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Article

Yield Implications of Site Preparation Treatments for Lodgepole Pine and White Spruce in Northern British Columbia

Francesco Cortini [1,*], Philip G. Comeau [1], Jacob O. Boateng [2] and Lorne Bedford [2]

[1] Department of Renewable Resources, University of Alberta, 751 General Services Building, Edmonton, AB, T6G 2H1 Canada; E-Mail: Phil.Comeau@ales.ualberta.ca (P.G.C.)

[2] Forest Practices Branch, B.C. Ministry of Forests and Range, PO Box 9513 Stn. Prov. Govt.,Victoria, BC, V8W 9C2 Canada; E-Mails: Jacob.Boateng@gov.bc.ca (J.O.B.); Lorne.Bedford@gov.bc.ca (L.B.)

* Author to whom correspondence should be addressed; E-Mail: fcortini@gmail.com; Tel.: +1-250-508-6904.

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Abstract: We evaluated the effects of site preparation treatments on growth of lodgepole pine and white spruce in north-eastern British Columbia, Canada. These treatments can provide yield gains of up to 10 percent for lodgepole pine and white spruce at 60 and 80 years, respectively (estimated using TASS). Stands of these two species are showing a Type 1 response. Using growth multipliers, based on measurements collected at ages 10 to 20 results in inflated estimates of potential yield responses while the age-shift method provides the most appropriate estimates of yield gains when measured during the first 20 years of growth.

Keywords: growth models; age-shift method; growth multiplier; site index; site preparation; vegetation control; conifer growth

1. Introduction

Site preparation and the management of competing vegetation are of primary importance for the successful growth and survival of conifers in the northern regions of Canada (e.g., [1-3]). Improvements in seedling survival and growth during the first 10 years after planting following site preparation can result in a substantial increase in yield [4]. Likewise the management of competing vegetation has the potential to produce significant gains in yield [5].

In boreal and sub-boreal forests the establishment of planted conifers is often limited by unfavorable soil or microsite conditions and competing vegetation such as green alder (*Alnus crispa* (Ait.) Pursh.), willow (*Salix* spp.), trembling aspen (*Populus tremuloides* Michx.), and paper birch (*Betula papyrifera* Marsh.) (e.g., [6-10]). Mechanical site preparation can modify these unfavorable conditions for conifer establishment by: 1) scalping, which removes the organic layer and exposes mineral soil, 2) mixing, which incorporates the organic layer into the underlying mineral soil, and 3) inverted mounds, which turns the surface organic layer upside down and the inverted organic layer may be covered with mineral soil [11]. By modifying the soil surface layer, these treatments can result in earlier warming of soils in the spring which effectively lengthens the growing season [4]. Exposure of mineral soil can improve heat exchange between the ground and the surface air, leading to reductions in frost injury to planted seedlings [4]. Mounding treatments create planting spots that are raised (higher than the ground level), which reduces the risk of flooding damage [11]. Moreover scalping treatments create a vertical profile of planting spots such as berms (raised planting spot favorable on wet sites), hinge (at ground level), and trenches or furrows (depressed planting spots favorable on dry sites) [11]. Site preparation treatments can also decrease soil bulk density, improve drainage, accelerate nutrient availability and enhance microsite conditions overall [4].

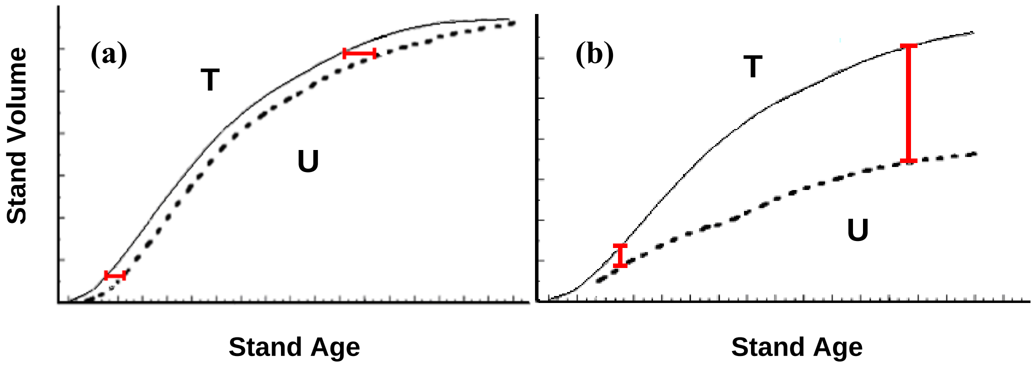
Burning is used to remove organic material from an area in order to provide a better environment for the growth and survival of crop trees [12]. This treatment can increase the short term (<5 years) availability of nutrients in the soil and also reduce competing vegetation [13]. However, slash-burning following a harvest may cause long-term nutrition losses on drier nutrient-poor sites [13].

Control of competing vegetation through manual brushing or herbicide treatments often provides an environment favorable to crop tree establishment [14]. There are many studies which have demonstrated the benefits of vegetation control in enhancing tree growth [5]. However, in some areas vegetation control alone may not be effective in ameliorating unfavorable microsite conditions such as cold soils or frost problems [15].

The long term effect of site preparation on crop yield at rotation age is still largely unknown, and needs to be addressed so that forest managers will have the ability to estimate growth and yield responses for economic and ecological comparison between various management options [16; 17]. While the long term effect of site preparation can be evaluated using growth models [18], few models directly address the effects of site preparation. There are currently no growth models available for northern B.C. that directly incorporate effects of site preparation or vegetation management on tree growth and stand dynamics.

Establishment and tending treatments can have variable effects on long term development and yield of plantations. These growth characteristics are represented in the literature by the concept of Type 1 and 2 growth responses [17]. A Type 1 growth response occurs when the establishment treatment, or more generally the silvicultural treatment, reduces the time needed for the stand to reach a given stage of maturity. Type 2 response is obtained when a proportional gain in volume increment is achieved throughout the rotation period (Figure 1).

Figure 1. Examples of Type 1 **(a)** and Type 2 **(b)** growth response respectively (modified from South and Miller [19]). The solid line represents the stand that underwent treatment (T) in relation to the untreated stand (U).



Later models have added complexity to the classification, and more 'types' of growth response models have been proposed including Type C, which characterizes non effective treatments that lead to an overall decrease in stand yield [19,20].

In the late 1980s several experiments were established in northern British Columbia (B.C.) to evaluate effects of a variety of mechanical and non-mechanical site preparation techniques on crop tree response [21]. Over the past 20 years these trials have provided information not only on early stand development of lodgepole pine (*Pinus contorta* Dougl. Ex Loud. Var. *latifolia* Engelm.), and white spruce (*Picea glauca* (Moench) Voss) plantations but also on plant community composition and diversity [22; 23].

