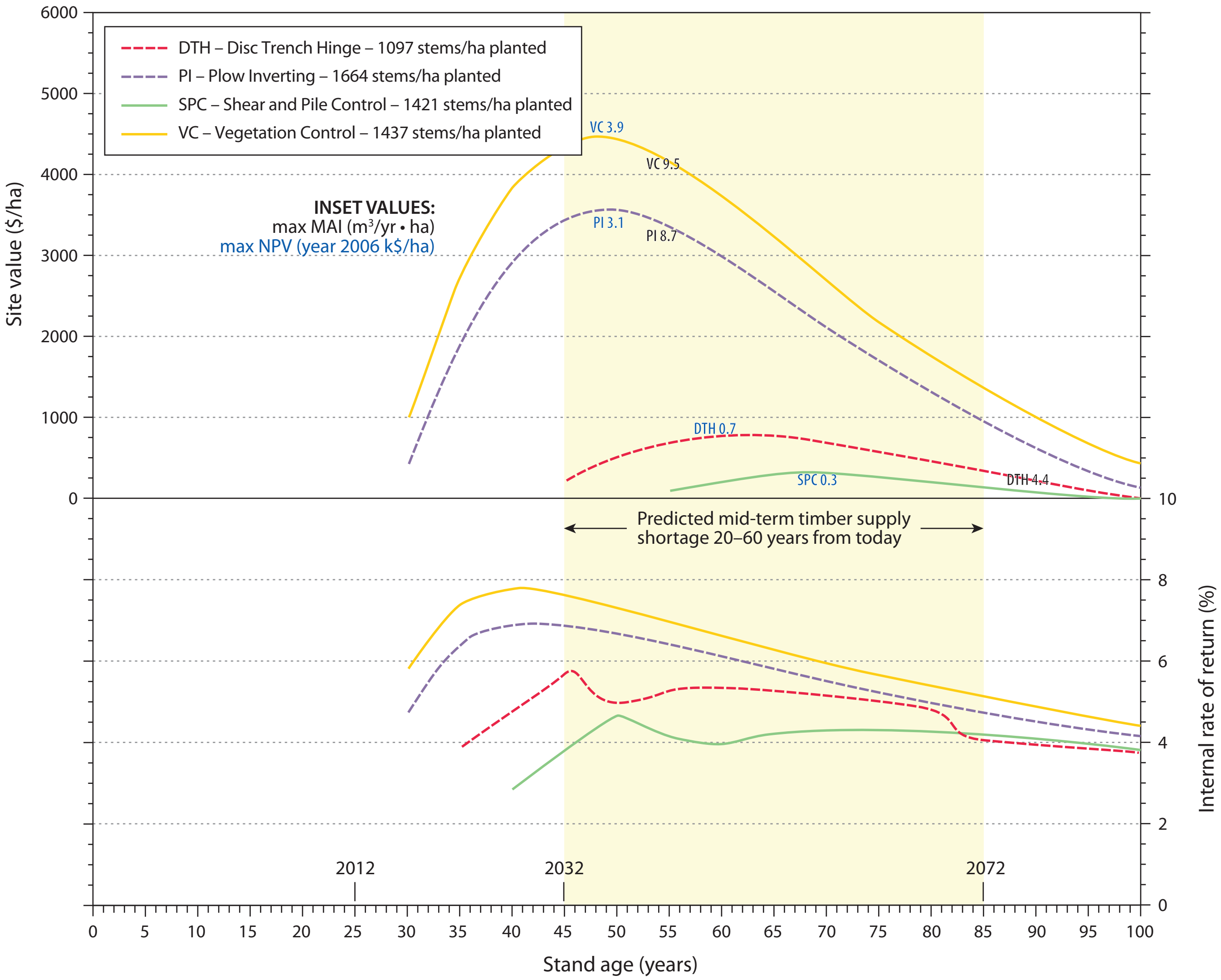


Figure 7. Site value and internal rate of return estimates (predicted by FAN$IER) for white spruce in the disc trench hinge (DTH), plow inverting (PI), shear and pile control (SPC), and vegetation control (VC) treatments at the Inga Lake long-term research site.

3.3 Lumber Output

At all three of the sites examined, the projected product spectra optimized for value illustrate that an increasing proportion and amount of merchantable volume is comprised of larger dimensional lumber as stand age increases (Figures 8–10). Interestingly, however, letting a stand grow long enough to recover large dimensional lumber appears incongruent with maximizing financial returns. At the age NPV and SV are predicted to be maximized, the proportion of 2 × 10 and 2 × 8 lumber is relatively small in comparison with the proportion of 2 × 4 and 2 × 6 lumber. In a narrow sense, it "costs" money to produce larger dimensional lumber. Assuming that enough stands are available to allow it, harvest timing could be managed in order to enable production of the particular lumber profile required to satisfy market needs. The demand for lumber is a derived demand that is largely dependent on new housing construction, with lumber prices changing according to supply and demand in that market, and this may also affect harvest timing decisions.

