Implications of alternate silvicultural strategies in Mountain Pine Beetle damaged stands

Technical Report

For

Forest Science Program Project Y051161

K. David Coates and Erin C. Hall

Bulkley Valley Centre for Natural Resources Research and Management, Box 4274, Smithers, BC, V0J 2N0, Canada.

and

British Columbia Forest Service, Research Section, Bag 6000, Smithers, BC V0J 2N0, Canada.

Corresponding Author Coates: E-mail: dave.coates@gems7.gov.bc.ca
Ph: 250 847-6386; Fax: 250 847-6353

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 is 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 100 years after disturbance. Planting these stand types with spruce shortly after MPB attack resulted in higher basal areas at 100 years, but increases were moderate and varied depending on starting stand type. 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 MPB killed snags are 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 underplanting prescriptions. These simulations allow us to explore how different stand types will be affected by MPB attack and how natural regeneration and underplanting 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 underplanting unsalvaged stand types after MPB attack
7) Examine the implications of delaying planting in MPB damaged stands

Methods

<u>Snag submodel</u>

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.

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 6-8cm 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 modelled 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 modelled 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 modelled the survival of 10 000 stems/ha of lodgepole pine seedlings established 10 years post-MPB attack. For both scenarios we modelled stand development for 20 years.

To compare the predictions of SORTIE-ND to TASS we modelled 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 modelled the four major stand types for 100 years.

To model the consequences of underplanting, we developed a set of simulations to assess the effect of underplanting 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 underplanting interior spruce under the Pine Dominant stand with a 95% level of mortality due to MPB. We delayed underplanting 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 parameter 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.

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 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).

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.

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 underestimation 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 results to TASS for density, basal area, and average DBH for three species.

Across all three species initial juvenile growth rates in SORTIE-ND are faster than TASS. However, SORTIE-ND adult growth rates for immature trees (roughly between 15 and 50 years) reflect the highly competitive environment at this time and result in slower growth rates than TASS. As a result growth rates of SORTIE-ND and TASS converge and total yield for lodgepole pine and interior spruce is similar. SORTIE-NDs prediction of subalpine fir growth is lower than TASS. 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 modelled the effect of severe mountain pine beetle damage on the four major stand types described previously. Despite poor natural regeneration conditions, the three stands containing a spruce component recovered from the attack. 100 years after attack, these three stands were merchantable with 47 to 67 m^2/ha in basal area and merchantable profiles. Figure 8a illustrates the change in basal area of the stands over 100 years. Figure 8b presents the final stand composition (of the three stands with a spruce component) 100 years post-attack. The pure *Pine Dominant* stand exhibits a very poor capacity to regenerate post-MPB. Table 2 provides a summary of the yield results 100 years post-MPB attack.

Stand Type	**Basal Area at 100 Years**		
	Spruce	Pine	Total
Pine minor Spruce	45.9	1.1	47.0
Mixed Pine / Spruce	67.1	0.5	67.6
Spruce minor Pine	53.9	0.1	54.0
Pine dominant	0.0	1.3	1.3

Table 2. Yield of the four major stand types 100 years post-MPB with no management intervention.

These results highlight the importance of targeting salvage operations toward stands with a minor spruce component as these stands will not likely regenerate well without management. If stands with a substantial spruce component are scheduled to be harvested our results highlight the importance of protecting the 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. This is due in part to the initial component of very large spruce. The *Mixed Pine-Spruce* stand type performed the best over 100 years after MPB attack. It yielded the same as the *Spruce Minor Pine* type at about 50 years post attack and continued to grow well (Figure 8a). **The *Mixed Pine-Spruce* and *Spruce Minor Pine* types, if left alone or protected from damage**

during snag salvage, can play a critical role in reducing the expected mid-term (30-50 years) timber supply shortage.

Underplanting Hybrid Spruce and Subalpine Fir

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

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. Comparison of 20 year survival of spruce and subalpine fir underplanted under four different stand types with severe MPB attack.

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 resulting from underplanting spruce or subalpine fir and comparison to stands with no underplanting.