These trials offer the opportunity to address the long-term effect of site preparation treatments such as fire, mechanical and vegetation control methods on growth of lodgepole pine, and white spruce (e.g., Type 1 or Type 2 growth responses). The objective of this study is to evaluate the ability of three modeling techniques (*i.e.*, the age-shift method, growth multipliers, and site index adjustments) to predict conifer growth which will be tested and compared to simulated rotation-length growth responses generated by the Tree and Stand Simulator model (TASS/TIPSY) [24]. These projected volumes will be also compared to data from Permanent Sample Plots (PSPs) and recently harvested cut blocks.

2. Experimental Section

2.1. Study sites, treatments and measurements

The data for this project was obtained from long term trials (20-year-old) in the boreal and sub-boreal forests of British Columbia (B.C.) where various mechanical and non-mechanical site preparation techniques were applied [21].

Data for lodgepole pine was from the Bednesti trial. Bednesti is situated 60 km west of Prince George B.C. (53° 52′ N, 123° 29′ W) at an elevation of 850 m in the Stuart Dry Warm variant of the Sub-Boreal Spruce Zone (SBSdw3) [25]. It is a mesic site with loamy soil containing 10-20% coarse fragments, and 3-6 cm forest floor at the time of treatment. The previous stand composed of lodgepole pine and black spruce (*Picea mariana* (Mill.) B.S.P) was harvested in 1971. The site was not regenerated with crop trees and was classified as not satisfactorily restocked. Grasses, shrubs, and non commercial broadleaved trees dominated the site. During the winter of 1986 all vegetation was sheared, piled into windrows, and burned [26].

At Bednesti nine site preparation techniques are compared in a randomized block design. One 750 m^2 plot of each nine treatments was established between burned windrows in each of five blocks. In each plot 48 trees were assessed and monitored. The treatments represented are: 1) control, trees were planted without site preparation, 2) burned windrow, trees planted in well burned areas free of slash, 3) patch shoulder, trees planted into the hinge of relatively deep patches, 4) Bräcke mineral mounds, trees planted into the center of the mound, 5) Delta disk trenching hinge-planting, trees planted in mineral soil at the edge of the berm, 6) Delta disk trenching furrow-planting, trees were planted into the mineral soil at the bottom of the trench, 7) Wadell cone scarifying, trees were planted into the mineral soil between the trench and the berm, 8) breaking plow, trees were planted deeply into berms of mineral soil overlying inverted forest soil, and 9) bedding plow, trees were planted in roughly mixed mineral soil and chunks of forest floor [1]. Site preparation treatments were applied between August and October of 1987, and the site was planted with lodgepole pine (PSB 221 1+0) in April of 1988. Trees were measured annually for diameter and height up to 15 years of age and measured again at age 20. Survival rate of planted trees was very good: five years after planting survival ranged between 92% and 100% and 20 years after planting between 80% and 93%.

Data for white spruce comes from the Inga Lake trial located 85 km northwest of Fort Saint John in north-eastern B.C. (56° 37′ N, 121° 38′ W) at an elevation of 890 m in the Peace variant of the moist warm subzone of the Boreal White and Black Spruce Zone (BWBSmw1) [27]. Soils are fine clayey to fine loamy basal till, with a 2-4 cm forest floor at the time of the treatment. The site where the trial was located was never harvested but regularly burned until the 1950s which resulted in a willow-dominated vegetation community that was sheared in winter 1987 [28].

The study has a randomized complete block design with seven treatments randomly allocated to 750 m^2 plots in five blocks. In each plot 48 trees were assessed and monitored. The treatments represented are: 1) control, trees were planted without site preparation, 2) burned windrow, trees planted in well burned areas free of slash, 3) Madge, trees planted in well-mixed layer of surface organic matter and mineral soil, 4) bedding plow, trees were planted in roughly mixed mineral soil and chunks of forest floor, 5) breaking plow, trees were planted deeply into berms of mineral soil overlying inverted forest soil, 6) Delta disk trenching hinge-planting, trees planted in mineral soil at the edge of the berm, 7) vegetation control, three years after shearing and planting, herbicide was applied followed by six manual cuttings [28]. Site preparation treatments were applied in July to October 1987 and the site was planted at the end of May to first week of June 1988 with interior spruce (PSB 313 2+0). Trees were measured annually for diameter and height up to 15 years of age and measured again at age 20. Survival rate of planted trees was very good: five years after planting survival ranged between 97% and 99% and 20 years after planting between 82 % and 98%.

2.2. Modeling methods

Three growth variables were used to determine the type of growth response for each treatment: mean height, mean diameter (at ground level), and mean stand volume per hectare. Stem volume (SV, cm^3) was calculated from stem height (HT, cm) and root collar diameter (RCD, cm) using a modified version of Honer's equation [29]:

$$SV = \frac{RCD^a}{b + \frac{c}{HT}}$$

where *a*, *b*, and *c* are parameters calculated by Cortini and Comeau [30] for lodgepole pine and white spruce plantations in north-western Alberta. By comparing the growth of the control treatment to the growth of the other treatments at any given time, it was possible to analyze the growth characteristics of the two species investigated.

In order to classify the type of growth response three techniques were tested: 1) the age-shift method (acceleration), which quantifies how much sooner a particular size is reached due to the treatment effect, 2) growth multipliers, which represent the treatment effect as the ratio of treated to untreated, and 3) site index adjustments, which imply that the treatment leads to a change in site productivity [19,31-33]. The Tree and Stand Simulator (TASS v2.07.61ws) growth model and the Table Interpolation Program for Stand Yields (TIPSY v4.1) growth and yield program provided the growth and yield projections for lodgepole pine and white spruce [24,34].

For the age shift method, a linear regression: $y = a + bx$, where *y* is conifer growth and *x* represents stand age, was fit to data from the untreated plots. This model was then used for each treatment to calculate the stand age relative to the untreated stand for the measured growth value (*i.e.*, $x = (y - a)/b$). The age-shift values were then calculated for each treatment as the difference between stand age values of the measured growth minus the calculated stand age relative to the untreated. When calculating the age-shift value the maximum size (volume per hectare, average diameter or average height) of the untreated stand defines the limit at which the age-shift can be calculated. For example, if the average diameter of the untreated stand is 15 cm at age 20 but the burn treatment reaches 15 cm at age 12, the age-shift value of the burn can be calculated only up-to age 12 in order to avoid extrapolating beyond the available dataset.

The growth multiplier (G.M.) factor was calculated as the ratio between the mean size in the treated block (i*) and the mean size of the untreated (i) (*i.e.,* G.M. = i*/i) [31].

