Implications of alternate silvicultural strategies in Mountain Pine Beetle damaged stands

Technical Report

For

Forest Science Program Project Y051161

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Abstract

We incorporated a robust snag dynamics submodel into SORTIE-ND. We found that Mountain Pine Beetle (MPB) killed pine snags block considerable light for at least 10 years after their death. Light levels in the understory of recently killed lodgepole pine stands are too low for survival of regenerating pine seedlings. This is a very different regeneration environment for pine than found after wildfire. We used data from the BC Ecological Classification program to identify four major stand types found in MPB damaged forests. Three of the four stand types identified had variable levels of residual spruce either in the overstory, the understory, or both. After pine mortality, the spruce in these stand types released and grew well resulting in well-stocked stands with good basal areas. Two of the stand types recovered to pre-attack basal areas within 50 years, the third by 80 years. These stand types can help mitigate mid-term (30-50 years) timber supply shortages if left unsalvaged or protected during partial salvage. Planting these stand types shortly after MPB attack resulted in higher basal areas at 100 years, but increases were moderate and varied depending on starting stand type. The pine dominant stand with little residual spruce did not recover. In pine dominated stands with few live residual trees either salvage and planting or under-planting is required. Delaying under-planting until pine snags transmit greater light to the understory (5-15 years after initial MPB attack) may result in much higher plantation survival and subsequent volume development. SORTIE-ND predicted growth of pine or spruce plantations after total salvage were very similar to TASS predictions (based on TIPSY v3.2 runs). SORTIE-ND subalpine fir plantations grew slower than those projected by TASS. Lastly, we were unable to predict the extent of natural regeneration in the four stand types due to lack of data to parameterize the recruitment submodel, however, we have a 2005/07 FSP funded study to address this short-coming. None-the-less, shading by a MPB killed snag is severe in the first few years after MPB attack and may greatly limit regeneration success.

Introduction

Various silvicultural strategies can be applied in Mountain Pine Beetle (MPB) damaged stands. Full salvage and planting is being employed widely. Other strategies may involve salvage with protection of advance regeneration and surviving residual canopy trees (with or without supplemental fill planting). Many areas will not be salvaged logged, but future yield predictions for such stands are still required.

There will be many different permutations of residual stand conditions across MPB damaged forests. Forest managers need models that predict future growth after different management strategies. Traditional growth and yield models have considerable difficulty predicting stand development in complex structured mixed species stands.

A significant challenge to modeling stand dynamics after MPB attack is the role of the dead pine trees or pine snags. Snag dynamics is not an issue after total salvage followed by planting. Traditional growth and yield models (e.g., TASS) can be used to predict stand growth after complete salvage and planting. Vast areas, however, will not be salvaged or will be only partially salvaged leaving variable levels of snags and residual trees. These stands may be very complex in structure. The impact snags will have on understory development is unknown. Our first objective for this project was to develop a snag submodel for SORTIE-ND. SORTIE-ND is a re-engineered version of the spatially explicit, individual tree model SORTIE (Pacala et al. 1996; Coates et al. 2003). Here, we use the new snag submodel combined with our previous Forest

Science Funded project that developed adult tree growth functions for Sub-Boreal Spruce tree species (FII Project R04-003 "Growth Prediction of Canopy Trees in Complex Structured Mixed-Species Stands") to model stand dynamics after MPB attack.

We have used SORTIE-ND to model stand development without salvage in four common stand types found in MPB attacked forests, to predict survival and growth rates of lodgepole pine natural regeneration, and to explore the effectiveness of different under-planting prescriptions. These simulations allow us to explore how different stand types will be affected by MPB attack and how natural regeneration and under-planting of different species will respond to MPB attack. In addition, the importance of considering the temporal nature of silvicultural strategies is explored.

SORTIE-ND Model Structure

SORTIE-ND retains the basic structure of the original model, but has been extensively upgraded in object-oriented programming. The core model is in C++ and Java software is used for the user interface. SORTIE-ND is a stand-level, spatially-explicit, individual-tree forest dynamics model. Forest dynamics is the change of forest composition and structure over time. The spatio-temporal development of forests may be described as changes of tree populations due to birth and colonization, growth and death of trees. The SORTIE-ND model structure uses field experiments and testing of alternate hypotheses to best parameterize the demographic processes and tree growth relationships found in the model (Kobe and Coates 1997; Wright et al. 1998, 2000; Canham et al. 1999, 2004; LePage et al. 2000). SORTIE-ND extrapolates from measurable fine-scale and short-term interactions among individual trees to large-scale and long-term dynamics of forest communities (Coates et al. 2003).

Objectives

1) Develop snag submodel for SORTIE-ND
    - Determine light transmission values of three snag classes
    - Determine snag fall down rate
    - Develop code for SORTIE-ND
2) Predict understory light environments in MPB damaged stands
3) Examine effect of MPB killed stands on survival and growth of naturally regenerated lodgepole pine
4) Growth comparison of SORTIE-ND and TASS for complete salvage and plant prescriptions
5) Predict development of unsalvaged stand types after MPB attack
6) Determine consequences of under-planting unsalvaged stand types after MPB attack
7) Examine the implications of delaying planting in MPB damaged stands

Methods

Snag submodel

The development of a snag submodel for SORTIE-ND required the definition of snag decay classes, the parameterization of light transmission coefficients for snags and the estimation of snag fall down rates. We defined three snag decay classes: class 1 as a newly dead tree where the shape of the crown is clearly defined by fine branches or twigs that still remain on larger branches, class 2 has lost most fine branches and the crown shape is less well defined but can still be extrapolated from larger branches, and class 3 where only sparse large diameter branches remain. Light transmission values for each individual snag class were determined following the methods detailed in Canham et al. (1999). To incorporate snag fall down rates, we examined the literature for any information on snag fall rates over time after tree death. There was limited information available. We then developed a predictive model that can be parameterized based on snag mortality data. Using available data, local knowledge and our own understanding of snag mortality rates we parameterized the model.

Starting Conditions

The plots established by the Provincial Ecology Program for ecological classification of the sub-boreal spruce (SBS) zone were used to identify the range of stand types susceptible to MPB in northwestern British Columbia. We examined stand types in the SBSdk and SBSmc2 subzones (Banner et al. 1993). We selected four stands from the SBSdk subzone to represent the major MPB susceptible stand types that are present across the landscape. Figures 1a and 1b provide graphical representations of these stand types prior to MPB attack. These stands were:

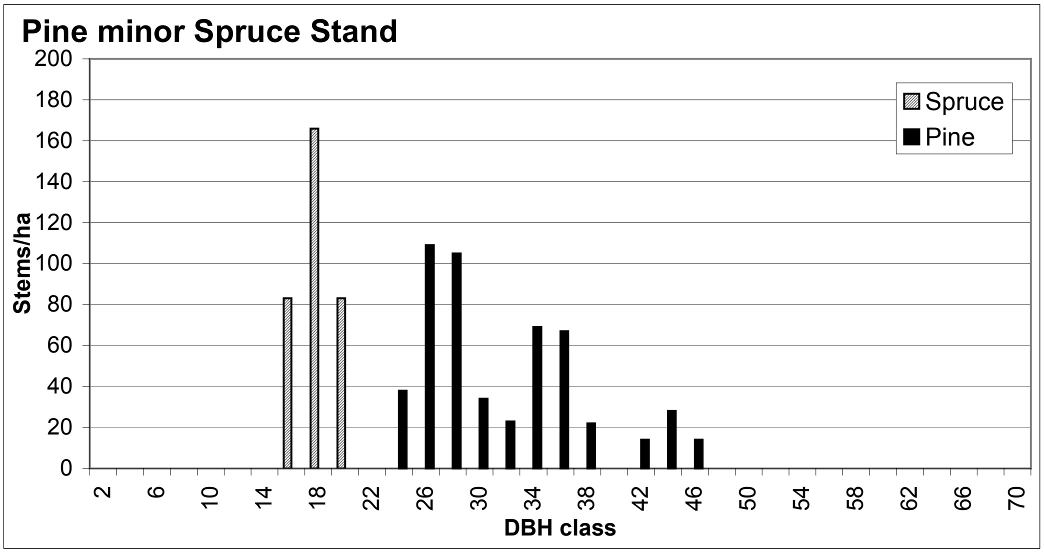
a) *Pine Minor Spruce* – A lodgepole pine stand on a mesic site consisting of 83% pine and 17% spruce (by basal area). This stand represents a mature lodgepole pine stand with a well-developed cohort of immature spruce.

b) *Mixed Pine – Spruce* – A stand consisting of 57% pine and 43% spruce (by basal area). This stand type contains both mature pine and spruce with a well-developed layer of understory spruce.