These results indicate that planting either subalpine fir or spruce substantially increases the yield of *Pine Dominant* stands after 100 years. 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 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 underplanting 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 underplanting 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.

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 underplanting, 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 modelled 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.

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 than TASS.

Mountain pine beetle attacked stands with a well-developed immature spruce component recover relatively well after MPB attack. Within 100 years these stands have reached merchantable size and provide a reasonable yield. Some stand types recover and become merchantable within 50 years (the *Mixed Pine-Spruce* and *Spruce Minor Pine* types). If salvage of the lodgepole pine in these stands is desired, salvage should target the pine while protecting the spruce. These stand types can help mitigate mid-term timber supply shortages if protected during partial salvage or left unsalvaged. However, the *Pine Dominated* stand type will require management intervention in the form of underplanting or salvage and planting. Delaying underplanting for 5 to 15 years after initial MPB attack may result in much higher survival and growth of interior spruce or subalpine fir.

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.

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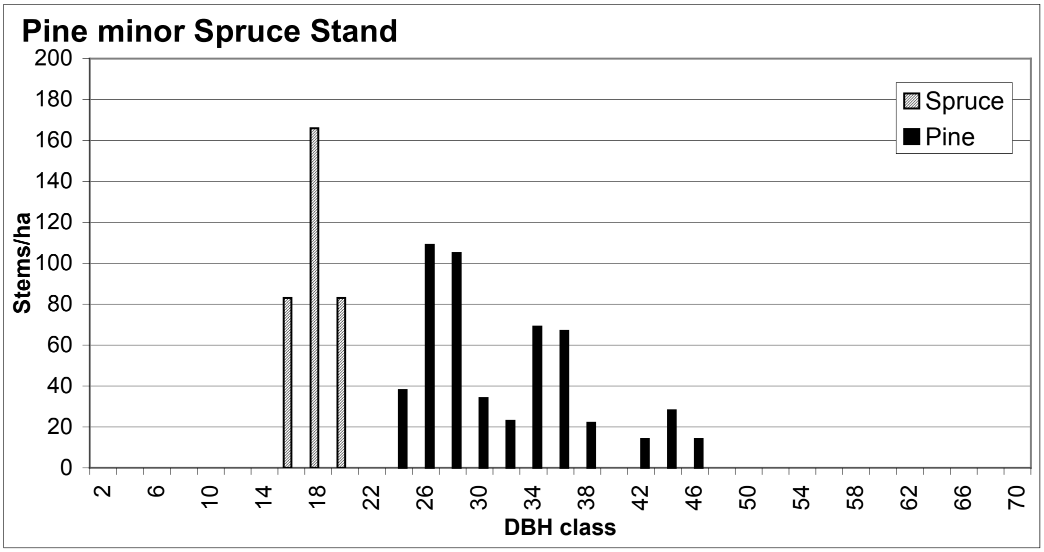
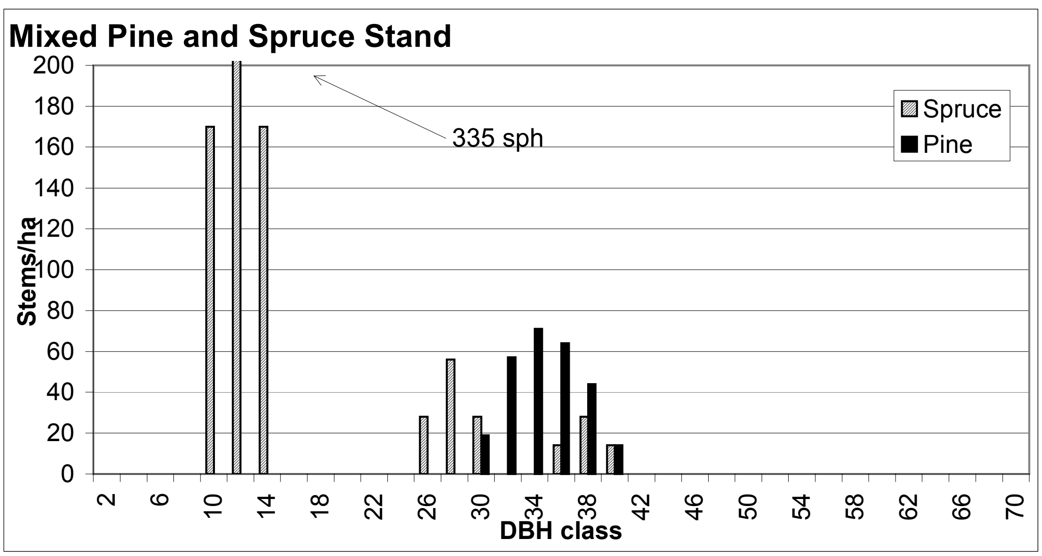
Figures