Site index adjustments were calculated using the growth intercept method described by Nigh [35] for lodgepole pine and Nigh [36] for white spruce. The growth intercept method can provide site index estimates for young stands by relating the average height growth rates of trees to site index; accordingly, site index was calculated for each treatment and the control.

The information provided by the three approaches (age-shift method, growth multiplier, and site index adjustments) was analyzed in the TASS/TIPSY growth model to calculate tree growth for the studied sites. The site index values calculated at stand age 19 or 20 were projected in TIPSY to provide estimates of top height for each treatment from age 19 or 20 to the end of the rotation period. This information was then modeled by TASS with customized runs using actual information from the trials.

For this study TASS input parameters were customized by using plot data to describe the number of trees per hectare up-to age 20, spatial tree distribution, height-age curves, and site index.

The effect of competing vegetation was also considered. Overall lodgepole pine growth at age 20 was not affected by competing vegetation [1] at the Bednesti site. Therefore the site index value calculated at age 20 for each treatment was used without modifications in the TASS runs. For white spruce at the Inga site the delta hinge treatment and the untreated plots were affected by competing vegetation through age 20. For the delta hinge treatment the projected growth was not modified from age 20. For the untreated plots, Boateng *et al*. [28] indicate that the overtopped white spruce is expected to be taller than competing vegetation at stand age 26. Consequentially, growth increments may differ from age 26. Therefore, for the untreated plots, three possible scenarios were tested. Up to age 25 the growth of white spruce for the untreated plots was projected based on the site index value calculated at age 20, and from age 26: for scenario A the top height-age curve of the best treatment (herbicide) was shifted from age 20 to that of the untreated at age 26 (simple age-shift), and for scenario B the top height-age curve of the slower growing treatment (breaking plow) was shifted from age 20 to that of the untreated at age 26. These two scenarios assume that once the untreated trees are above the competing vegetation they will grow faster and follow the curve of either the best site preparation treatment (herbicide) (Scenario A), or the less effective site preparation treatment (breaking plow) (Scenario B). The third scenario (C) projects the growth of the untreated using the site index value at stand age 20 without modifying the growth curve at age 26.

2.3. Validation

The information generated by TASS on growth and yield was then compared with inventory data for naturally regenerated stands from PSP data for the same biogeoclimatic sub-zone and variant of British Columbia. Only the PSPs having more than 80% lodgepole pine or white spruce were selected in order to be representative of the experimental trials.

Stand age of the PSPs is measured at breast height (1.3 m) therefore it was necessary to estimate stand total age of the PSPs to match that of the TASS outputs. For these untreated plots to reach breast height it takes on average: six years for lodgepole pine at the Bednesti trial and 10 years for white spruce at the Inga Lake trial. In addition the seedlings were 2 years old at planting. These factors required adjusting stand age of the PSPs by 8 years for lodgepole pine, and by 12 years for white spruce. Smith [37] reports that the natural regeneration delay for lodgepole pine cut blocks in west central Alberta ranges from seven to 11 years while for white spruce the length of time required to reach breast height under open conditions ranges from 10 to 20 years depending on the site [38]. Nigh [39] developed juvenile height models for British Columbia which indicate that lodgepole pine reaches breast height in 5-10 years and white spruce in 10-15 years.

The information provided by TASS was compared to the PSP data as: 1) total stand volume per hectare *versus* top height, and 2) total stand volume per hectare *versus* stand age.

The merchantable volumes projected by TASS were also compared against harvested volumes billed to the Revenue Branch of the B.C. Ministry of Forests and Range for the period 2005-2009 (Personal communication with Stephen Davis, Reporting Analyst of the Revenue Branch. December 16, 2009). The selected cut blocks are located close to the experimental trials within the same forest district (*i.e.*, Prince George for pine and Peace for spruce). Additional information such as harvested area and vegetation survey was acquired from the Reporting Silviculture Updates and Land Status Tracking System (RESULTS, B.C. Ministry of Forests, British Columbia, Canada. Data extracted as of December 17, 2009. Data on RESULTS available at: http://www.for.gov.bc.ca/his/results/). For both lodgepole pine and white spruce only cut blocks with more than 75% of each species were selected. Information relating to the last available survey was also collected including trees per hectare, site index and crown closure which is calculated by photo interpretation and then verified on the ground.

The harvested volumes provided by the Revenue Branch include logs of all grades billed to the Crown. The logs are measured by weight-scaling to inside bark diameter of 10 cm [40]. Merchantable volume is calculated in TASS using, 12.5 cm as minimum diameter at breast height, 10 cm as minimum top diameter inside bark, and 30 cm as minimum stump height. Knowing that the merchantable volumes calculated by TASS projected the growth of fully stocked stands (crown closure: 100%) we calculated for the selected cut blocks the relative merchantable volume to that of the TASS runs at age 90 for pine and 130 for spruce (*i.e.*,. age-class midpoints of the cut blocks). The relative merchantable volume of the cut blocks was then compared to the average value of crown closure provided by the surveys.

3. Results and Discussion

3.1. Lodgepole pine results

For lodgepole pine ages 9 and 15 were used to explore age-shift changes over the measured period (Table 1).

Table 1. Age-shift values calculated for lodgepole pine at stand ages 9 and 15 for volume, diameter, and height.