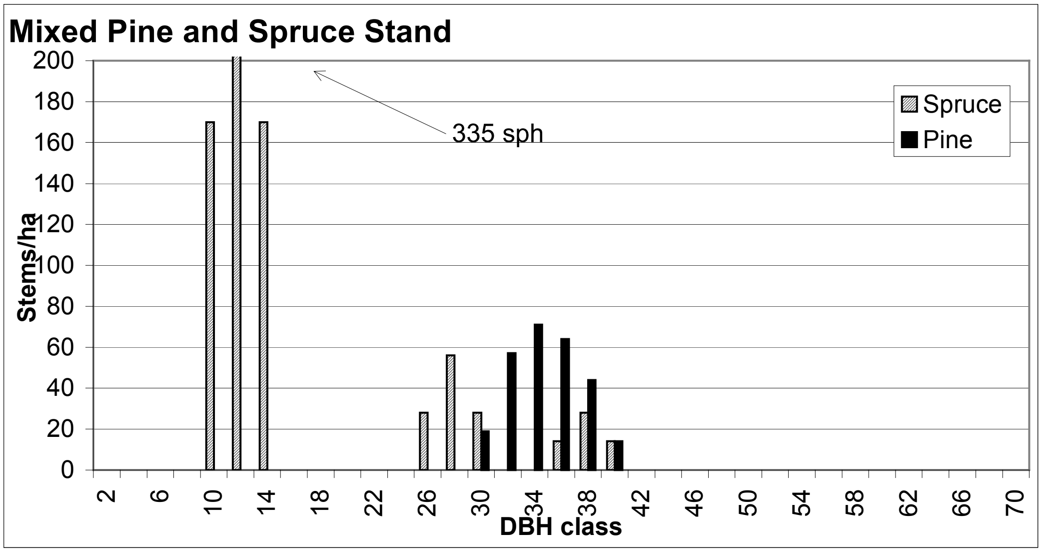
c) *Spruce Minor Pine* – This stand consists primarily of spruce (83% of the basal area) with a minor component of pine in the overstory. This diverse stand type contains mature spruce and pine, immature spruce and scattered large veteran spruce.

d) *Pine Dominant* – A pure lodgepole pine type from a SBSdk 03 site was chosen to represent lodgepole pine out-wash sites.

Across the spectrum of stand types described by the ecology program, differences between SBSmc2 overstories and the SBSdk overstories are relatively minor. Nearly 60% of the mesic and submesic SBSmc2 stand types containing a lodgepole pine component did not contain a subalpine fir component. Therefore we use the SBSdk canopy types to test growth of under-planted subalpine fir as well.

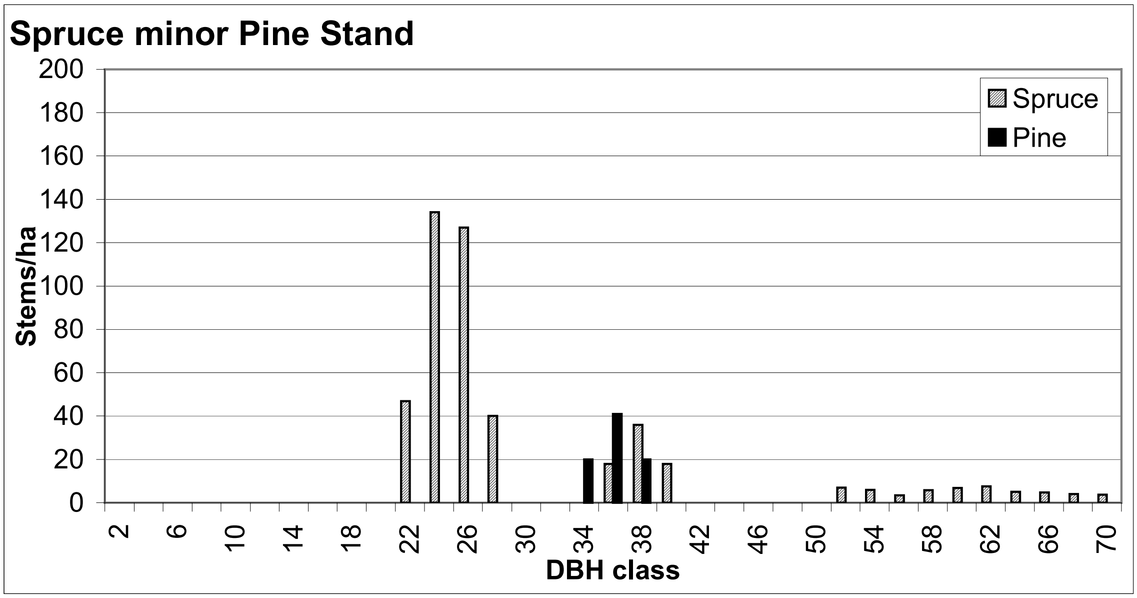


	Density	Basal Area
Spruce	332	7.6
Pine	523	39.8
Total	855	47.4

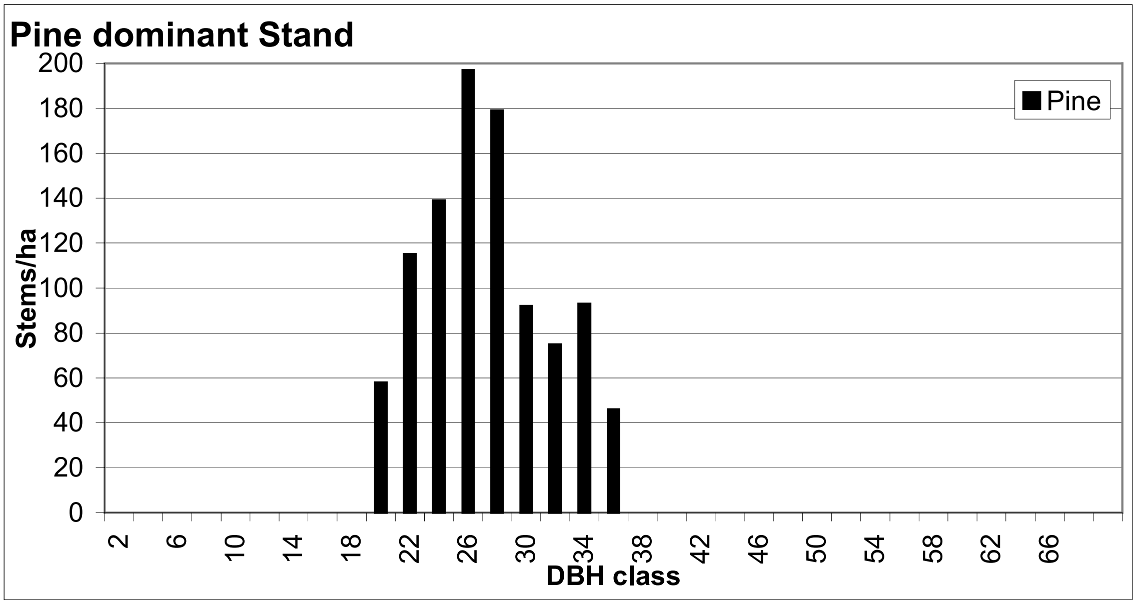


	Density	Basal Area
Spruce	848	19.1
Pine	269	24.2
Total	1117	43.3

Figure 1a. Overstory composition of the *Pine Minor Spruce* and *Mixed Pine – Spruce* stand types. The tables below each figure present the density (stems/ha) and basal area (m2/ha) of each stand.



	Density	Basal Area
Spruce	474	38.799
Pine	81	7.8
Total	555	46.6



	Density	Basal Area
Pine	994	55.5

Figure 1b. Overstory composition of the *Spruce Minor Pine* and *Pine Dominant* stand types. The tables below each figure present the density (stems/ha) and basal area (m2/ha) of each stand.

Mountain Pine Beetle Damage:

In order to mimic severe mountain pine beetle damage, 100% of the larger pine trees in each stand type were killed and 90% of the smaller pine trees were killed. This pattern of damage was intended to mimic the cumulative result of several years of successive mountain pine beetle attack rather than one lone year of attack.

Model Simulations

We used SORTIE-ND version 6.03 to test the results of objective 1 and to examine objectives 2 through 7. We used a 1-yr timestep and simulations varied from 20 to 100 years depending upon the objective.

To address objective 2, testing the snag submodel, we designed a set of three runs that would allow us to compare the growth of immature pine under a mature *Pine Dominant* canopy, under a MPB attacked *Pine Dominant* canopy, and in full open conditions. All runs assessed the growth of 1500 stems/ha of 6-8 cm DBH lodgepole pine. The first run consisted of the immature pine grown under the live *Pine Dominant* canopy. The second began with the same stand composition but incorporated a severe mountain pine beetle attack with 95% mortality of the overstory. The third run modeled the growth of the 1500 stems/ha of immature pine without the influence of an overstory canopy. Stand growth was tracked for 50 years in each simulation.

To examine the survival of natural regeneration of lodgepole pine under a MPB attacked canopy we modeled the following situation. We established 10 000 stems/ha of lodgepole pine seedlings 1 year after a severe mountain pine beetle attack in the *Pine Dominant* stand type. We also modeled the survival of 10 000 stems/ha of lodgepole pine seedlings established 10 years post-MPB attack. For both scenarios we modeled stand development for 20 years.

To compare the predictions of SORTIE-ND to TASS we modeled complete salvage and plant prescriptions. We simulated the growth of individual stands of lodgepole pine, interior spruce, and subalpine fir planted at densities of 1600 stems/ha. We used Tipsy version 3.2 for the interpolation of yield tables from TASS to model runs for mesic sites in the Lakes TSA.