3.4 Overall Interpretation of Financial Outcomes and Operational Implications

The FAN$IER model produces a range of output variables; depending on the perspective of the user, the nature of their professional responsibilities, and the tenure system they work under, the variables of greatest interest will vary. The importance or relevance of a financial outcome will also vary relative to others evaluated under different criteria. A forest economist conducting risk analysis (e.g., uncertainty regarding returns on silviculture investments, future cash flow, and market potential) may be more interested in

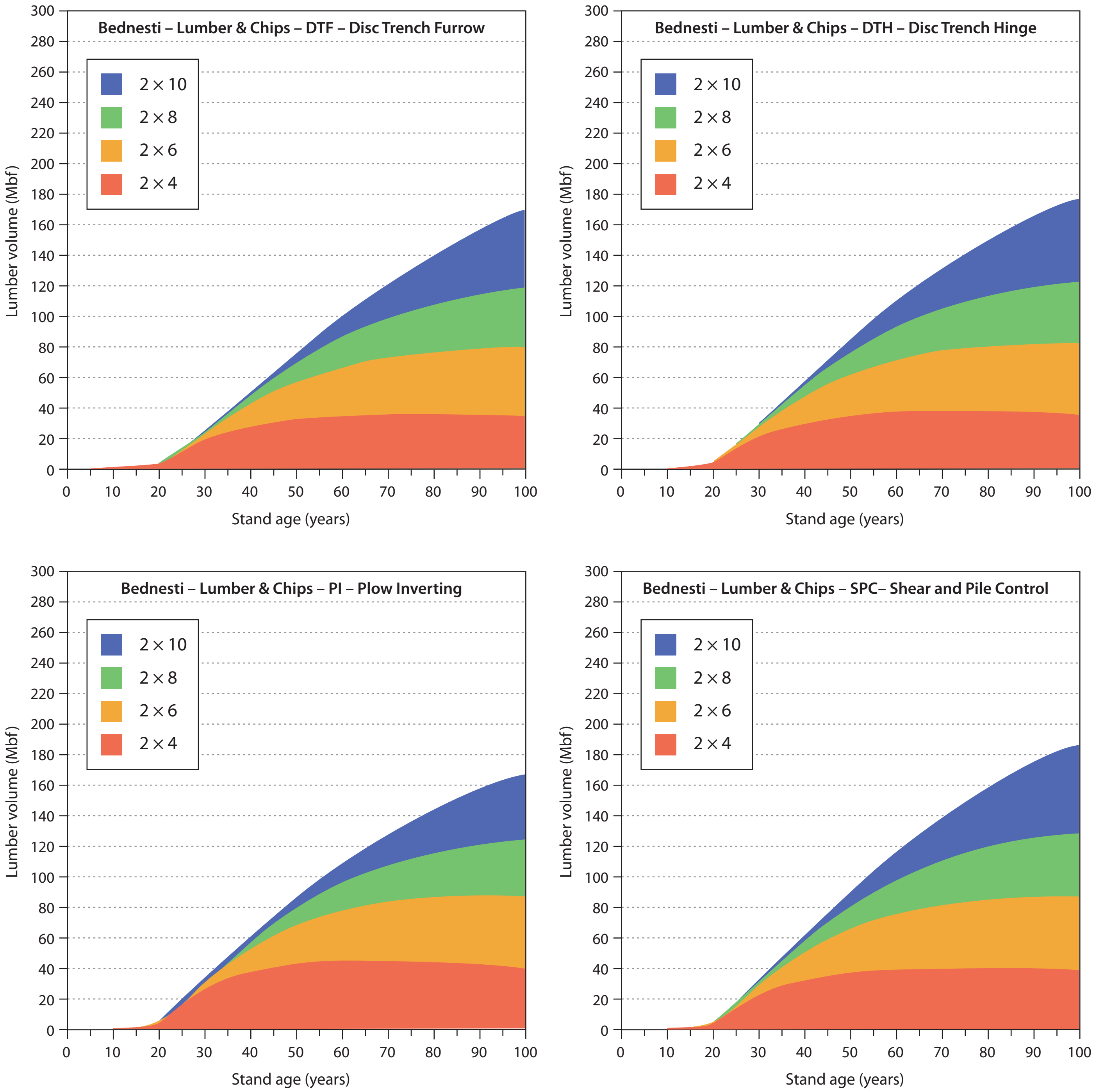
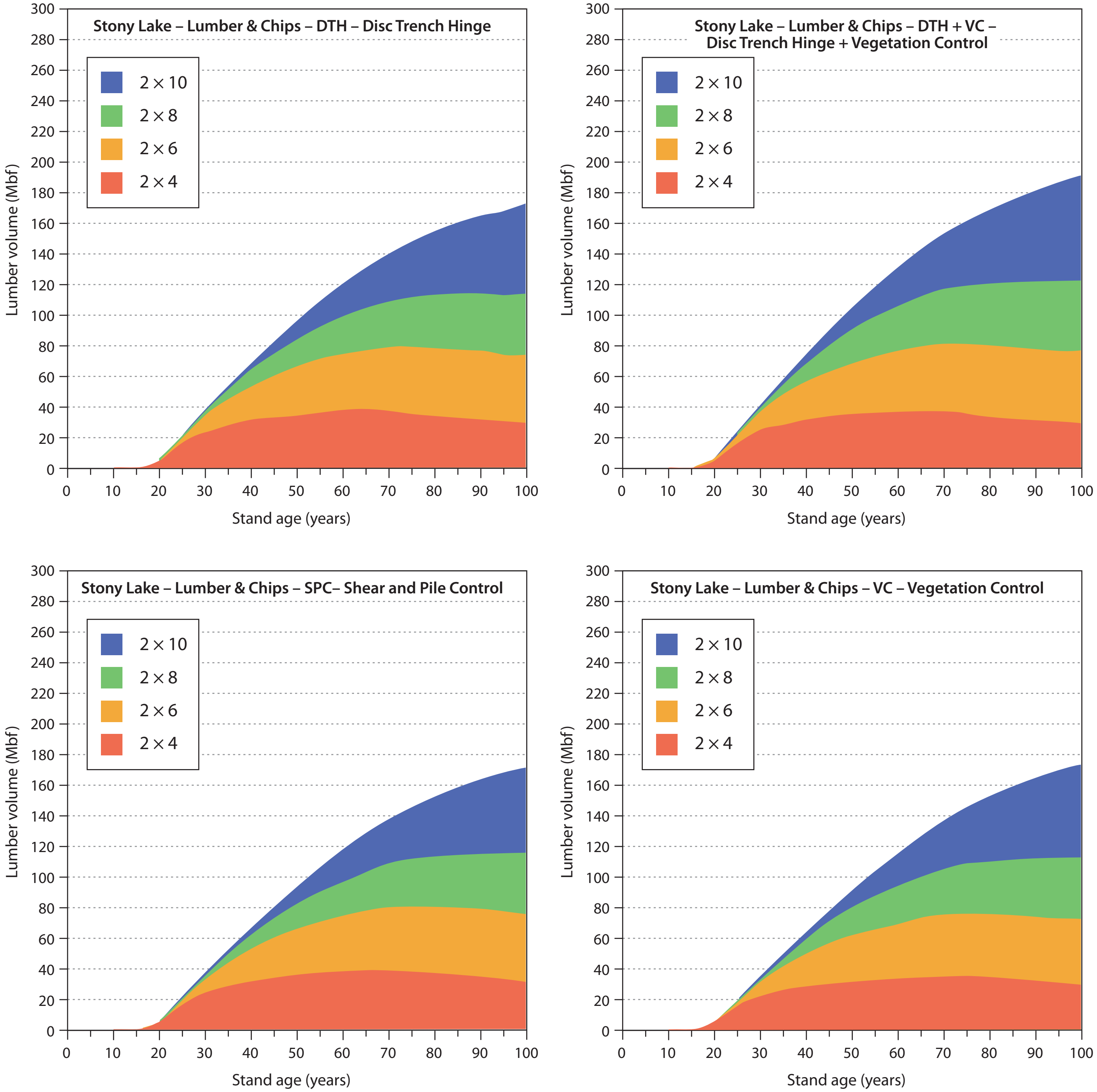