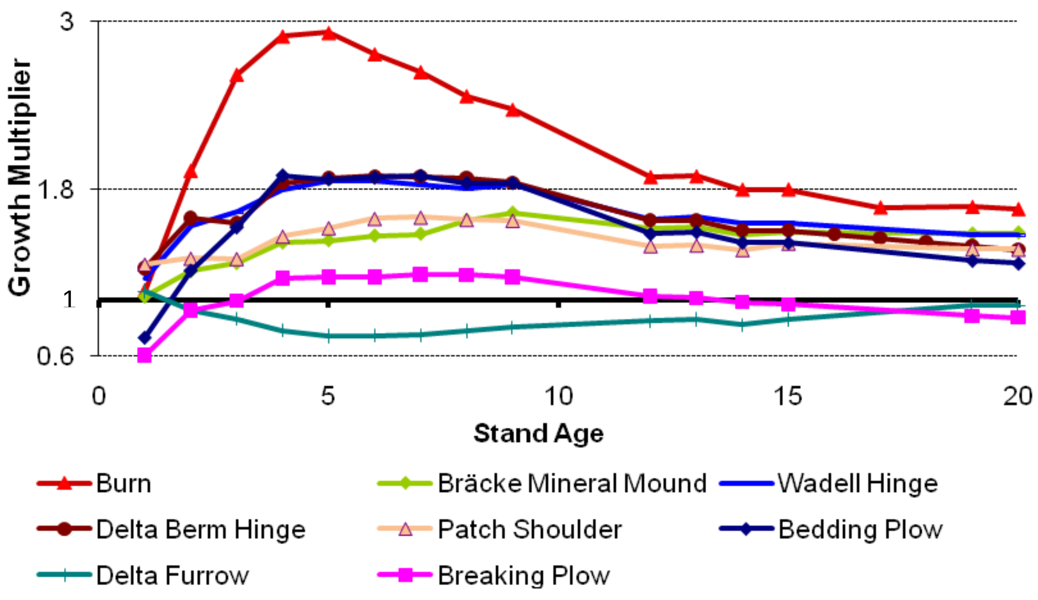
Treatment	*Age-shift*					
	Volume per ha		Diameter		Height	
	Yr 9	Yr 15	Yr 9	Yr 15	Yr 9	Yr 15
Bedding Plow	1.4	1.9	2.4	3.5	1.4	2.5
Bräcke Mineral Mound	1.1	2.4	0.5	1.3	0.0	0.8
Patch Shoulder	1.0	1.9	0.5	1.4	0.1	0.6
Breaking Plow	0.6	-0.8	1.0	1.5	0.8	1.8
Burn	2.0	4.3	3.1	4.9*	1.8	2.6
Delta Berm Hinge	1.4	2.5	1.3	2.1	0.8	1.4
Delta Furrow	0.1	-1.5	-1.2	-1.2	-1.0	-0.9
Wadell Hinge	1.3	2.8	1.4	2.7	0.8	1.8
Untreated	-	-	-	-	-	-

*Yr 14

The smallest age-shift value calculated is -1.5 years for the delta furrow treatment at age 15, indicating that volume growth in this case is slower than that of the untreated, while the largest age-shift value calculated is 4.9 years for diameter in the burn treatment at age 15, indicating faster diameter growth compared to the untreated. For every treatment, age-shift values calculated from diameter are larger than those related to height, and values calculated at age 15 are substantially larger than values calculated at age 9. The burn treatment is consistently the best treatment while the delta furrow treatment shows the worst performance compared to the untreated.

Growth multipliers were compared at stand ages 9, 15, and 20. Volume multipliers range between 0.9x (delta furrow) and 1.7x (burn) at age 20. For every treatment the growth multipliers for diameter are consistently higher than those related to height. Growth multipliers also indicate that the burn treatment is the more productive compared to the untreated, and the delta furrow is the least productive. Every treatment shows an initial shift in growth compared to the untreated, but after age 5, treatments tend to follow growth patterns similar to that of the untreated (Figure 2).

Figure 2. Changes in growth multipliers for lodgepole pine stem volume (m^3 ha^{-1}) with age for treatments applied at the Bednesti site.



Every treatment (except the delta furrow treatment) shows a decreasing growth multiplier factor from year 9 to year 20. Growth multipliers calculated at ages 4-8 for all treatments (except the delta furrow treatment) are higher than values obtained at ages 18-20. For the burn treatment the multiplier is 2.9x at age 5 but declines to 1.7x at age 20.

The site index adjustments show that site index values are fairly constant at the treatment level and the changes from age 9 to 20 range from -0.6 (patch shoulder) to 0.7 m (mineral mound and untreated) (Table 2).

At year 20 the bedding plow treatment shows the highest site index value compared to the untreated (0.8 m difference); and again the delta furrow is the worst performing treatment compared to the untreated (-0.4 m difference).

The growth estimates for lodgepole pine provided by TASS/TIPSY show small differences at age 90 between treatments and untreated. Volume growth multipliers were calculated from age 27 forward and results show that each treatment converges by age 90 to the untreated.

Table 2. Site index adjustments calculated for lodgepole pine at stand ages 9, 15 and 20.

Treatment	*Site Index*			*Difference with Untreated*		
	Yr 9	Yr 15	Yr 20	Yr 9	Yr 15	Yr 20
Bedding Plow	22.4	22.2	22.2	1.6	0.8	0.8
Bräcke Mineral Mound	21.1	21.8	21.8	0.4	0.5	0.4
Patch Shoulder	22.0	21.8	21.4	1.3	0.5	0.0
Breaking Plow	21.6	21.9	21.8	0.9	0.6	0.4
Burn	22.0	21.9	22.1	1.3	0.5	0.7
Delta Berm Hinge	22.0	21.7	21.6	1.2	0.3	0.3
Delta Furrow	21.1	20.4	21.0	0.4	-1.0	-0.4
Wadell Hinge	21.7	22.4	22.0	1.0	1.1	0.6
Untreated	20.7	21.4	21.4	-	-	-

Maximum mean annual increment (MAI) occurs on average at stand age 55.6 and corresponds to average merchantable volume of 284 $m^{-3}ha^{-1}$ and top height of 20 m (Table 3).

The bedding plow and the breaking plow treatment reach maximum MAI earlier than the untreated and the other treatments with resulting age-shifts of 7 and 2 years, respectively. They are represented in both cases by a 1.1 growth multiplier factor. The narrow range of growth multiplier values (*i.e.*, 0.9-1.1) indicates that model estimates of volume for every treatment at culmination are within 10% of that of the untreated.

Table 3. Results from TASS simulations of lodgepole pine at age of maximum mean annual increment (MAI).

Treatment	Age at Max MAI	Merch.Vol. $m^3\ ha^{-1}$	*Age-shift from Untreated*	*Growth Multiplier*	Top Height *m*
Bedding Plow	48	258	7	1.1	18.5
Bräcke Mineral Mound	59	300	-4	1	20.7
Patch Shoulder	62	299	-7	1	20.9
Breaking Plow	53	284	2	1.1	20
Burn	55	292	0	1	20.5
Delta Berm Hinge	56	279	-1	1	20.2
Delta Furrow	56	271	-1	1	18.7
Wadell Hinge	57	296	-2	0.9	20.6
Untreated	55	275	-	-	20.1

For lodgepole pine, the PSP data indicates that the projections provided by TASS/TIPSY are representative of young naturally regenerated stands (up-to stand age 20), but overestimate the growth of natural stands after age 40 (Figure 3). According to the projections at stand age 60 every treatment shows a growth multiplier factor of either 1.0 or 1.1 indicating a marginal or small treatment effect (Table 4).

Lodgepole pine information provided by the recent cut blocks in the same forest district indicates an average merchantable volume of 260 m^3 ha^{-1} (age-class: 81-100) and the latest available survey indicates an average crown closure of 62% (Table 5). For these cut blocks the merchantable volume relative to that projected by TASS (at 100% crown closure) is 62% which is the same value as the averaged crown closure for the selected cut blocks.