To model the development of major stand types after MPB attack and without management intervention we modeled the four major stand types for 100 years.

To model the consequences of under-planting, we developed a set of simulations to assess the effect of under-planting stands with interior spruce and subalpine fir. We simulated planting in each stand type one year post-MPB attack. Planting immediately after attack was chosen to mimic conventional planting strategies and minimise the risks to tree planters associated with planting under snags.

To model the implications of delaying planting under MPB damaged stands, we simulated under-planting interior spruce under the *Pine Dominant* stand with a 95% level of mortality due to MPB. We delayed under-planting by 2, 4, 6, 8, and 10 years post-MPB attack.

Results

Snag Submodel

We have estimated light transmission coefficients and residency time by snag decay class for the four major tree species in the SBSdk and SBSmc2 subzones (Table 1; Poulin et al., *in prep*). We estimate class 1, 2 and 3 lodgepole pine snags will transmit 37.6, 61.4 and 87.8% of full sunlight, respectively (Table 1).

		Light Transmission Coefficients (0-1)			
Snag Class	Age of Snags in Each Class	Subalpine Fir	Interior Spruce	Lodgepole Pine	Trembling Aspen
1	0-7	0.423	0.446	0.376	0.695
2	8-17	0.554	0.502	0.614	0.755
3	17+	0.713	0.673	0.878	0.833

Table 1. Light transmission coefficients for snags of major sub-boreal spruce tree species.

We were unable to locate any data for snag fall down rates of MPB killed lodgepole pine trees in the sub-boreal spruce zone. We developed a Weibull equation to model the functional relationship for snag fall rate from data provided in Keen (1955), model (1):

$$S = e^{-(a*T)^{b}} \qquad (1)$$

where *S*= probability of snag survival, *T*=time since death, *a* is a scale and *b* a shape parameter of the Weibull function. We thank Peter Ott, Statistician, BC Forest Service, Victoria for assistance. We used the 'cumulative density function' for year x and subtract from it the 'cumulative density function' from the previous year to give us a probability of fall for individual snags:

Yearly probability of fall = (1-EXP(-((a*year x)^b))) - (1-EXP(-((a*year x-1)^b)))

Note that for the end of year 1 you just calculate the Weibull function once, no subtraction, i.e.,

Prob. of fall after 1 year = (1-EXP(-((a*1)^b))).

Based on available data, local knowledge (observations of Patience Rakochy during extensive surveys of MPB damaged stands in 2004), and our own understanding of snag mortality rates we determined the following snag fall down rate parameters for the SBS: a = 0.05 and b = 2.5.

Limitations to analysis

No studies are available that track the changes in lodgepole pine snags overtime with respect to either increasing light transmission or snag fall down rates. We have used three snag classes to approximate increasing light transmission of snags whereas we realise snags are continually changing. We have based our predictions of the time frame upon which snags move from one class to the next upon our observations and the observations of Patience Rakochy among others.

Predicting understory light environments in MPB damaged stands

Incorporating the snag submodel into SORTIE-ND results in effectively modeling changes in light environments as snags deteriorate over time. Figure 2 illustrates the changes in light transmission through an overstory with varying proportions of snags. Figure 3 presents the distribution of light levels at three specific periods of time after mountain pine beetle attack. At 1 and 5 years post-MPB attack there is little difference in light environments as few snags have fallen and the deterioration of the snags is limited. At 10 years post-MPB attack, a more significant increase in light levels is evident due to both a shift in snag class and fall down of an increasing numbers of snags.

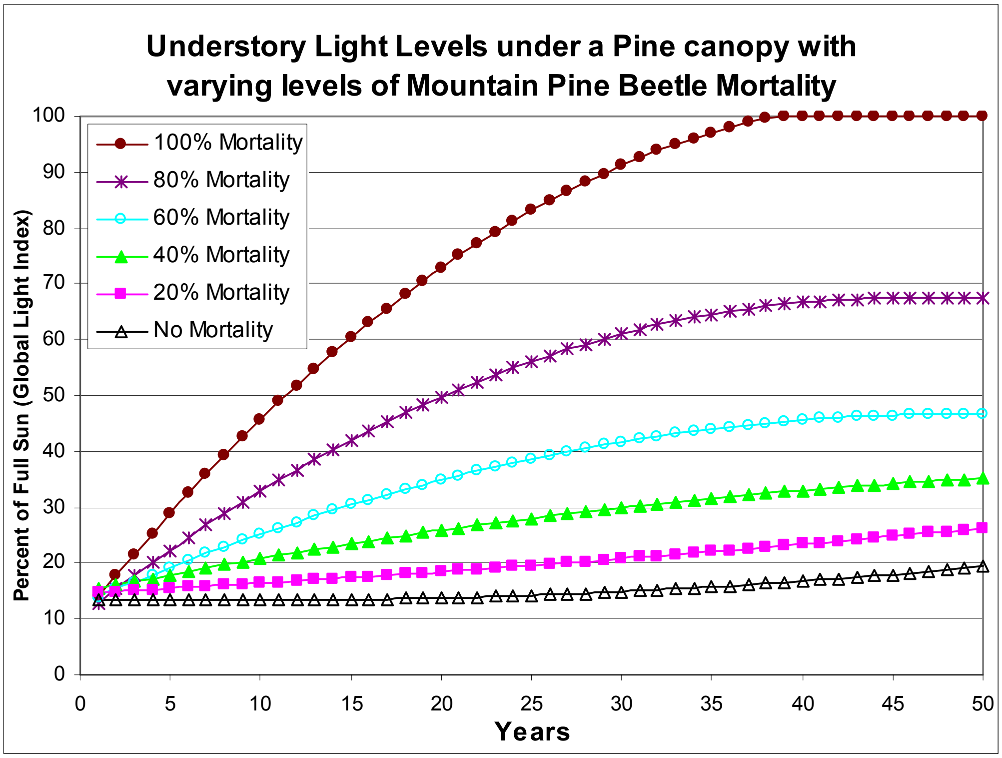


Figure 2. Change over time of understory light levels (as percent of full sun) under mature, 100% lodgepole pine canopies with varying levels of MPB attack.

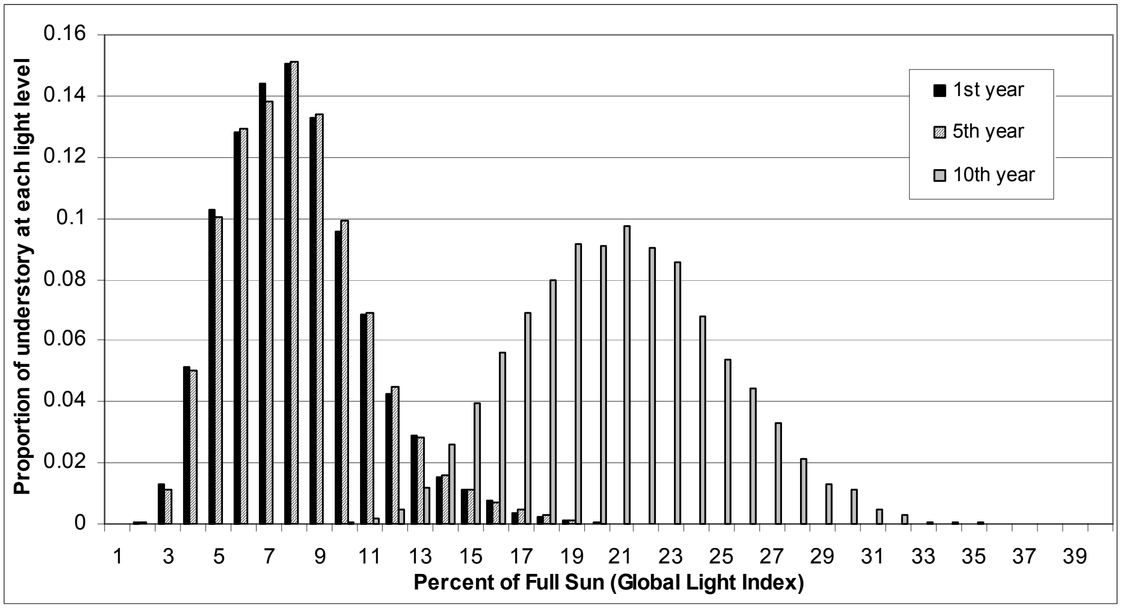


Figure 3. Light levels the first, fifth, and tenth year after mountain pine beetle attack.