Figure 8. Dimensional lumber product spectrum estimates (predicted by SYLVER) for lodgepole pine in the disc trench furrow (DTF), disc trench hinge (DTH), plow inverting (PI), and shear and pile control (SPC) treatments at the Bednesti long-term research site.


Stony Lake – Lumber & Chips – DTH – Disc Trench Hinge

Stony Lake – Lumber & Chips – DTH + VC – Disc Trench Hinge + Vegetation Control

Stony Lake – Lumber & Chips – SPC– Shear and Pile Control

Stony Lake – Lumber & Chips – VC – Vegetation Control

Figure 9. Dimensional lumber product spectrum estimates (predicted by SYLVER) for lodgepole pine in the disc trench hinge (DTH), disc trench hinge + vegetation control (DTH+VC), shear and pile control (SPC), and vegetation control (VC) treatments at the Stony Lake long-term research site.

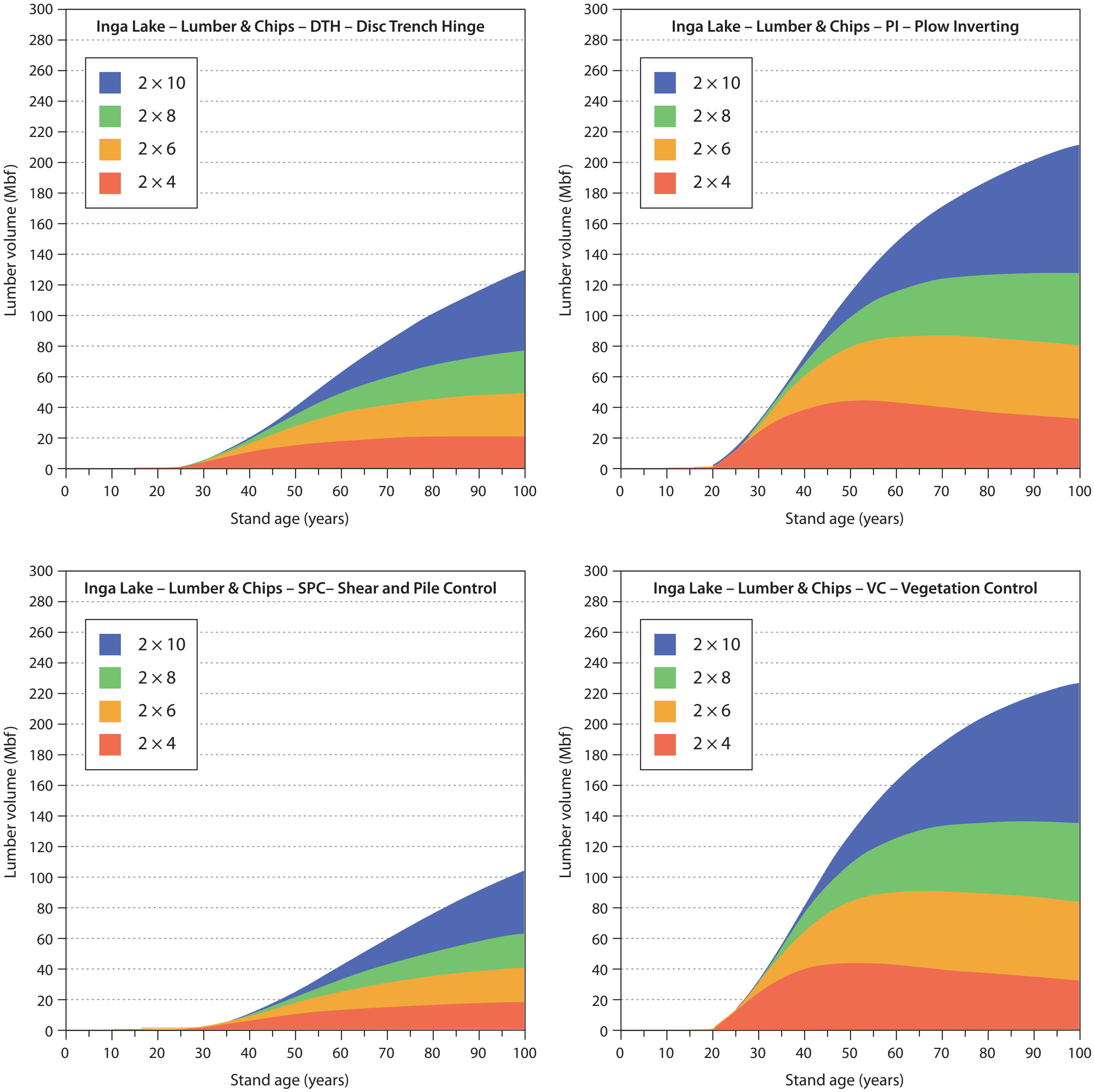


Figure 10. Dimensional lumber product spectrum estimates (predicted by SYLVER) for white spruce in the disc trench hinge (DTH), plow inverting (PI), shear and pile control (SPC), and vegetation control (VC) treatments at the Inga Lake long-term research site.

SV than NPV, and may also consider IRR for purposes of comparing returns on forestry investment with those in other sectors. A forestry professional working in private industry may be interested in NPV from the perspective of their company's fiscal soundness, but is also mandated by their professional code to manage the forest resource according to "sound ecological principles [that are] consistent with the public interest in the maintenance of all forest values."[11] Therefore, while forestry professionals can consider financial outcomes as part of public and corporate interest, they must also assess whether or not the best choice from a financial perspective coincides with that of maintaining all forest values.

In British Columbia, the majority of forest land is publically owned, with the right to harvest timber managed through a tenure system (B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development 2012a). The most common forms of tenure are primarily volume-based (e.g., Timber Sale Licence [TSL]; Forest Licence [FL]), and they grant the right to harvest standing timber in a specific management unit, but not the ongoing right to timber produced in subsequent rotations in that unit. There is a requirement for land harvested under this tenure system to be reforested and for the regenerated stand to meet free growing obligations (B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development 2016), after which it reverts to the Crown. Consequently, financial incentive is related primarily to meeting these obligations in a timely manner so as to reduce carrying costs and risk (e.g., tree crop failure due to insects and disease prior to reaching free growing status), rather than to augmenting stand value over the long term (possibly for the next licensee's gain). Under this tenure system, the Crown has the responsibility to consider the implications of early silviculture treatments on long-term stand value, which could be assessed using metrics such as NPV and SV, but it has little control over the extent to which these treatments are used as long as legislated obligations are met. Area-based tenure over the land (e.g., Tree Farm Licence [TFL]) persists for multiple rotations. Holders of these licences are likely to be interested in the same variables as holders of volume-based licences, and they have the same need to manage in accordance with both ecologically appropriate and financially sound principles, but they have additional incentive to apply treatments that will increase their returns in future rotations.