Figure 3. Projected stand volume over stand age for lodgepole pine for the best treatment (breaking plow) and the untreated scenario. The PSP data represents measured volume of natural stands in the same biogeoclimatic subzone and variant (SBSdw3). The polynomial fitting the PSP data is represented by: Y =1.27554*X+0.06359*X2-0.00023*X3 (n=10; Adj.R2=0.96; P<0.0001).

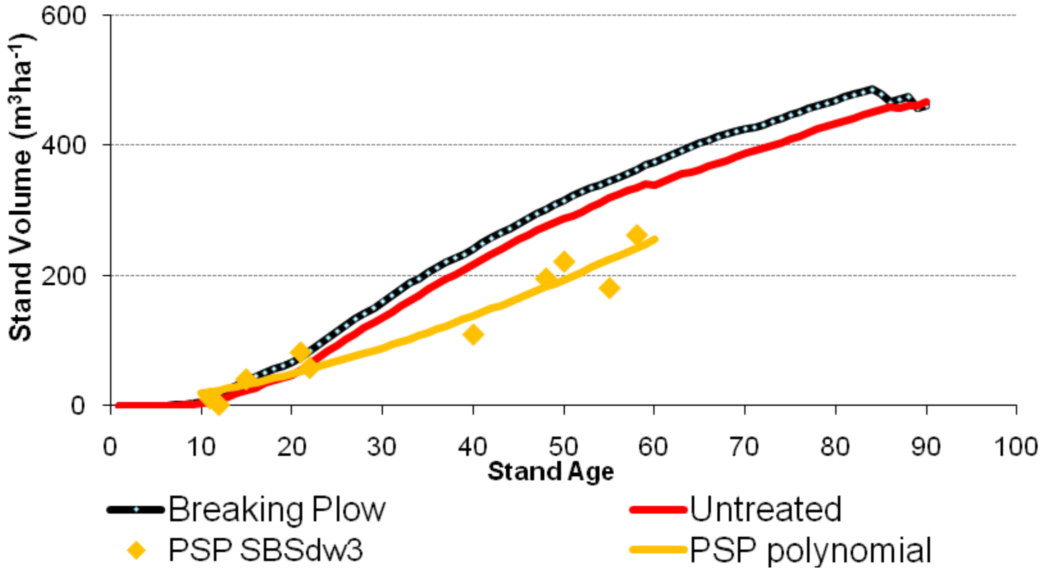


Table 4. Stand yield data from TASS simulations to age 60 for lodgepole pine together with growth multiplier values.

Treatment	Stand Age	Density *Trees* ha^{-1}	Total Volume m^3 ha^{-1}	Merch.Vol. m^3 ha^{-1}	Basal Area m^3 ha^{-1}	Top Height *m*	*Growth Multiplier*
Bedding Plow	60	1185	372	327	47.2	21	1.1
Bräcke Mineral Mound	60	964	344	306	45.3	20.8	1
Patch Shoulder	60	1015	327	288	44.4	20.6	1
Breaking Plow	60	1426	375	324	48.6	21.3	1.1
Burn	60	1073	360	319	46.1	21.5	1.1
Delta Berm Hinge	60	1052	341	301	45.7	21	1
Delta Furrow	60	1060	330	290	44.5	19.4	1
Wadell Hinge	60	1064	353	312	46.1	21.2	1
Untreated	60	1133	339	298	45.1	21	-

Table 5. Merchantable volumes from recently harvested cut blocks of pure lodgepole pine for the Prince George Forest District (DPG) (Source: Database of Revenue Branch, and RESULTS database of Forest Practices Branch, BC Ministry of Forests and Range).

								Latest Survey				
Latitude, Longitude	BEC Zone	Merch. Volume *m*^{3}	Harvested *Year*	Pine *%*	Age-Class	Area *ha*	**Merch. Volume** *m*^{3} *ha*$^{-1}$	Year	Pine *%*	**Crown Closure** *%*	Trees *ha*$^{-1}$	Site Index *m*
54° 13' 8.4" N, 123° 16' 4.8" W	SBS	23064	2009	83	81-100	99	**232**	2001	100	60	1042	19
54° 14' 28.2" N, 123° 30' 11" W	SBS	19077	2009	80	81-100	75	**254**	2003	100	70	790	19
54° 13' 17.8" N, 123° 18' 32" W	SBS	28994	2009	86	81-100	105	**276**	2001	100	60	1042	19
54° 14' 47.9" N, 123° 29' 4.3" W	SBS	31917	2009	93	81-100	114	**279**	2001	90	60	1045	18
				Average Values:			**260**			**62**		

3.2. White spruce results

For white spruce stand ages 6 and 11 were selected to compare age-shift values over the measured period (Table 6). Age-shift values range from 0.3 years for the herbicide treatment at age 6, indicating that height growth in this case is close to that of the untreated, to 10.9 years for the burn treatment at age 11, indicating much faster volume growth compared to that of the untreated. The burn treatment is consistently the best treatment and the delta hinge is by far the worst in comparison to the untreated. For the majority of the treatments age-shift values for diameter are higher than those related to height and values calculated at age 11 are larger than at age 6 except for volume per hectare for the delta hinge treatment.

Table 6. Age-shift values calculated for white spruce at stand ages 6 and 11 for volume, diameter, and height.

	Age-shift					
Treatment	Volume per ha		Diameter		Height	
	Yr 6	Yr 11	Yr 6	Yr 11	Yr 6	Yr 11
Bedding Plow	1.9	3.7	1.5	6.4	1.6	7.0
Breaking Plow	2.5	7.1	4.0	9.2*	2.8	10.0
Burn	2.8	10.9	4.3	8.3**	2.4	10.1
Delta Hinge	1.9	1.1	0.7	1.4	0.7	2.5
Herbicide	1.8	9.3	0.6	7.8**	0.3	8.2
Madge	2.3	6.0	2.3	10.4*	1.8	7.8
Untreated	-	-	-	-	-	-

* Year 10 **Year 9

Growth multipliers were compared at ages 6, 11, and 20 and results show that the volume multiplier values range between 2.2x (delta hinge) and 8x (burn) at age 20. For the majority of the treatments, growth multipliers for diameter are higher than those related to height. Growth multipliers increase to age 20 and indicate that the treatment effect steadily enhances spruce growth up to age 20 compared to the untreated (Figure 4).

The burn is overall the best treatment although the diameter values for the herbicide and the height values for the breaking plow treatment are similar to those for the burn. The delta hinge still represents the worst treatment in relation to the untreated.

The site index adjustments show that site index values decrease from age 11 to age 20 with differences between the two ages ranging from -0.8 (bedding plow) to -2.7 m (herbicide) (Table 7).

At year 20 the herbicide shows the highest site index value (25.5) which is 6.5 m higher than that of the untreated. The worst treatment is the still the delta hinge with a site index equal to the untreated (19).