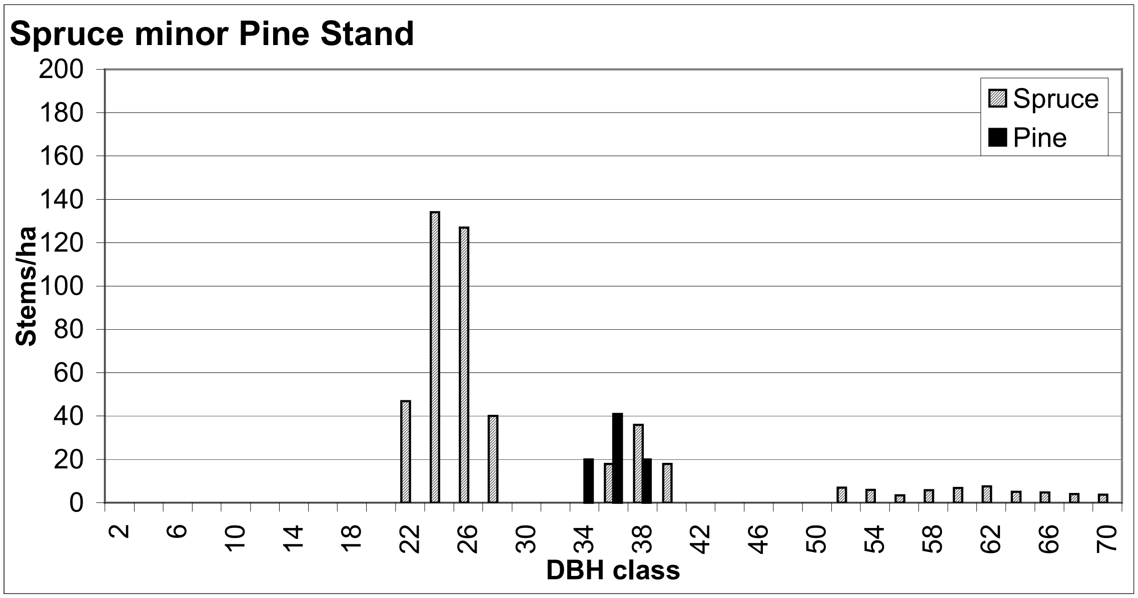


	Density	Basal Area
Spruce	332	7.6
Pine	523	39.8
Total	855	47.4

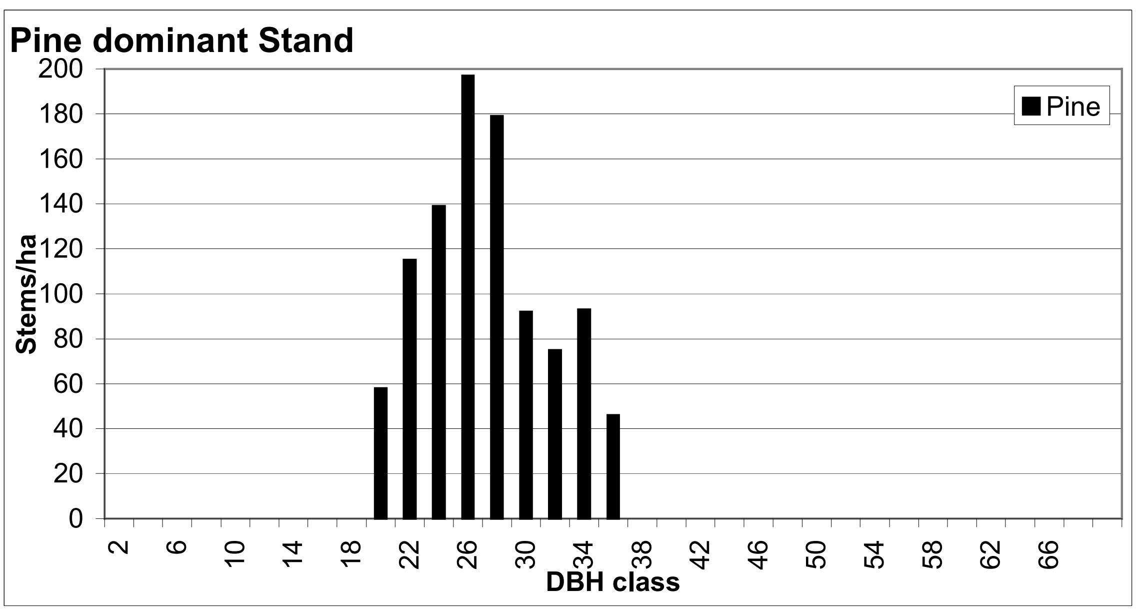


	Density	Basal Area
Spruce	848	19.1
Pine	269	24.2
Total	1117	43.3