The mid- to long-term effects of site preparation treatments on financial outcomes are an important management consideration in the SBS and BWBS zones of British Columbia because 60 and 63%, respectively, of the area harvested in those biogeoclimatic units between 1980 and 2013 received some form of site preparation (Figure 11a). These stands are comprised of trees that will be harvested during the mid-term timber supply shortage predicted to occur between 2032 and 2072 as a result of the mountain pine beetle epidemic of the early 21st century (B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development 2012b). In the SBS zone, mechanical techniques were used on 57% of the area that was treated from 1980 to 2013, and of the treatments that were applied on a broadcast basis (i.e., excluding spot treatments and those that are specific to roads and landings) disc trenching was most widely used. Since 1980, disc trenching has been applied on over 100 000 ha in the SBS zone, accounting for approximately 40% of the area that received broadcast treatments in that biogeoclimatic unit (Figure 11b). Consequently, financial projections concerning disc trenching are of considerable operational interest. Our projections for the disc trenching treatments at the Stony Lake site (where planting densities were equal) suggest that this treatment could reduce by up to 1 year the time required to reach a merchantable volume of 250 m^3/ha in the SBS zone, and that NPV could be maximized 5 years earlier than for untreated sites. Depending on management objectives, these differences may or may not prove operationally relevant in relation to the mid-term timber supply shortage (B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development 2012b).

In addition to allowing users to project the financial value of forests currently developing on the British Columbia timber harvesting landbase, FAN$IER can be useful to decision makers in evaluating site preparation options for future harvest cutblocks. The Stony Lake projections suggest that applying a disc trenching treatment and a follow-up vegetation control treatment could reduce the time required to reach a merchantable volume of 250 m^3/ha by approximately 2 years relative to no treatment (as represented by the shear and pile control) (Table 4). This treatment combination resulted in projected NPV and SV that were higher than those projected in the shear and pile control treatment, and the maximum value of NPV was projected to be reached 5 years earlier (Table 3). Mean annual increment was maximized at the same age in the disc trench hinge + vegetation control and shear and pile control treatments, but was 0.7 m^3/ha higher in the combination treatment.

---

[11] Association of British Columbia Forestry Professionals Code of Ethics – Guidelines for Interpretation (March 2009).