To test the impact of snags on mortality and growth of a lodgepole pine understory, we conducted three simulations that compared the growth of immature pine under an unaffected mature pine canopy, under a MPB attacked canopy and in full open conditions (Figure 4). These results illustrate that under a MPB attacked canopy, lodgepole pine trees do not grow as well as in full open clearcut conditions but do not grow as poorly as under a live pine canopy. In open conditions lodgepole pine mortality is low and pine basal area increases by 43 m^2/ha. Under a live pine canopy, the understory pine grow poorly, with limited increase in yield (0.7 m^2/ha) and high mortality. The growth of pine under snags reflects the influence and expected changes in snag structure. That is, initially, post MPB attack, there is relatively little difference in light transmission between live pine and MPB attacked pine. Even over the first few years as dead needles fall light transmission is relatively similar due to the presence of fine branches and the low rate of snag fall. Therefore, in the first five to eight years understory pine growth and

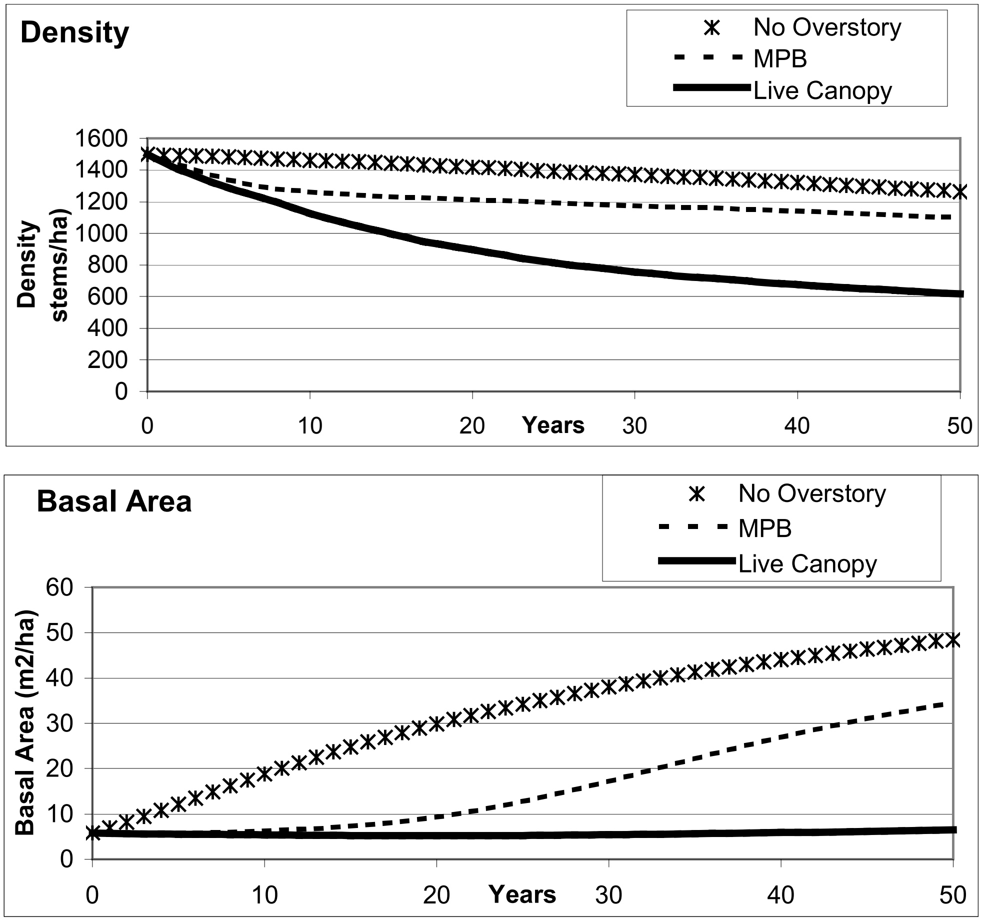


Figure 4. Predicted change in density and basal area of immature pine (1500 stems/ha, DBH 6-8 cm) under three canopy conditions: traditional clearcut with no overstory, a MPB attacked stand with 95% mortality, and under a live mature pine canopy. Under a MPB attacked stand, growth and survival of the immature pine significantly improves over time reflecting the deterioration of snags and progressive increase in understory light levels.

mortality is similar under snags as under a live canopy. After these first few critical years, the growth rate of pine under the snags begins to accelerate until it approaches the growth rate anticipated from pine in full open conditions. This change in growth rate reflects the shift in light conditions as snag deteriorate and fall with increasingly open conditions being created. Overall, under the canopy of snags, lodgepole pine yield increases by 29 m^2/ha.

Natural Regeneration of Lodgepole Pine under MPB damaged stands

As is shown by the test of immature pine under differing canopy environments, changes to the light environment in which a tree grows has significant implications for growth and mortality. Kobe and Coates (1997) have quantified the relationship between the probability of mortality and recent growth rates for juvenile trees and Wright et al. (1998) have studied the effect of light levels upon seedling and sapling growth. Using these functional relationships, we linked light level to probability of mortality for lodgepole pine, interior spruce and subalpine fir (Figure 5). At the light levels predicted by SORTIE-ND for 1, 5, and 10 years after a severe MPB attack with 95% mortality, lodgepole pine have an exceptionally high probability of mortality (Figure 5).

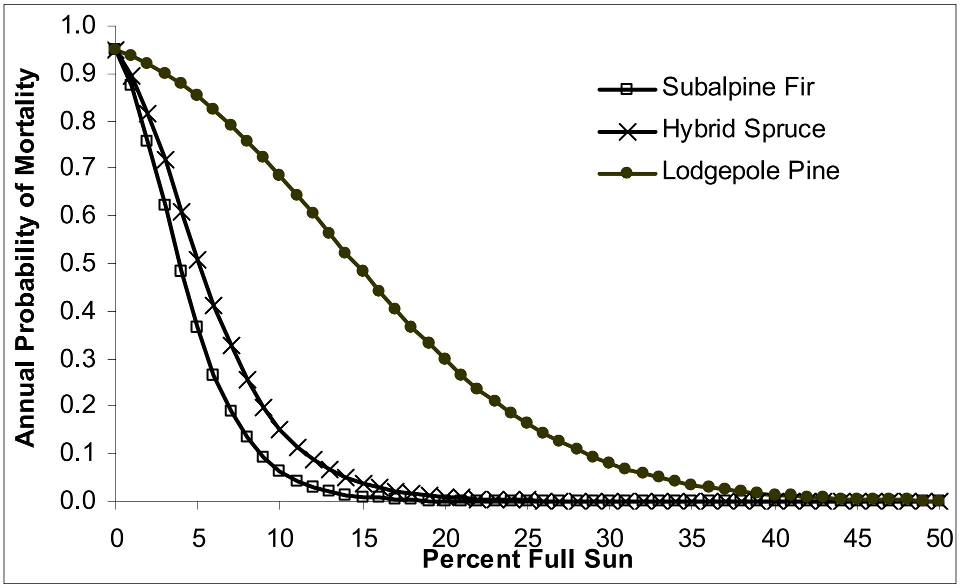


Figure 5. Juvenile mortality as a function of percent full sun (measured using global light index). SORTIE-ND predicts average light levels in the understory of severely MPB damaged stands to begin at 8% of full sun and increase to 21% full sun in the first ten years following MPB attack. This translates to very high annual probabilities of mortality for lodgepole pine (from 76% to 27% respectively). Immediately post-MPB attack, subalpine fir and hybrid spruce have relatively high annual probabilities of mortality (13% and 25% respectively). However within 10 years, light levels increase sufficiently such that the probability of mortality of both species drops and most seedlings are likely to survive.

The results of our tests of lodgepole pine regeneration survival and growth are presented in Figure 6. All 10,000 stems/ha of lodgepole pine regeneration we established 1 year post-MPB attack died within thirteen years. We also tested establishing 10,000 stems/ha 10 years post-MPB attack; about 300 stems/ha of these trees survived another ten years later (Figure 6). These results confirm that the light environment under lodgepole pine snags following MPB attack is extremely limiting for survival of lodgepole pine seedlings. In addition, the light environment continues to remain highly limiting 10 to 20 years post-MPB attack.

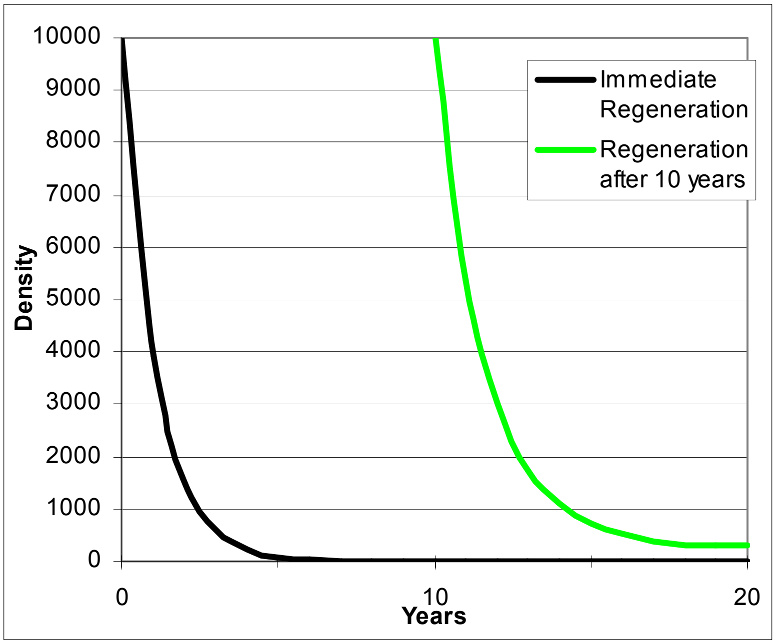


Figure 6. Survival of lodgepole pine regeneration under a MPB attacked pure pine stand. 10 000 stems/ha of natural regeneration were modeled 1 year and 10 years after MPB attack. Of the 10 000 stems/ha of natural regeneration originating 1 year post-MPB attack only 2 stems/ha were alive after 10 years (0.02% survival). Of the natural regeneration that originated 10 years post-MPB attack, 300 stems/ha remained after 10 years (3% survival).