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.

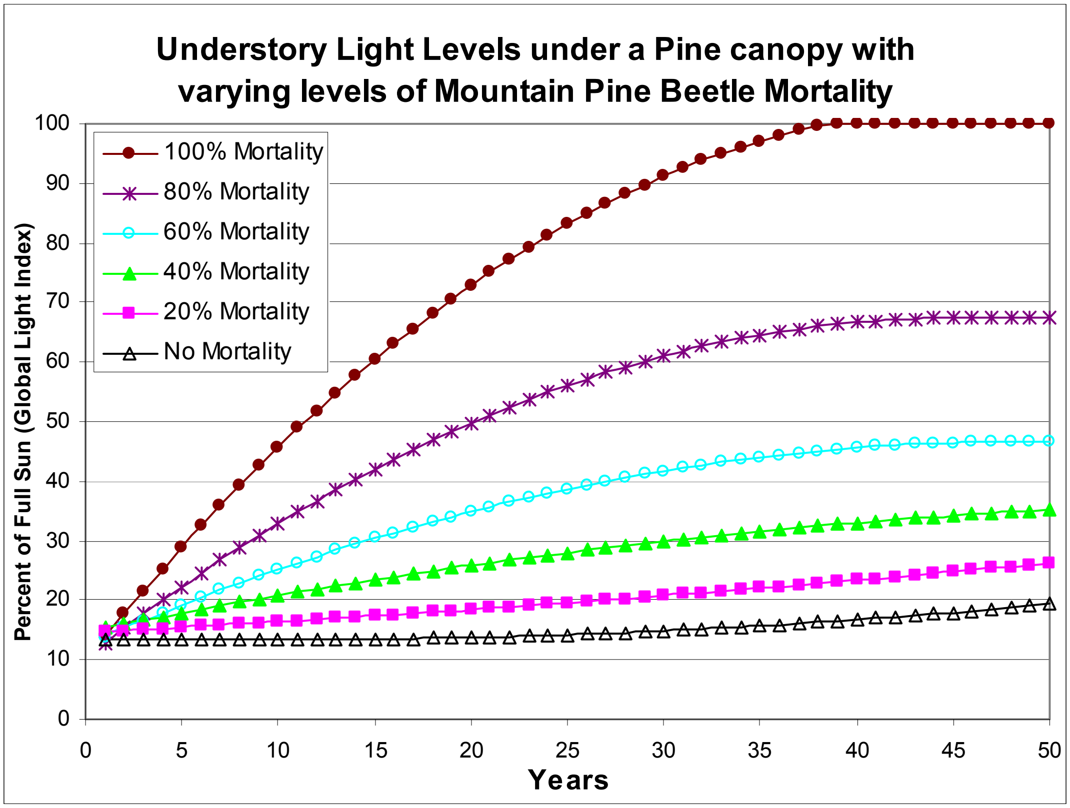


Figure 2. Change over time of understory light levels (as percent of full sun) under mature, 100% lodgepole pine canopies with varying levels of MPB attack.