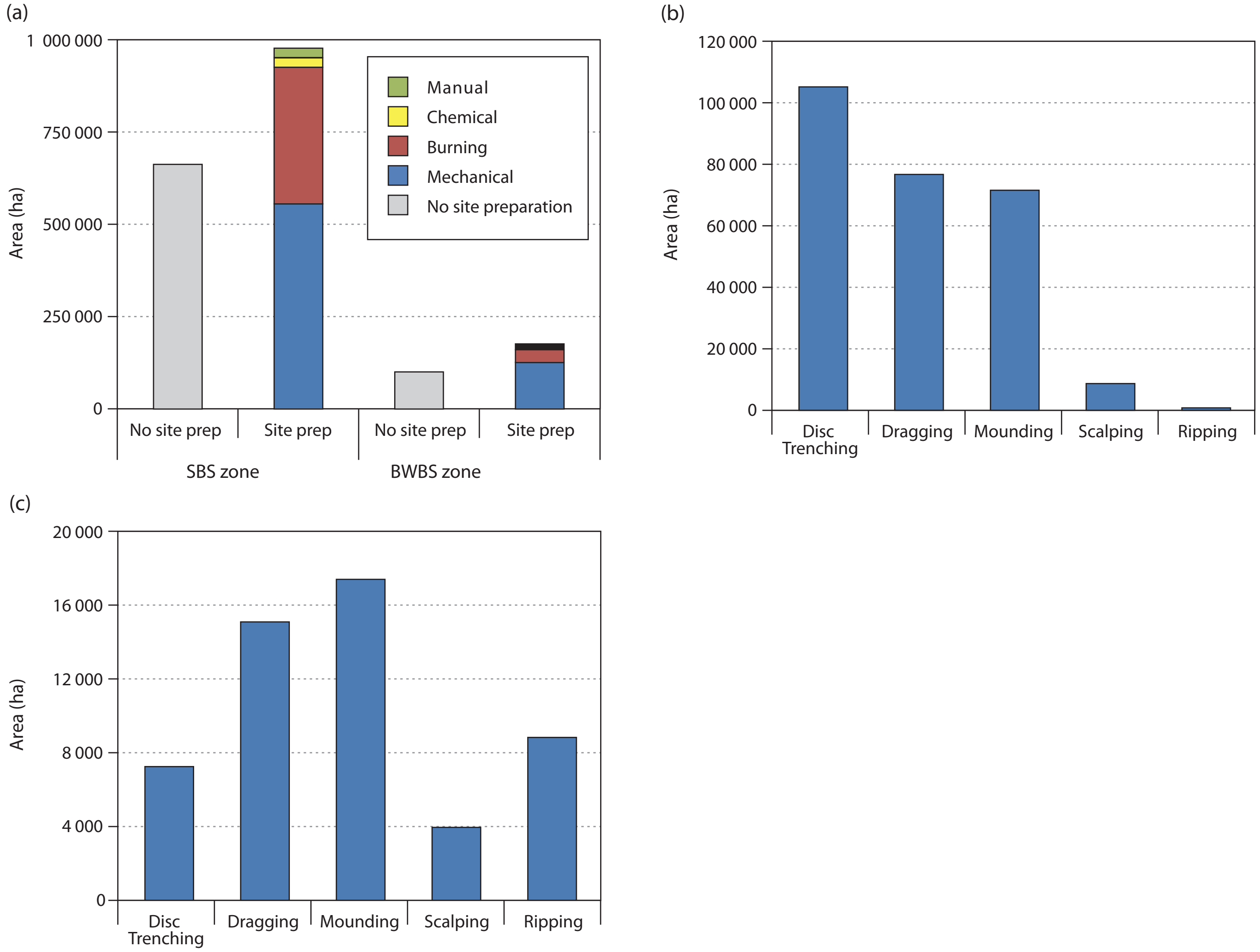


Figure 11. Site preparation activities in the northern SBS and BWBS zones from 1980 to 2013: (a) area prepared/not prepared by broad categories of site preparation (including all SBS and BWBS zone area in the RESULTS database), (b) area prepared by main mechanical techniques in the SBS zone, and (c) area prepared by main mechanical techniques in the BWBS zone; area prepared by main mechanical treatments includes broadcast treatments only and does not include activities on roads and landings or spot treatments. Based on B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development RESULTS database (accessed May 2014).

The unanticipated and extreme negative effects of overtopping vegetation on white spruce growth in the shear and pile control at the Inga Lake site make it difficult to use our FAN$IER projections as a basis for discussing the financial implications of site preparation treatments applied to facilitate the restocking of NSR sites on the BWBS zone landbase. Since mounding was the most commonly used mechanical technique in the BWBS zone between 1980 and 2013 (Figure 11c), the lack of an operationally representative treatment of this type at the Inga Lake site further complicates our interpretation. Disc trenching was examined at the Inga Lake site, but this treatment is not widely used in the BWBS zone; it was applied on only 7300 ha between 1980 and 2013, four-fifths of which had mesic or drier soil moisture regimes.[12] Disc trenching would likely not be selected as an operational treatment for a site at such high risk of vigorous vegetation development as Inga Lake, a decision that is supported by the low volumetric and financial returns projected in our study. The FAN$IER projections based on the Inga Lake experiment primarily demonstrate that financial returns are

---

[12] From the B.C. Ministry of Forests, Lands and Natural Resources RESULTS (Reporting Silviculture Updates and Landstatus Tracking System) database (May 2014).

likely to be low on BWBS zone sites managed for white spruce production where vigorous, well-established tall shrub vegetation is not controlled.