Limitations to analysis

Survival of lodgepole pine is highly sensitive the light levels. We use snag classes rather than a continuous function which might lead to an under prediction of available light near the end of each snag class residency time. If we are predicting lower light under snags than is actually occurring then it is possible that our predictions of seedling mortality will be too high. Light levels in the first 15 years after MPB attack appear to be critically important.

The severe level of mountain pine beetle attack used in our simulations (95% mortality in one year) may not be typical. Rather mortality occurs differentially over several years. Simplification of severe attack into 95% mortality in one year results in an under estimation of the length of time in which natural regeneration grows under dark canopy environments.

Despite these limitations, our results are consistent with observations from foresters across the MPB affected area that there is a severe lack of natural pine regeneration under mountain pine beetle attacked stands.

Validation using TASS/TIPSY

TASS has been extensively developed to model single species, even-aged stands and is widely accepted across British Columbia. Figures 7a, 7b, and 7c present the results of comparisons of SORTIE-ND to TASS for density, basal area, and average DBH for three tree species established at 1,600 stems/ha after total salvage of MPB damaged stands.

Juvenile growth rates of three species in SORTIE-ND (less than 5 cm DBH, based on available light) are a little faster than predicted by TASS. SORTIE-ND adult growth rates (based on neighbourhood crowding and shading) for immature adult trees (roughly 5-20 cm DBH) reflect the highly competitive environment at this time and result in slightly slower growth rates than TASS. As a result growth rates of individual trees and stand-scale basal area development in SORTIE-ND and TASS converge by about 40-50 years. Growth rates of larger adult individual lodgepole pine and interior spruce trees are very similar in SORTIE-ND and TASS (Figures 7a and b, average DBH panels). SORTIE-NDs prediction of larger adult tree subalpine fir growth is a little lower than TASS (Figures 7c, average DBH panel). Overall, SORTIE-ND and TASS growth rates are quite similar. SORTIE-ND has been specifically designed to model complex structured stands, not even-age single-species plantations. It is encouraging that SORTIE-ND produces similar results to TASS in single-species plantations.

Development of major stand types after mountain pine beetle attack

We modeled the effect of severe mountain pine beetle damage on the four major stand types described previously (Figure 1a and b). Despite poor natural regeneration conditions, the three stands containing a spruce component (all but *Pine Dominant*) recovered well from the attack (Table 2). At 50 years after MPB attack, stand basal area of two of the three stands with residual understory and overstory spruce had exceeded that of the pre-attack stands (*Mixed Pine-Spruce* and *Spruce Minor Pine*, Table 2). By about 80-yrs the *Pine Minor Spruce* type had recovered to pre-attack basal areas (Figure 8a).

The *Mixed Pine-Spruce* type continued to grow well over time reaching a stand basal area of 68 m^2/ha and merchantable profiles at 100-yrs (Table 2 and Figure 8b). The pure *Pine Dominant* type with little spruce residual component was unable to recover after MPB attack (Table 2).

Stand Type	**Basal Area**						
	Pre-MPB	**50 years post-MPB**			**100 years post-MPB**		
		Spruce	Pine	Total	Spruce	Pine	Total
Pine minor Spruce	47.4	33.4	1.9	35.2	45.9	1.1	47.0
Mixed Pine / Spruce	43.3	51.9	0.9	52.7	67.1	0.5	67.6
Spruce minor Pine	46.6	53.7	0.2	53.9	53.9	0.1	54.0
Pine dominant	55.5	0.0	3.9	3.9	0.0	1.3	1.3

Table 2. Basal area (m^2/ha) of the four major stands pre-attack, 50 and 100-yrs post-attack with no management intervention. Detailed pre-attack stand conditions are shown in Figures 1a and 1b. Figure 8a tracks basal changes over time and Figure 8b shows stand diameter distributions at 100 years post MPB attack for stands with an initial spruce component.

These results highlight the importance of targeting salvage operations toward stands with a low spruce component (e.g., like the *Pine Dominant* type) as these stands will not likely regenerate and recover without management intervention. If stands with a substantial understory spruce component are scheduled to be salvaged our results highlight the importance of protecting the residual spruce so these stands will become merchantable as early as possible. Note that the *Spruce Minor Pine* type reach their maximum yield at approximately 50 years post attack. This is due in part to the initial component of large spruce in the mid-30 cm DBH classes (Figure 1b).

The stand development pattern of the *Mixed Pine-Spruce* type (that performed the best over 100-yrs) can be explained by the large number of smaller diameters spruce present in the stand pre-MPB attack (Figure 1a). **Stands with structure similar to the *Spruce Minor Pine* and *Mixed Pine-Spruce* types can play a critical role in reducing the expected mid-term (30-50 years) timber supply shortage when unsalvaged or when the spruce are protected from damage during salvage**.

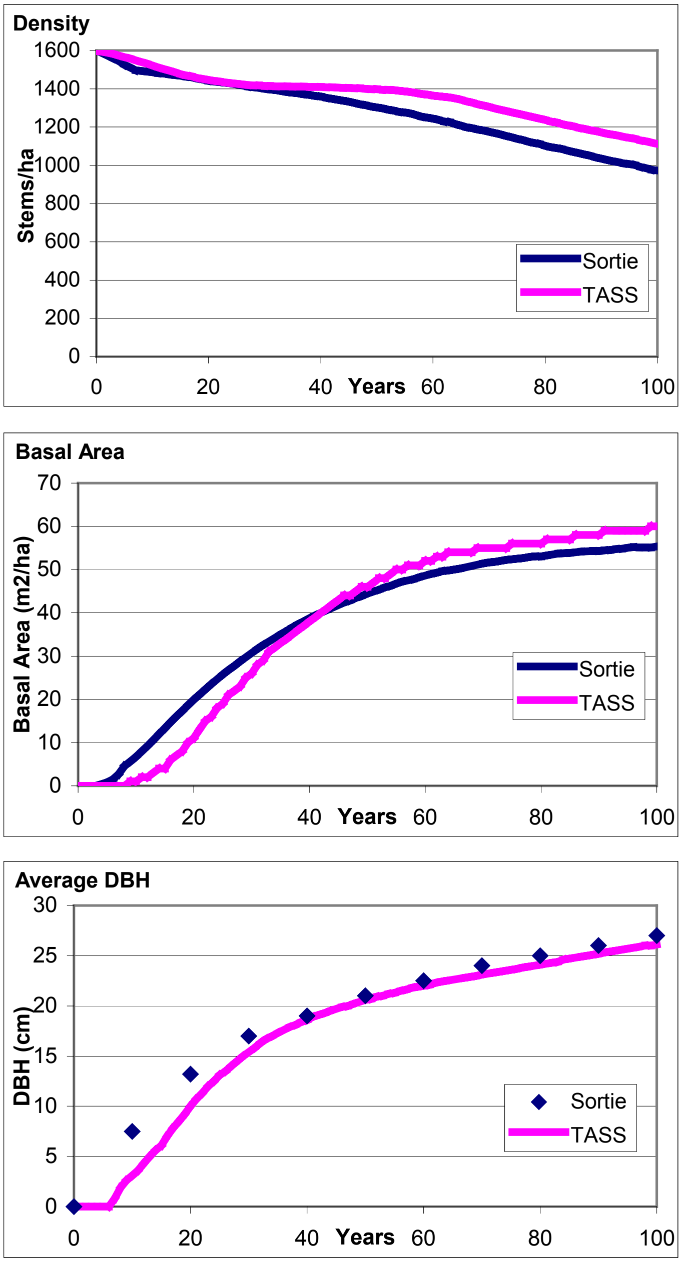


Figure 7a. Lodgepole Pine comparison of SORTIE-ND and TASS predictions of density, basal area, and average DBH for an even-aged lodgepole pine plantation with initial density of 1600 stems/ha. Over 100 years SORTIE-ND and TASS predictions of growth are similar.