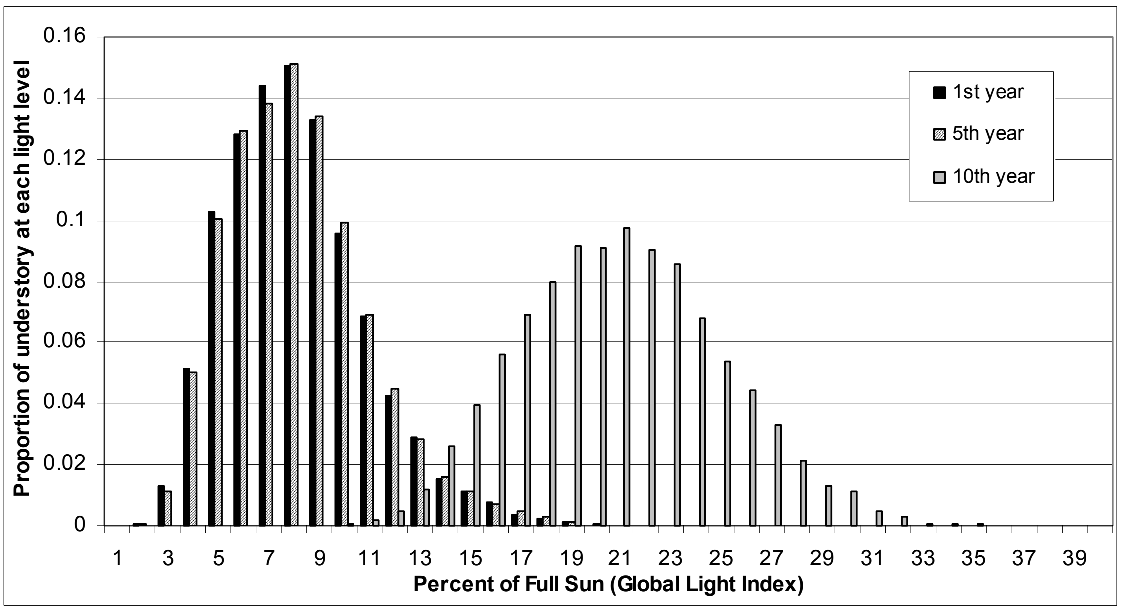


Figure 3. Light levels the first, fifth, and tenth year after mountain pine beetle attack.