The uncontrolled and therefore confounding treatment densities at the Bednesti site limit our ability to interpret site preparation treatment effects on financial outcomes; however, the observed outcomes raise questions about the effect of stand density on the projections. These issues can only properly be examined through experimental or modelling work that controls density – this would be a potentially useful undertaking, because increases in target stocking levels are being considered for lodgepole pine to ensure that stands meet health, wood quality, and carbon sequestration objectives. At present, target lodgepole pine stocking is generally 1200 stems/ha for most zonal sites (B.C. Ministry of Forests 2000); however, some experts consider that planting densities as high as 1800 stems/ha are necessary to ensure that enough trees survive to harvest, and to accelerate canopy closure and crown lift that lead to good bole form and reduced number and size of knots. The plow inverting treatment at the Bednesti site had a high planting density of 1891 lodgepole pine stems/ha, and the FAN$IER projections based on observed stand development to year 25 represent the potential effect of this higher planting density on financial outcomes over the course of a rotation. During a field trip to the Bednesti site, operational managers indicated that, from the perspective of eventual suitability for milling, pine developing in the plow inverting treatment plots had more desirable crown height, branch size, and bole form than those in any other treatment at the site. These characteristics were subjectively attributed to higher planting density in those plots rather than to site preparation treatment effects. Maximum mean annual increment was projected to occur 5 years earlier in the plow inverting treatment than in the disc trench hinge or shear and pile control treatments, albeit at a lower value (Table 3). From a financial perspective, however, despite having maximum NPV projected at the same time as in the disc trench hinge and shear and pile control treatments, the plow inverting treatment had $226/ha lower maximum NPV than the disc trench hinge treatment and $642/ha lower maximum NPV than the shear and pile control treatment. It is possible that a slightly lower initial density could have produced better all-around outcomes in the plow inverting stands. Observations similar to those made at the Bednesti site regarding the positive effects of relatively high planting density on tree form in lodgepole pine stands have been made in other parts of British Columbia, and it is now broadly accepted that planting densities higher than 1200 stems/ha are desirable for this species. Identifying lodgepole pine planting densities that improve both tree form and merchantable volume under different site conditions is therefore an important issue. Site preparation and planting density may also interact to some extent, and further research and modelling would be necessary to evaluate the effects on volumetric and financial returns. In addition, it would also be interesting to know whether these quantitative effects and outcomes are in accord with professional but purely subjective stand value or wood quality assessments of immature stands.

In contrast to their opinions of the Bednesti site plow inverting stands, operational managers deemed that lodgepole pine growing in the disc trench hinge treatment had undesirable form and potentially low value, and that this was largely related to the relatively low pine density in those plots. This observation is supported by anecdotal comments from forestry professionals in other parts of British Columbia. Interestingly, maximum NPV projected using FAN$IER in the disc trench hinge stand holds contrary to that opinion, being 10% higher than that projected in the plow inverting treatment. The FAN$IER model could be overestimating value in the disc trench hinge treatment because we selected outputs that take knots into consideration, but do not account for juvenile wood degrade. We made this decision based on industry feedback indicating that there is little concern for juvenile wood content. Planting density was relatively low (1142 stems/ha) in the disc trench hinge treatment, and by age 25, density had declined to 1029 stems/ha (Figure 1). Low planting density is associated with a high degree of stem taper, which reduces wood volume that can be milled into dimensional lumber, and also with delayed self-pruning, which results in more juvenile wood (crown wood) with larger, more abundant knots and a high proportion of sapwood to basal area (Ballard and Long 1988). Pine in the disc trench hinge treatment also had a higher incidence of western gall rust (*Endocronartium harknessii*) infection than the pine in any other treatment at the Bednesti site (Reich et al. 2015), which is likely to further reduce recovery of merchantable wood volume as well as wood quality. Although TASS does not, at present, account for hard pine stem rust–related defects, work is currently underway to incorporate this aspect of forest health into growth and yield projections (Association of BC Forest Professionals 2015).

4 CONCLUDING REMARKS

Maxima of NPV, SV, and IRR were projected at stand ages no older than 50 years in all but one of the treatments planted with lodgepole pine, and in the two better treatments planted with white spruce. Harvesting at the biological culmination age when MAI is maximized is an accepted management strategy (Smith 1986), and current timber supply planning in the Prince George TSA in central British Columbia is based on harvest at 95% of the MAI culmination age.[13] However, FAN$IER outputs suggest that value is actually lost through this approach because stands are being harvested later than their financial rotation age. Model outcomes are governed by assumptions regarding current market conditions, but we have to take into account that markets may change. For example, although current markets allow for a profit to be made by managing for short rotations that produce a large volume of fibre, appropriate sites could also be managed with the objective of producing higher-value end products such as clear or machine stress rated (MSR) lumber, or (utility) poles. The FAN$IER model can be used to evaluate the premium MSR lumber and poles would need to sell for to make longer rotations financially viable. According to current FAN$IER parameters, managing strictly to maximize financial returns would result in harvesting younger stands more frequently, an approach that would likely reduce landscape-level structural diversity of forests, potentially having a range of negative effects on other forest values. Furthermore, eliminating the potential for older stands to develop would limit the future capacity to respond to market changes and to develop secondary manufacturing that requires locally sourced wood with old-growth attributes. Growing intensively managed shorter-rotation stands not too far from processing facilities, and allowing other stands further away to reach older rotation ages, could be a viable strategy to stratify the fibre basket, and help the profitability of the forest sector while maintaining ecological and eco-social attributes across the landscape.

The decision to harvest when NPV is maximized, or when a pre-defined technical rotation target is reached, will vary depending on the licensee and their particular objective(s). Market conditions near the time of harvest are also likely to influence the decision; for example, target markets may change during periods of global economic fluctuation, potentially affecting the relative value of individual products. Our model projections of the best site preparation outcomes show NPV rising steeply from age 30 to a maximum value around age 45–50 and then dropping steeply afterwards, roughly following a negative parabolic shape in this region of the curve. In the treatments investigated, over 5-year periods between stand ages 40–65 years, NPV is projected to change upward or downward by up to \$329/ha and \$611/ha in lodgepole pine and white spruce stands, respectively, highlighting the importance of carefully determining harvest timing to maximize financial returns, while that ensuring an adequate supply of logs (volume) to mills is maintained. This highlights the importance of selecting treatments that will increase value and/or volume, while also managing risk (e.g., losses to insects, disease, or wildfire). Interestingly, our projections indicate that the industry merchantable volume target of 250 m^3/ha was consistently achieved at an even younger age than were the maxima for NPV, SV, or IRR; this suggests that setting a technical target rotation may have negative financial implications if it happens to be set before maximum financial returns are achieved. This point is emphasized by outcomes for white spruce in the vegetation control and plow inverting treatments at the Inga Lake site, where stands were projected to achieve a merchantable volume of 250 m^3/ha at ages 36 and 38 years, respectively, but at NPVs that were \$1522/ha and \$1135/ha below maxima. At present, mature spruce stands still comprise part of the forest landbase in northern British Columbia, and managers are unlikely to consider harvesting these productive stands before culmination of MAI at the earliest.