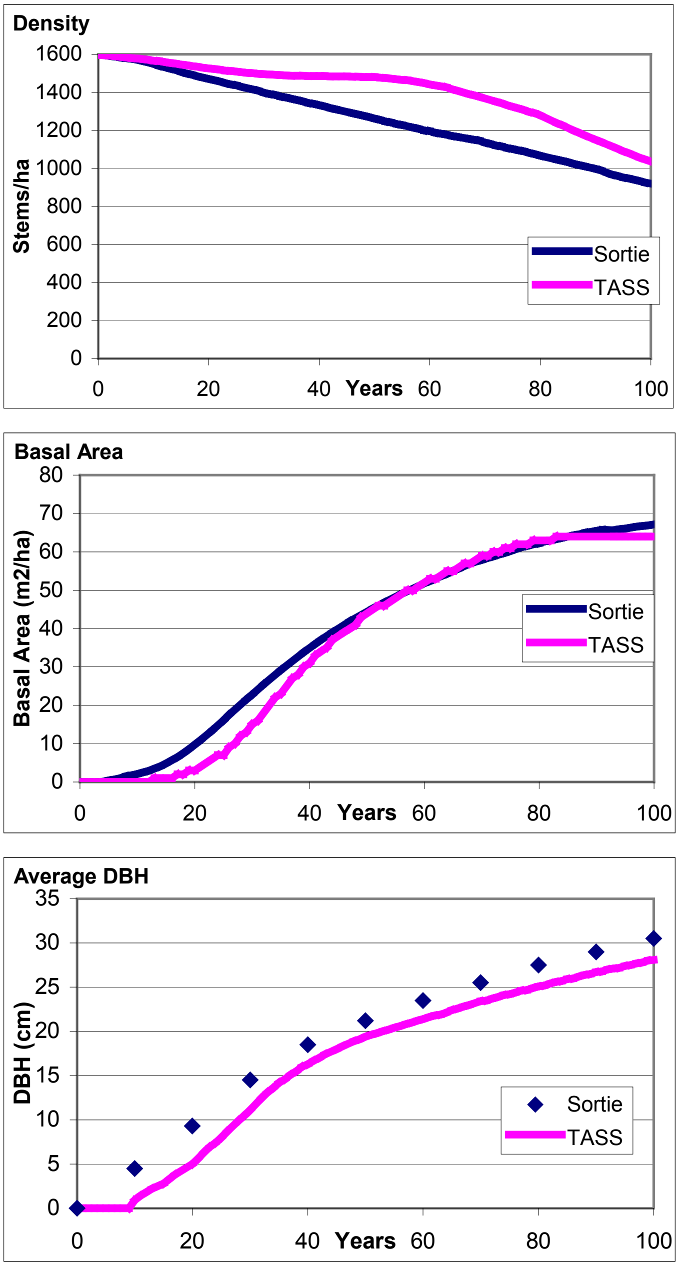


Figure 7b. Interior Spruce comparison of SORTIE-ND and TASS predictions of density, basal area, and average DBH for an even-aged interior spruce plantation with initial density of 1600 stems/ha. Over 100 years SORTIE-ND and TASS predictions of growth are similar.

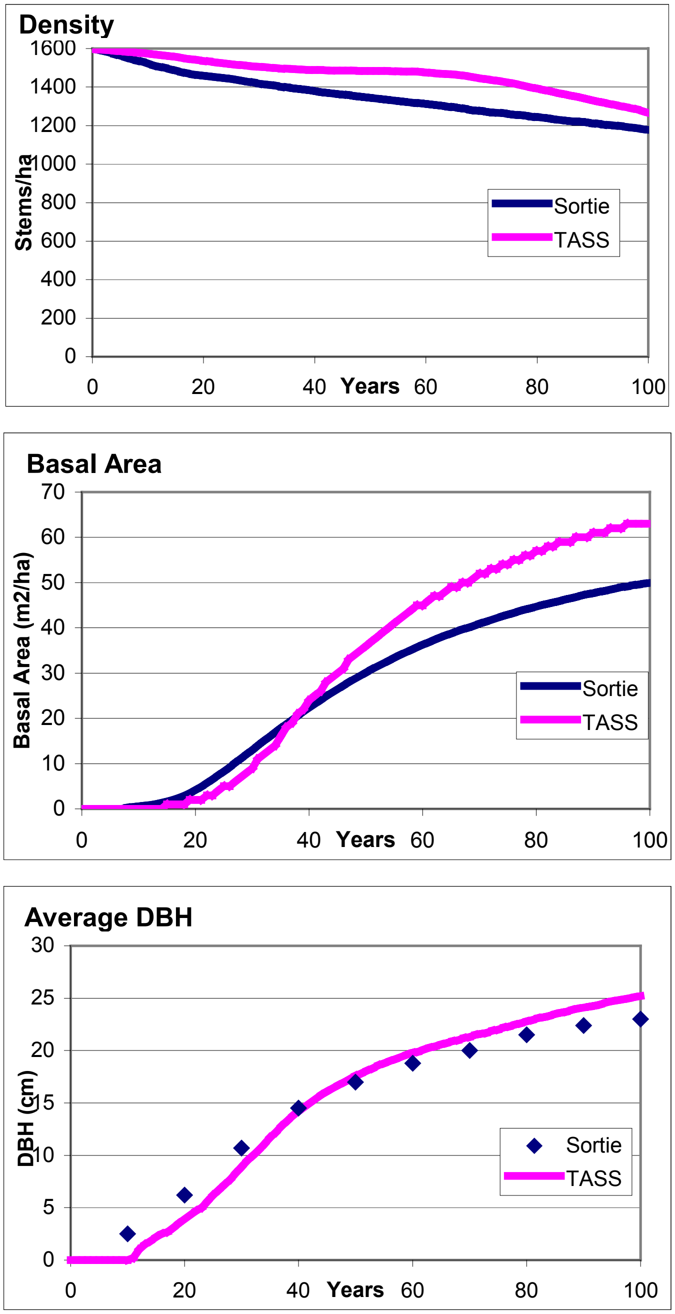


Figure 7c. Subalpine Fir comparison of SORTIE-ND and TASS predictions of density, basal area, and average DBH for an even-aged subalpine fir plantation with initial density of 1600 stems/ha. SORTIE-ND the growth rates of subalpine fir are lower over 100 years.

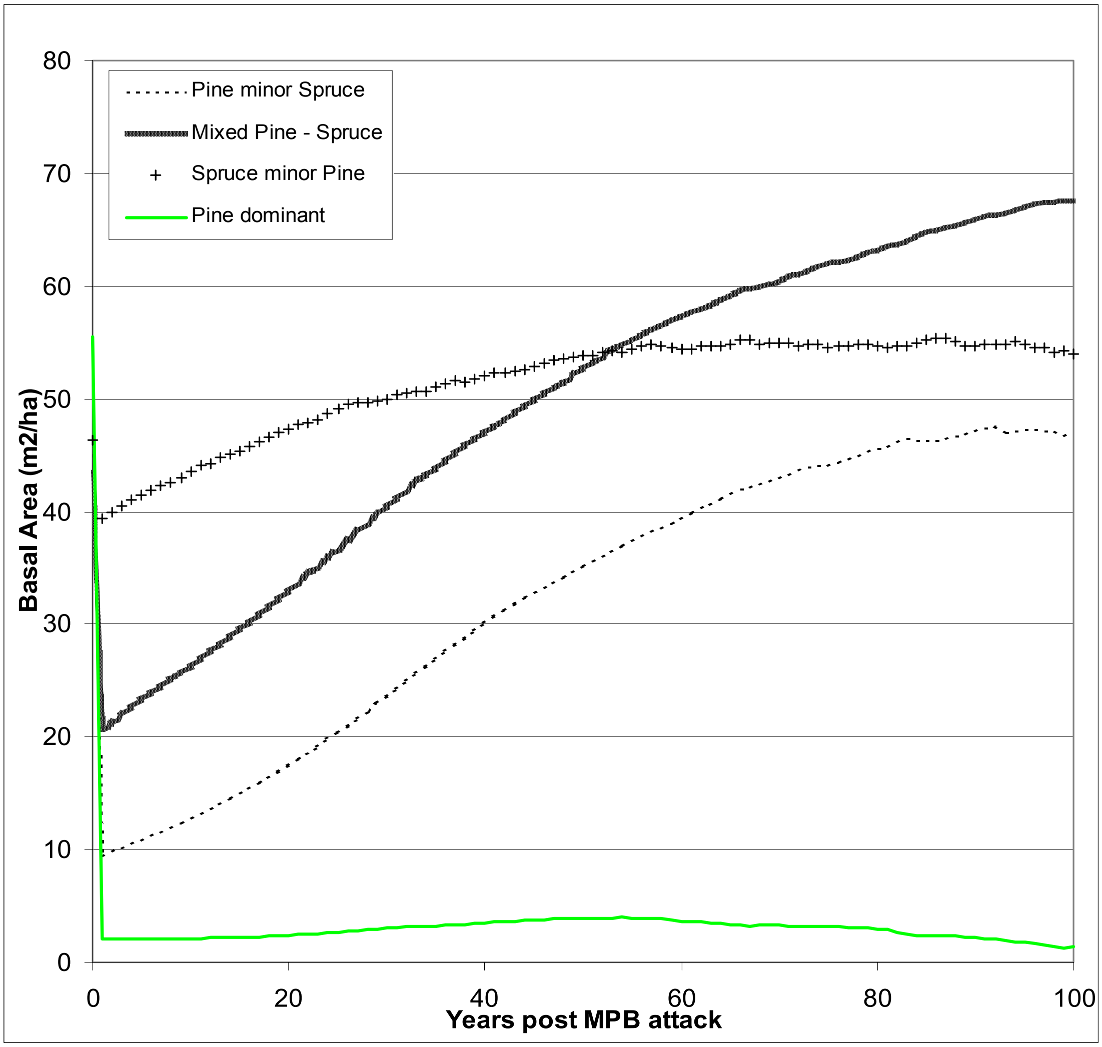


Figure 8a. Basal area growth of four stand types in the 100 years following severe mountain pine beetle attack. Stands with a spruce component recover reasonably well following MPB attack. The *Pine Dominant* stand lacking a spruce component does not recover within 100 years.