For white spruce the growth projections included three scenarios for the untreated plots and volume growth multipliers were calculated from age 27 on. For scenario A and B the growth curve of every treatment (except delta hinge) converges to the untreated scenario by age 85. For scenario C most treatments have a higher volume at age 85 than the untreated (1.3x) although the growth multiplier curve is gradually approaching a value of 1.0x.

Figure 4. Changes in growth multipliers for white spruce stem volume (m^3 ha^{-1}) with age for treatments applied at the Inga Lake site.

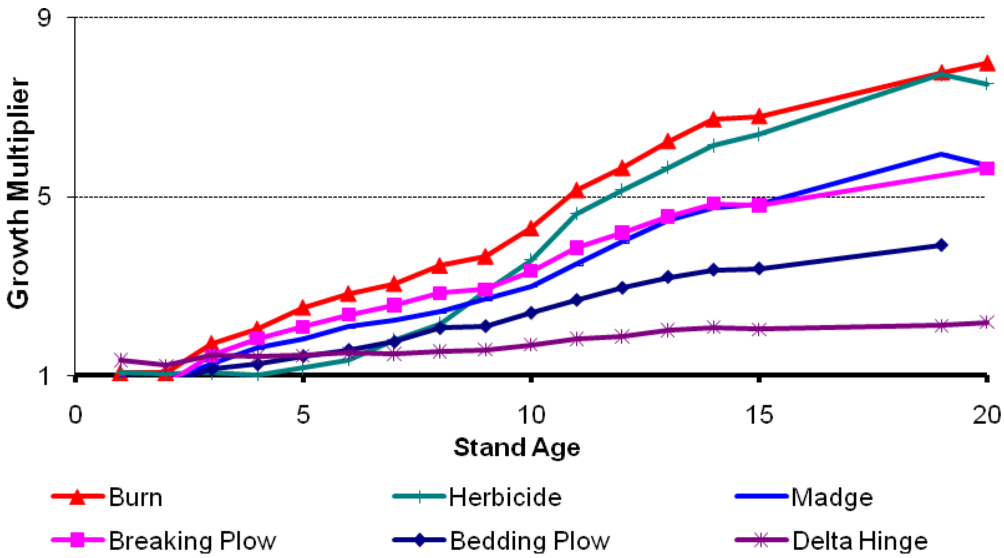


Table 7. Site index adjustments calculated for white spruce at stand ages 11 and 20.

Treatment	*Site Index*		*Difference with Untreated*	
	Yr 11	Yr 20	Yr 11	Yr 20
Bedding Plow	25.3	24.5*	4.4	5.5
Breaking Plow	25.3	24.1	4.4	5.1
Burn	25.6	24.7	4.7	5.7
Delta Hinge	21.1	19.0	0.2	0.0
Herbicide	28.2	25.5	7.3	6.5
Madge	26.5	24.7	5.6	5.7
Untreated	20.9	19.0	-	-

* Yr 19

The maximum mean annual increment (MAI) for white spruce occurs at stand age 68.5 on average and corresponds to an average merchantable volume of 505 m^3ha^{-1} and a top height of 27.3 m (Table 8).

The bedding plow treatment reaches maximum MAI earlier (61) than the other treatments and the three projections for the three untreated scenarios; and the worst treatment is the delta hinge that reaches maximum MAI at age 86. The growth multiplier values indicate that a group of treatments (bedding plow, breaking plow, burn, herbicide, and madge) show similar MAI values while the delta hinge and the untreated (depending on the scenario) have lower MAIs.

Table 8. Results from TASS simulations of white spruce at age of maximum mean annual increment (MAI) together with age-shift and growth multiplier values by scenarios.

Treatment	Age at Max MAI	Merch.Vol. $m^3\ ha^{-1}$	*Age-shift from Untreated*			*Growth Multiplier*			Top Height *m*
			Scenario			*Scenario*			
			A	*B*	*C*	*A*	*B*	*C*	
Bedding Plow	61	495	4	9	17	1	1.1	1.5	26.5
Breaking Plow	66	514	-1	4	12	1	1.1	1.4	27.9
Burn	63	513	2	7	15	1	1.1	1.5	28
Delta Hinge	86	485	-21	-16	-8	0.8	0.8	1	26.5
Herbicide	63	544	2	7	15	1.1	1.2	1.6	28.2
Madge	65	524	0	5	13	1	1.1	1.5	28.2
Untreated:									
Scenario A	65	513	-	-	-	-	-	-	27.6
Scenario B	70	513	-	-	-	-	-	-	27.6
Scenario C	78	445	-	-	-	-	-	-	25.2

The results for white spruce show that the TASS projections and the PSP data from natural stands follows the projections of scenario A and B of the untreated better than the projected growth in scenario C (Figure 5). At stand age 80 every treatment except the delta hinge shows a growth multiplier factor of either 1.0 or 1.1 for scenario A and scenario B indicating a marginal or small treatment effect (Table 9).

For white spruce the information provided by the recent cut blocks in the Peace Forest District indicate an average merchantable volume of 364 $m^3\ ha^{-1}$ (age class: 121-140) and the latest available survey indicates an average crown closure of 57% (Table 10). The merchantable volume for these cut blocks is 59% of the values estimated by TASS for scenario B (at 100% crown closure) which is similar to the average crown closure value of these cut blocks.

Figure 5. Projected stand volume over stand age for white spruce for the best treatment (herbicide) and the untreated scenarios. The PSP data represents measured volume of natural stands in the same biogeoclimatic subzone and variant (BWBSmw1). The polynomial fitting the PSP data is represented by: $Y = -3.9276*X+0.33743*X^2-0.00248*X^3$ (n = 6; Adj.R^2 = 0.96; $P < 0.0048$).