Particularly during the expected mid-term timber shortage, we suggest that harvest should, to the extent possible, be conducted between the ages at which NPV (or SV) and MAI are maximized. This period represents a window of opportunity where a balance between the most financially and biologically efficient harvest ages occurs; timing within this period could be adjusted according to mill needs between volume and value. Harvesting before or after this period of maximized "bio-financial" efficiency, leaves either value or volume in the forest. The enormous discrepancy between the predicted time to reach maximum NPV and maximum MAI, and the difference in volume between those two stand ages, suggest that we need to think carefully about how we view, use, and manage forest land and the timber harvesting land base. Are we interested in managing our forests according to agricultural principles where trees are grown on short rotations, or do we want to manage according to principles that allow for more "natural" forest development? Do we wish to maximize financial returns or biological returns? In other words, what is the cost of managing for maximum biological returns, when financial returns dictate a different management strategy? And is there an ecological cost to managing for

---

[13] B.C. Ministry of Forests, Lands and Natural Resource Operations. https://www.for.gov.bc.ca/hts/tsa/tsa24/index.htm.

maximized financial returns? There is probably no single "best" answer, and we may benefit from setting different objectives for different sites to achieve landscape-level goals. Nature abounds with variation, and we may be wise to follow that lead in our management decisions. The FAN$IER model is a useful tool for evaluating financial outcomes that are projected for various silviculture treatment options; used in concert with biologically focussed decision aids and scientific knowledge it increases our ability to approach management decisions from a variety of perspectives.

LITERATURE CITED

Association of BC Forest Professionals. 2015. BC Forest Professional, pp. 14–15. http://www.cef-cfr.ca/uploads/Membres/bcmagazine.pdf (Accessed Aug. 3, 2016).

Ballard, L.A. and J.N. Long. 1988. Influence of stand density on log quality of lodgepole pine. Can. J. For. Res. 18: 911–916.

Bedford, L., J.L. Heineman, J. McClarnon, R.A. Powelson, A.F.L. Nemec, T. Kaffanke, and J.O. Boateng. 2017. Responses of hybrid white spruce to site preparation in wet and very wet Sub-Boreal Spruce subzones over three decades. Prov. B.C., Victoria, B.C. Tech. Rep. 109. www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr109.htm

Boateng, J.O., J.L. Heineman, L. Bedford, G.J. Harper, and A.F.L. Nemec. 2009. Long term effects of site preparation and post-planting vegetation control on *Picea glauca* survival, growth, and predicted yield in boreal British Columbia. Scand. J. For. Res. 24: 111–129.

Boateng, J.O., J.L. Heineman, L. Bedford, and A.F.L. Nemec. 2010. Twenty-year effects of mechanical site preparation and windrow burning treatments on soil properties and *Pinus contorta* var. *latifolia* nutrition in sub-boreal British Columbia. Scand. J. For. Res. 25(6): 515–533.

Boateng, J.O., J.L. Heineman, L. Bedford, A.F.L. Nemec, J. McClarnon, and R.A. Powelson. 2012. Twenty year site preparation effects on sub-boreal lodgepole pine performance. New Forests 43: 457–472.

British Columbia Ministry of Forests. 2000. Establishment to free growing guidebook. Prince George Forest Region. Revised ed., Vers. 2.2. Forest Practices Code of British Columbia Guidebook, For. Prac. Br., B.C. Min. For., Victoria, B.C.

British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development. 2012a. Timber Tenures in British Columbia: Managing public forests in the public interest. https://www.for.gov.bc.ca/ftp/HTH/external/!publish/web/timber-tenures/timber-tenures-2012.pdf

______. 2012b. Mid-Term Timber Supply. https://www.for.gov.bc.ca/hfp/mountain_pine_beetle/mid-term-timber-supply-project/timber%20supply%20project%20glossary.pdf. Accessed Aug. 2, 2016.

______. 2016. Silviculture Survey Procedures Manual – April 1st 2015. Resource Practices Branch, B.C. Ministry of Forests, Lands, and Natural Resources Operations, Victoria, B.C. Available at: https://www.for.gov.bc.ca/hfp/silviculture/Silviculture%20Survey%20Procedures%20Manual%202016.pdf. Accessed June 14, 2016.

Cortini, F., P.G. Comeau, J.O. Boateng, and L. Bedford. 2010. Yield implications of site preparation treatments for lodgepole pine and white spruce in northern British Columbia. Forests 1(1): 25–48. doi:10.3390/f1010025.

DeLong, C. 2003. A field guide to site identification and interpretation for the southeast portion of the Prince George Forest Region. Res. Br., B.C. Min. For., Victoria, B.C. Land Manage. Handb. No. 51.