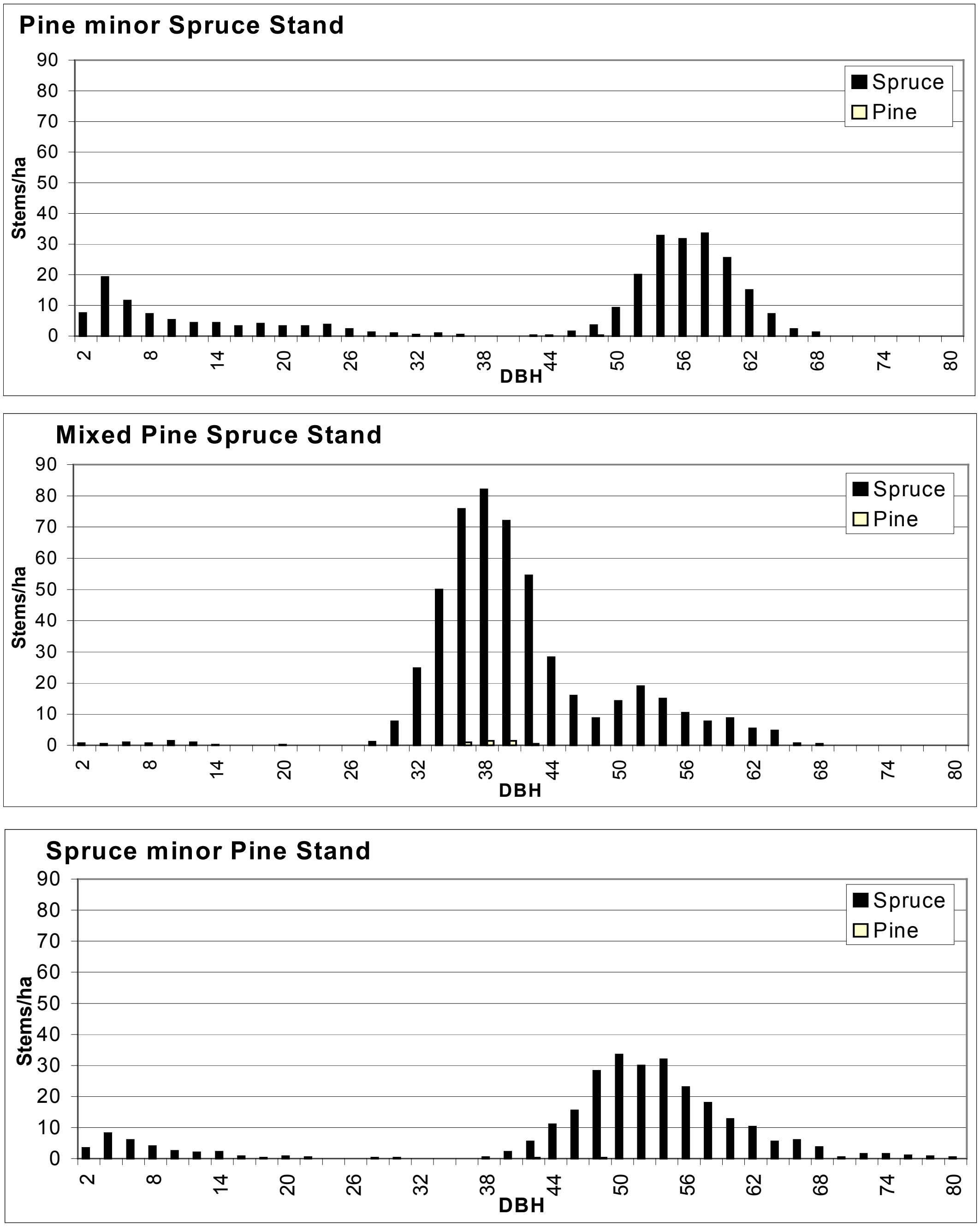


Figure 8b. Stand composition of the three stand types with spruce components 100 years after MPB attack. These stands have recovered well and the spruce have grown to a merchantable size. Note that the *Pine Minor Spruce* stand has higher levels of natural regeneration in the understory than the other two stands. This is likely due to the lower density of spruce initially present in the stand. This lower density of live trees post-MPB resulted in higher light levels and therefore greater survival and growth of spruce natural regeneration.

Under-planting Hybrid Spruce and Subalpine Fir

One possible prescription to mitigate the impact of the mountain pine beetle is to under-plant affected stands. Figure 9 shows the impact to basal area of under-planting the four stand types with interior spruce and subalpine fir. Table 3 summarizes the survival of the under-planted seedlings at 20 years, and Table 4, the differences in yield at 100 years related to under-planting.

Stand Type	**Spruce**	**Subalpine Fir**
Pine minor Spruce	~350sph	1012 sph
Mixed Pine - Spruce	~75sph	911sph
Spruce minor Pine	~75sph	882sph
Pine dominant	~323sph	988sph

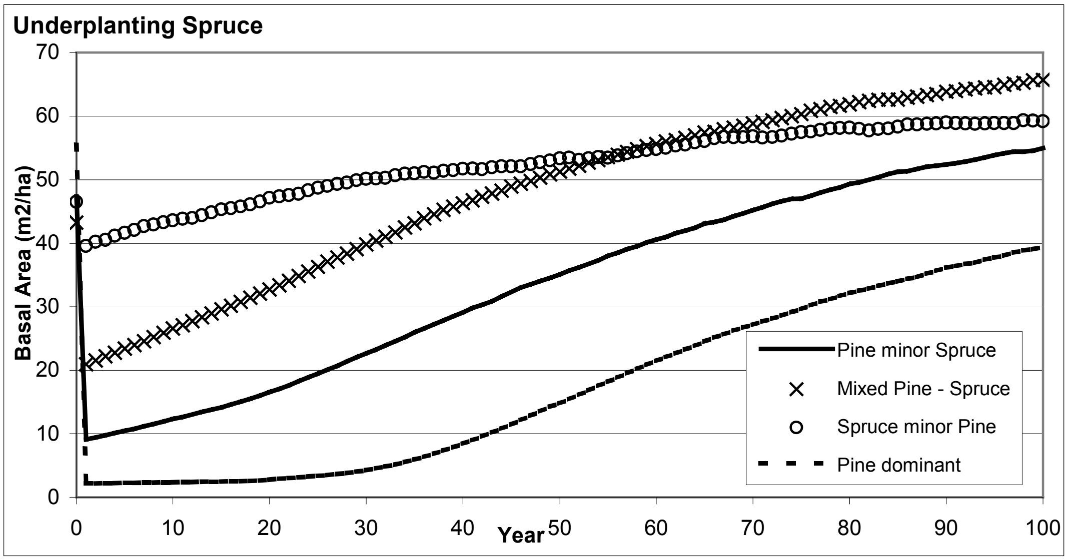
Table 3. Density of surviving spruce and subalpine fir 20-yrs after planting (at 1,600 stems/ha) the understory immediately after severe MPB attack in the four major stand types.

Stand Type	**No Planting**	**Species Under-Planted**			
		Spruce		Subalpine Fir	
		Basal Area	% change due to planting	Basal Area	% change due to planting
Pine minor Spruce	47.0	55.0	17%	56.7	21%
Mixed Pine - Spruce	67.6	65.7	-3%	66.6	-1%
Spruce minor Pine	54.0	59.2	10%	58.2	8%
Pine dominant	1.3	39.4	2875%	36.6	2668%

Table 4. Stand basal area (m^2/ha) at 100-yrs post MPB attack after under-planting either spruce or subalpine fir and percent change in basal area compared to stands with no under-planting.

Planting either subalpine fir or spruce substantially increased the yield of *Pine Dominant* stands after 100 years compared to no management intervention. Although survival significantly differs between spruce and subalpine fir, yield values are relatively similar. This is due in part to the trade-off between lower density and increased growing space. In addition, this difference may also be partly attributed to the lower growth rates of subalpine fir compared to interior spruce presently incorporated into SORTIE-ND. These results also reflect the difference in shade tolerance between spruce and subalpine fir shown in Figure 5. Under the same light conditions, subalpine fir has the highest survival rate. Spruce seedlings survive under the lodgepole pine snags but mortality is higher and 67% more seedlings die.

The benefit of under-planting stand types with a greater residual spruce component depends on the distribution of canopy and understory trees at the time of planting. The *Pine Minor Spruce* stand type with a low density of immature spruce realized an improved yield due to under-planting both species. This increase is likely due to the low initial stocking of residual spruce. Yield also increased on the *Spruce Minor Pine* type when under-planted with spruce or fir. This increase can be attributed to the under-planted trees contributing to the stand basal area as the older, larger spruce fall out of the stand.