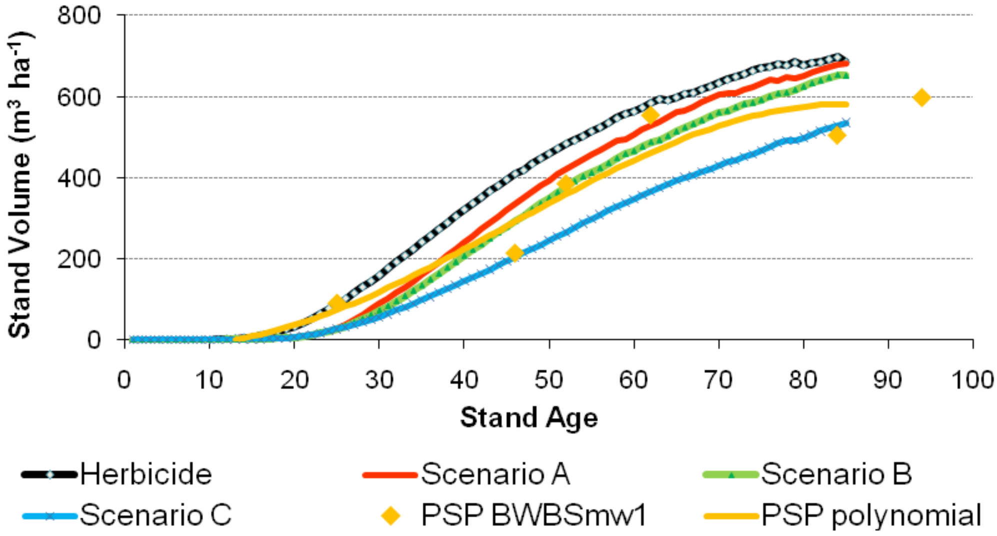


Table 9. Stand yield data from TASS simulations to age 80 for white spruce together with growth multiplier values by scenarios.

Treatment	Stand Age	Density *Trees ha^{-1}*	Total Volume *m^3 ha^{-1}*	Merch.Vol. *m^3 ha^{-1}*	Basal Area *m^3 ha^{-1}*	Top Height *m*	*Growth Multiplier Scenario* A	*B*	*C*
Bedding Plow	80	971	669	619	66.1	31.4	1	1.1	1.3
Breaking Plow	80	922	627	580	61.4	31.3	1	1	1.3
Burn	80	886	661	613	64.9	31.7	1	1.1	1.3
Delta Hinge	80	862	484	442	54.8	25.2	0.7	0.8	1
Herbicide	80	951	681	631	66.8	31.8	1	1.1	1.4
Madge	80	1003	649	598	63.7	31.9	1	1	1.3
Untreated:									
Scenario A	80	885	652	606	63.4	31.6	-	-	-
Scenario B	80	944	625	577	63.2	30.2	-	-	-
Scenario C	80	1062	485	438	55.9	25	-	-	-

Table 10. Merchantable volumes from recently harvested cut blocks of pure white spruce for the Peace Forest District (DPC) (Source: Database of Revenue Branch, and RESULTS database of Forest Practices Branch, BC Ministry of Forests and Range).

								Latest Survey				
Latitude, Longitude	BEC Zone	Merch. Volume *m^3*	Harvested *Year*	Spruce *%*	Age-Class	Area *ha*	**Merch. Volume** *m^3 ha^{-1}*	Year	Spruce *%*	**Crown Closure %**	Trees *ha^{-1}*	Site Index *m*
56° 46' 17.4" N, 122° 4' 55.9" W	BWBS	1792	2006	87	121-140	5	**381**	2004	75	55	636	16
57° 48' 14" N, 122° 2' 43" W	BWBS	106800	2005	82	121-140	310	**345**	1996	85	65	1142	10
55° 39' 26.8" N, 122° 21' 40" W	ESSF	6247	2006	76	121-140	17	**367**	1969	36	50*	895	14
56° 33' 38.5" N, 121° 22' 0.1" W	BWBS	46131	2007	85	121-140	127	**364**	2000	80	50	1200	12
					Average Values:		**364**			**57**		

* Not included in the average value because the last survey was conducted in 1969

3.3. General Discussion

For lodgepole pine the best treatments at age 60 are the bedding plow, the breaking plow, and the burn that are showing 10% more productivity than the untreated with an average merchantable volume of 323 m^3ha^{-1}. The other treatments show productivity levels close to that of the untreated plots. Previous studies at the Bednesti site have indicated that the main limiting factors are: low fertility, compact subsoil, and low water-holding capacity with rooting zone as thin as 10 cm [1]. While mechanical site preparation typically reduces soil bulk density without reducing nutrient availability one study reports that the bedding plow treatment had significantly greater total C than the untreated indicating an overall increased level of organic matter [26]. The fire treatment resulted in higher productivity for lodgepole pine up-to age 60 as a consequence, among the others, of the ash layer that replaces the forest floor and allows more solar radiation to penetrate the soil [26,41,42]. The Delta disk trenching furrow-planting is the worst treatment. For this treatment trees were planted into the mineral soil at the bottom of the trench where compact subsoil and low fertility have shown to affect pine growth [1].

The growth projections for lodgepole pine indicate that the treatments have accelerated growth compared to the untreated but the treatment effect largely ceases by stand age 90 (Figure 3). This outcome is characteristic of treated stands following a Type 1 growth response [17]. A similar study on *Pinus taeda* L. concluded that enhanced growth following site preparation treatments, which improve soil aeration early in the rotation (*i.e.*, ditching and bedding), decreases over long periods of time [43].

The data from the selected PSPs shows lower volume growth compared to the growth projected by the TASS model for the untreated. Many factors influence this outcome. For example, TASS projects the growth of a plantation under ideal conditions and tends to overestimate its productivity compared to naturally regenerated pine stands [24,44]. Studies in Alberta and British Columbia have concluded that post-harvest lodgepole pine stands grow at a faster rate than mature fire origin stands where stand conditions are different and density is less uniform [45,46]. Fire origin stands usually start at higher densities compared to post-harvest pine stands, which may lead to reduced height growth and less vigour [45,47]. Information from harvested blocks in the Prince George Forest District corroborates these merchantable volume projections calculated by TASS for the untreated scenario.

For white spruce the best treatments at age 80 are the bedding plow, the burn, and the herbicide which show 10% higher standing volume than the untreated plots (*i.e.*, scenario B) with an average merchantable volume of 621 m^3ha^{-1}at age 80. In boreal forests white spruce establishment is often limited by severe vegetation competition and unfavorable soil conditions, therefore treatments that affect these factors have proven to increase growth and survival of spruce (e.g., [8,26,28,48]). Both mechanical site preparation treatments and the removal of competing vegetation, by applying herbicide or fire, result in a shift in the plant community from tall shrubs (e.g., green alder and willow), as in the untreated, to mainly grasses and forbs [22,28,49]. At the Inga Lake site the treatment effect (e.g., decreased soil density and improved nutrient availability) was still significant 15 years after planting [8], but a later study at age 20 found that early microsite amelioration caused by the establishment treatments was ceasing and was having less impact on spruce growth than the negative response to competing vegetation [28].

For white spruce, if the untreated follows either scenario A or B, the projected growth of the treated blocks by stand age 85 will result in productivity levels similar to that of the untreated; thus implying a Type 1 growth response (Figure 5). If the untreated growth follows scenario C then the best treatments will have 25-30% more volume than the untreated at stand age 85; thus implying a Type 2 growth response. The delta hinge treatment is showing reduced volume growth compared to the other treatments and the untreated as a consequence of hare (*Lepus americanus*) damage and high levels of competing vegetation [49]. Results from scenario B (untreated) match the curve for the PSP data more closely than Scenario A or C (Figure 5). Also the information provided by the harvested blocks in the Peace Forest District corroborates the merchantable volume projections calculated by TASS.