DeLong, C., A. Banner, W.H. MacKenzie, B.J. Rogers, and B. Kaytor. 2011. A field guide to ecosystem identification for the Boreal White and Black Spruce Zone of British Columbia. B.C. Min. For. Range, For. Sci. Prog., Victoria, B.C., Land Manag. Handb. No. 65. www.for.gov.bc.ca/hfd/pubs/Docs/Lmh/Lmh65.htm

Delong, C., D. Tanner, and M.J. Jull. 1993. A field guide for site identification and interpretation for the southwest portion of the Prince George Forest Region. B.C. Min. For., Victoria, B.C., Land Manage. Handb. No 24. www.for.gov.bc.ca/hfd/pubs/Docs/Lmh/Lmh51.htm

Hawkins, C.B.D., T.W. Steele, and T. Letchford. 2006. The economics of site preparation and the impacts of current forest policy: evidence from central British Columbia. Can. J. For. Res. 36: 482–494.

Klinka, K., J. Worrall, L. Skoda, and P. Varga. 2000. The distribution and synopsis of ecological and silvical characteristics of tree species of British Columbia's forests. Canadian Cartographics Ltd., Coquitlam, B.C.

Lutz, J. 2011. IRR vs. NPV. Forest Research Notes, Vol. 8, No. 1. Copyright © 2011, Jack Lutz. http://www.forestresearchgroup.com/Newsletters/V8N01.pdf (Accessed Feb. 6, 2017).

McClarnon, J., J.L. Heineman, R.A. Powelson, J.O. Boateng, L. Bedford, A.F.L. Nemec, and T. Kaffanke. 2016. Lodgepole pine responses to mechanical site preparation and burning in sub-boreal British Columbia: 19- to 25-year results from three SBS zone studies (EP995). Prov. B.C., Victoria, B.C. Tech. Rep. 094.

Meidinger, D. and J. Pojar (editors). 1991. Ecosystems of British Columbia. B.C. Min. For., Victoria, B.C. Spec. Rep. Ser. No. 6.

Mitchell, K.J. 1975. Dynamics and simulated yield of Douglas-fir. Forest Science Monographs, 17, Society of American Foresters.

Mitchell, K.J., R.M. Kellogg, and K.R. Polsson. 1989. Silvicultural treatments and end-product value. In: Second growth Douglas-fir: Its management and conversion for value. A report of the Douglas-fir Task Force, R.M. Kellogg (editor). Forintek Canada Corp. Spec. Publ. No. SP-32, Vancouver, B.C., pp. 130–167.

Mitchell, K.J., M. Stone, S.E. Grout, C.M. Di Lucca, G.D. Nigh, and J.W. Goudie, et al. 2007. TIPSY, version 4.3. B.C. Min. For. Range, Victoria, B.C. [online]. Retrieved May 6, 2013, from www.for.gov.bc.ca/hre/gymodels/tipsy.

Newsome, T.A., J.L. Heineman, and A.F.L. Nemec. 2016. Plantation establishment strategies for hybrid spruce and lodgepole pine on high-elevation sites in wet Cariboo ESSF subzones: 17-year results (EP1021). Prov. B.C., Victoria, B.C. Tech. Rep. 093. www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr093.htm

Nigh, G.D. 1997. Revised growth intercept models for lodgepole pine: comparing northern and southern models. B.C. Min. For., Victoria, B.C. FRDA Report 177.

______. 2004. Growth intercept and site series-based estimates of site index for white spruce in the Boreal White and Black Spruce biogeoclimatic zone. B.C. Min. For., Victoria, B.C. Tech. Rep. 13.

Powelson, R.A., J.L. Heineman, L. Bedford, J. McClarnon, A.F.L. Nemec, and J.O. Boateng. 2016. White spruce responses to mechanical site preparation, chemical site preparation, and post-planting vegetation control over three decades in the boreal white and black spruce zone of British Columbia. Prov. B.C., Victoria, B.C. Tech. Rep. 103. www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr103.htm

Reich, R.W., J.L. Heineman, A.F.L. Nemec, L. Bedford, J.O. Boateng, and T. Kaffanke. 2015. Hard pine stem rusts on lodgepole pine at a site preparation study in sub-boreal British Columbia: effects over 24 years. Can. J. For. Res. 45: 411–421.

Smith, D.M. 1986. The practice of silviculture. 8th ed. John Wiley &. Sons, New York, N.Y.

Stearns-Smith, S. 2001. Making sense of site index estimates in British Columbia: a quick look at the big picture. B.C. J. Ecosystems Manag. 1(2):1–4.

Taylor, S.W., B.C. Hawkes, R.H. Silversides, and M.G. Weber. 1991. Initial effects of prescribed fire and mechanical site preparation on seedling environment and establishment on a backlog NSR site in central interior British Columbia. For. Can. and B.C. Min. For., Victoria, B.C. FRDA Rep. 177.

von der Gönna, M. 1992. Fundamentals of mechanical site preparation. For. Can. and B.C. Min. For., Victoria, B.C. FRDA Rep. 178.

Wagner, R.G., G.H. Mohammed, and T.L. Noland. 1999. Critical-period of interspecific competition for northern conifers associated with herbaceous vegetation. Can. J. For. Res. 29: 890–897.

Wang, T., A. Hamann, D.L. Spittlehouse, and T. Murdock. 2012. Climate WNA – high-resolution spatial climate data for Western North America. J. Appl. Meteorol. and Climatol. 51:16–29. http://cfcg.forestry.ubc.ca/projects/climate-data/climatebcwna/ (Accessed Feb. 11, 2016).

Whitehead, R.J., F. Cortini, S.W. Taylor, A.F.L. Nemec, J.W. Goudie, J. Vallentgoed, and K.R. Polsson. 2011. Condition, growth, and projected yield of lodgepole pine and interior spruce 20 years after rehabilitation of an understocked site in north-central British Columbia: The Stony Lake trial. NRC, Can. For. Serv., Can. Wood Fibre Centre Inf. Rep. FI-X-006.