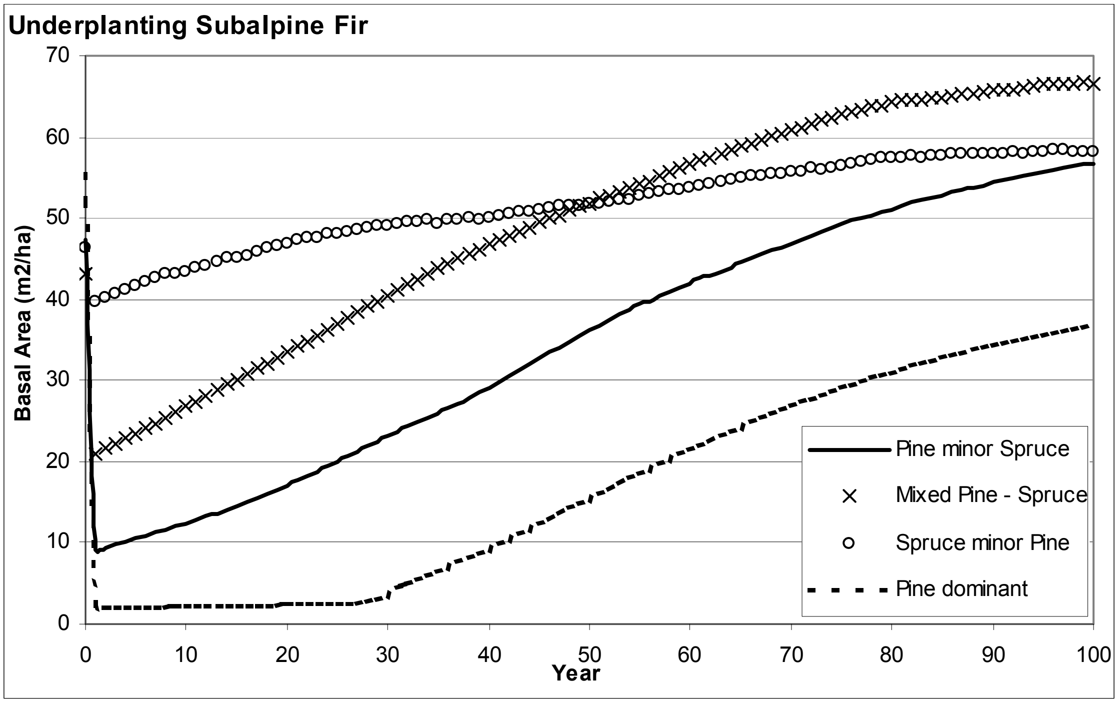


Figure 9. Yield, in terms of basal area, resulting from under-planting the four major stand types with spruce or subalpine fir. Under-planting improves the yield of three of the four major stand types; yield of the *Mixed Pine – Spruce* stand is not significantly changed. Although all of the stand types with a spruce component recovered reasonably well without under-planting, under-planting is required to significantly improve the yield of the *Pine Dominant* stand type. Differences in total yield between under-planting spruce or subalpine fir are not large. However, due to higher initial mortality of the interior spruce, the individual tree size of the under-planted spruce after 100 years is much higher.

Temporal Management of Mountain Pine Beetle Damaged Stands

As snags deteriorate following mountain pine beetle attack, the light environment for natural regeneration or planted seedlings is expected to steadily improve (refer to Figures 2 and 3). However when considering under-planting, the improved light environment must be balanced against the increased safety hazards posed by snags and the increased levels of brush and other competing natural regeneration that will also take advantage of steadily improving light environments. We simulated the effect of delaying planting of spruce under the *Pine Dominant* stand for 2, 4, 6, 8 and 10 years after mountain pine beetle attack. Table 5 shows that, as the light environment under the deteriorating snags improves, survival and yield of spruce seedlings significantly increases. This effect highlights the importance of considering the effect of time and changing overstory conditions when developing prescriptions to mitigate the effect of the mountain pine beetle.

Planting Delay (years)	Planting Survival at 20 years (stems/ha)	Basal Area at 100 Years: (m2/ha)
2	237	47.0
4	452	50.5
6	758	57.2
8	1134	60.4
10	1297	60.8

Table 5. Effect of changing planting delay on planted spruce survival at 20 years and yield after 100 years (pure pine stand).

Conclusions and Management Implications

There is significant interest among foresters in northern B.C. as to the impact of the mountain pine beetle on stands that are not harvested and potential opportunities to mitigate the impact. SORTIE-ND, with the inclusion of the new snag submodel, is ideally suited to exploring these questions. We modeled a variety of silvicultural strategies aimed at exploring the implications of MPB attack on understory light environments, natural regeneration survival and growth, and other silviculture treatments.

Developing the snag submodel for SORTIE-ND required the definition of snag classes, assessing light transmission values for each snag class, and developing an equation that models snag fall down rates. Faced with a lack of detailed snag analysis post-MPB this model simplifies the continually changing nature of snag dynamics. However, the results predicted by SORTIE-ND, when incorporating the snag submodel, mirror field observations of professionals throughout the mountain pine beetle affected area. In addition, they confirm past studies that have examined the relationship of light level to seedling mortality rates. Modeling the understory light environment under MPB attacked stands reveals low light levels for an extended period of time. This results in very high levels of lodgepole pine natural regeneration mortality.

We were unable to predict the extent of natural regeneration in the four stand types due to lack of data to parameterize the recruitment submodel. A 2005/2007 FSP funded study will address this short-coming.

The comparison of SORTIE-ND to TASS predictions revealed extraordinarily similar results for lodgepole pine and interior spruce growth. Given the different approaches used by the two models this was a very encouraging result. SORTIE-ND predicted somewhat lower subalpine fir growth rates for adult trees than TASS. This suggests the yield results from SORTIE-ND should be suitable for inclusion in Timber Supply Analysis calculations for complex structured stands after MPB damage.

Mountain pine beetle attacked stands with a well-developed immature spruce component recover quickly after MPB attack without salvage. Within 50 years these stands have reached merchantable size and provide a reasonable yield (the *Mixed Pine-Spruce* and *Spruce Minor Pine* types). If salvage of the dying and dead lodgepole pine in these stands is desired, salvage should target the pine while protecting the spruce. These stand types can help mitigate mid-term (30-50 years) timber supply shortages if protected during partial salvage or left unsalvaged. However, the *Pine Dominant* type stands will require management intervention in the form of under-planting or salvage and planting. Delaying under-planting for 5 to 15 years after initial MPB attack may result in much higher survival and growth of interior spruce or subalpine fir.

Literature Cited

Banner, A., W. MacKenzie, S. Haeussler, S. Thomson, J. Pojar and R. Trowbridge. 1993. A field guide to site identification and interpretation for the Prince Rupert Forest Region. B.C. Ministry of Forests, Victoria, B.C. Land Manage. Handb. 26.

Canham, C.D., LePage, P. and Coates, K.D. 2004. A neighbourhood analysis of canopy tree competition: effects of shading versus crowding. Can. J. For. Res., 34:778-787.

Canham, C.D., Coates, K.D., Bartemucci, P. and Quaglia, S. 1999. Measurement and modeling of spatially-explicit variation in light transmission through interior cedar-hemlock forests of British Columbia, Can. J. For. Res. 29: 1775-1783.

Coates, K.D., Canham, C.D., Beaudet, M. Sachs, D.L. and Messier, C. 2003. Use of a spatially explicit individual-tree model (SORTIE/BC) to explore the implications of patchiness in structurally complex forests. For. Ecol. Manage. Vol 186, Issue 1-3:297-310

Keen, F.P. 1955. The rate of natural falling of beetle-killed ponderosa pine snags. J. For. 53:720-723.

Kobe, R.K., and Coates, K.D. 1997. Models of sapling mortality as a function of growth to characterize interspecific variation in shad tolerance of eight tree species of northwestern British Columbia. Can. J. For. Res. **27**: 227-236.

LePage, P.T., Canham, C.D., Coates, K.D., Bartemucci, P. 2000. Seed source versus substrate limitation of seedling recruitment in interior cedar-hemlock forests of British Columbia. Can. J. For. Res. 30:415-427.

Ministry of Forests. 2001. Mensuration data from the provincial ecology program. For. Sci. Prog., B.C. Min. For., Victoria, B.C. Work. Pap. 62/2001.

Pacala, S. W., Canham, C. D., Saponara, J., Silander, Jr., J. A., Kobe, R. K., Ribbens, E. 1996. Forest models defined by field measurements: II Estimation, error analysis, and dynamics. Ecol. Mon. 66: 1-43.

Poulin, J., Coates, K.D., Messier, C. 200_. Light transmission of snags in boreal forests. *In prep*.

Wright, E.F., K.D. Coates, C.D. Canham and P. Bartemucci. 1998. Species variability in growth response to light across climatic regions in northwestern British Columbia. Can. J. For. Res. **28**: 871-876.

Wright, E.F., Canham, C.D., Coates, K.D. 2000. Effects of suppression and release on sapling growth for eleven tree species of northern, interior British Columbia. Can. J. For. Res. 30:1571-1580.