As shown for lodgepole pine, the productivity of spruce stands is also generally overestimated by TASS thus the proximity between the PSP data and the projected growth of scenario B provides a good indication of the potential growth of the untreated. Moreover, in 15-year-old white spruce stands Feng *et al*. [50] found that the height of the current top height trees was approximately 14% greater than the height of the top trees that would be selected to calculate site index at breast height age 50. These findings also suggest a Type 1 growth response for white spruce [17].

Results from this study suggest that the age–shift approach is the best method, among the modeling techniques tested, for representing growth differences for a given treatment in relation to the untreated. However, at early stages the age-shift value can be calculated only up to the relative age of the maximum size of the control treatment. This limits its application when the growth of the untreated is significantly slower compared to the treated [38]. For this reason our data for white spruce growth limited calculating age-shift values up to age 11 for the majority of the treatments. For faster growing lodgepole pine [51] it was possible to calculate age-shift values up to age 14-15 for every treatment.

Age-shift values can also be calculated for older stands using growth and yield information although it is important to consider that age-shift values will fluctuate depending on stand age. For example, at maximum MAI age-shift values indicate that the bedding plow treatment has the potential to shorten the time to reach maximum MAI by 13% compared to the untreated for both lodgepole pine and white spruce, although this gap declines at culmination age.

The growth multiplier method provided valuable information on growth characteristics of treated and untreated plots and also helped in interpreting the growth and yield projections of the future stands. Unlike the age-shift method it is possible to calculate growth multipliers using every growth measurement available (Figure 2 and 4) [31]. For lodgepole pine the early growth multiplier factors and trends for diameter and height are similar to those calculated for older plantations using the projected growth, which implies that growth multipliers can provide indications on the future development of the stand even at early stages (*i.e.*, stand age 15-20). Nevertheless, at age 20 the growth multiplier values for volume suggest that treated stands could be up-to 70% more productive than untreated (e.g., burn = 1.7x). This outcome is consistent with the findings that slash-burning reduces brush competition and increases short term availability of nutrients in the soil [13]. However, while such early increases in growth are widely observed, it is unlikely that these will translate into yield increases of this magnitude.

Early growth multipliers for white spruce indicate an increasing value of the multiplier with age between treated and untreated stands whereas the values from the projected growth suggest a decreasing trend. In this case the early indications of stand development for any of the growth sizes would not be representative of the stand at the end of the rotation period and could potentially mislead managers regarding the long-term effect of the treatments. For example, at stand age 20 the volume growth multiplier factor for the burn was 800% (*i.e.*, 8x) of the untreated area but at stand age 80 the value drops to 10% (*i.e.*, 1.1x). Differences between pine and spruce in observed relationships between growth multiplier and model estimates of yield are related to differences in patterns of early growth of these two species, number of years to maximum MAI, and the duration of the treatment effects.

This outcome indicates that multipliers calculated up to age 20 do not predict volume gains at stand age 85 or older. For white spruce, vegetation management and forest productivity studies indicate that volume gains compared to the untreated stands at age 10 or 12 range from 194% to 591% [52-54], at stand age 19 gains are around 188% [55], and at stand age 30 volume gains decline to 53-96% [5,56]. These percentage volume gains are consistent with the range of measured and predicted values for white spruce at the Inga Lake installation. At stand age 15, Simard *et al.* [57] indicate that vegetation management increases total lodgepole pine stand volume by 57% which is consistent with the gains measured for pine at the Bednesti Lake installation. These factors corroborate the finding that early estimates of volume gains are more representative of the final yield for lodgepole pine than are those for white spruce.

Age shift values and growth multipliers for lodgepole pine and white spruce indicate that diameter growth was affected more by treatment than height; which is consistent with the findings from many other studies which show that diameter growth is more sensitive than height growth to competing vegetation or site preparation treatments (e.g., [8,58]).

The site index adjustments calculated using the growth intercept method provided the base information to create customized growth curves for stands projected with TASS/TISPY. For lodgepole pine, the site index values calculated did not show significant differences between stand age 9, 15 or 20. Huang *et al.* [46] have also shown that site index estimates stabilize after stand breast height age 5 in juvenile stands planted after harvesting and drag scarification. The site index estimates at age 20 for white spruce were lower by only 0.4% than the values calculated at age 11. Growth intercept models which relate the early average height growth of trees to site index, have been shown to provide reasonable site index estimates for young stands [35,36,46,59]. Although the growth intercept model has proven to provide significant information on growth and yield of conifers, it still represents an early estimate of the stand productivity. More data, especially for treated stands, is needed in order to validate estimates of the effect of establishment treatments on site productivity.

It is important to mention that this study is based on relatively young stands and that growth models including TASS/TIPSY provide long term growth estimates for the 'average' stand using inventory data of similar locations. For these reasons the projected growth estimates evaluated hereby are only valid for this case study and might not be representative of the future characteristics and development of the stand.

4. Conclusions

For lodgepole pine the best treatments at age 60 are the bedding plow, the breaking plow, and the burn and show 10% more productivity than the untreated plots with an average merchantable volume of 323 $m^3 ha^{-1}$. The other treatments show productivity levels close to that of the untreated plots. This study indicates that before age 60 the best treatments can still result in increased lodgepole pine yield compared to the untreated plots but this gap will likely diminish at stand age 90 and older in accordance to the Type 1 growth response characteristics.

For white spruce the best treatments at age 80 are the bedding plow, the burn, and the herbicide which show 10% higher standing volume than the untreated plots (*i.e.*, scenario B) with an average merchantable volume of 621 m^3 ha^{-1}. The other treatments show yield levels close to that of the untreated plots. This study shows that the best treatments can result in an increase in white spruce stand volume up to age 80 compared to the untreated plots but this gap will be likely filled at stand age 85 and older in accordance to the Type 1 growth response characteristics.

Understanding the long-term effect of silvicultural treatments on conifer growth is of fundamental importance in planning sound forest management. In order to project conifer yield at northern latitudes, growth models are needed since the rotation length of conifer plantations generally exceeds 50 years and no experimental trial has been monitored for such length of time. Growth models such as TASS/TIPSY are mainly developed using inventory data from naturally regenerated forests and tend to provide conservative projections for stands with planted trees. Moreover climate change adds uncertainty to growth models that do not include a representation of climate effect. For these reasons the projected growth estimates evaluated hereby are only valid for this case study and might not be representative of the future characteristics and development of the stand.

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