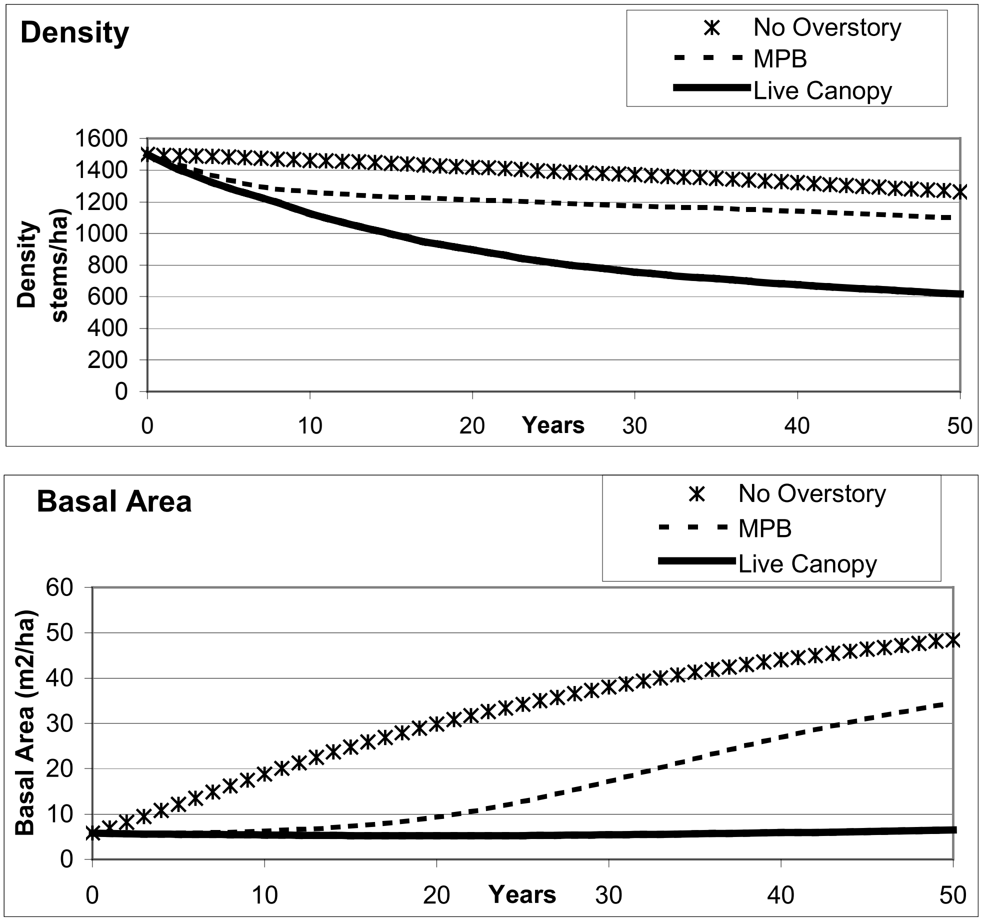


Figure 4. Predicted change in density and basal area of immature pine (1500 stems/ha, DBH 6-8cm) under three canopy conditions: traditional clearcut with no overstory, a MPB attacked stand with 95% mortality, and under a live mature pine canopy. Under a MPB attacked stand, growth and survival of the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

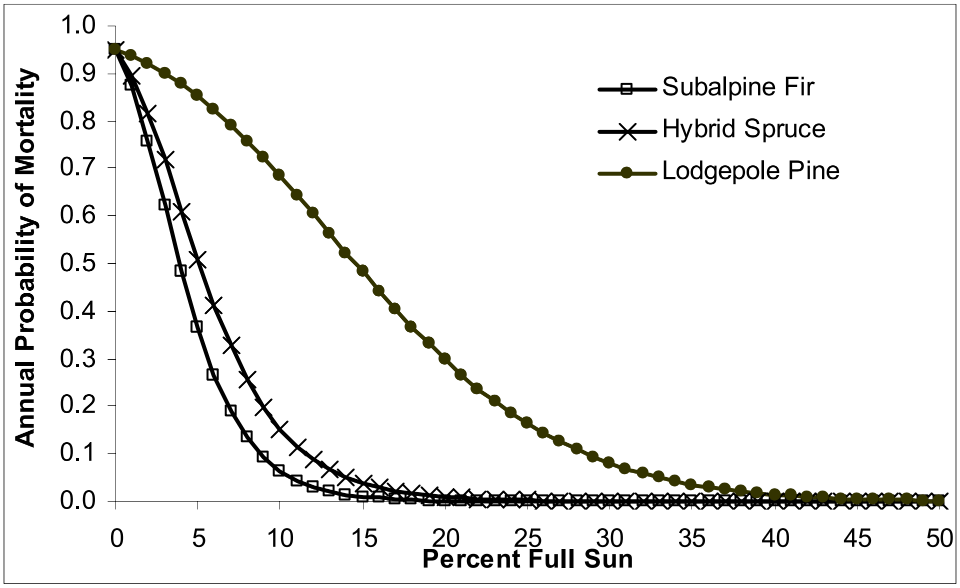


Figure 5. Juvenile mortality as a function of percent full sun (measured using global light index). SORTIE-ND predicts average light levels in the understory of severely MPB damaged stands to begin at 8% of full sun and increase to 21% full sun in the first ten years following MPB attack. This translates 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.

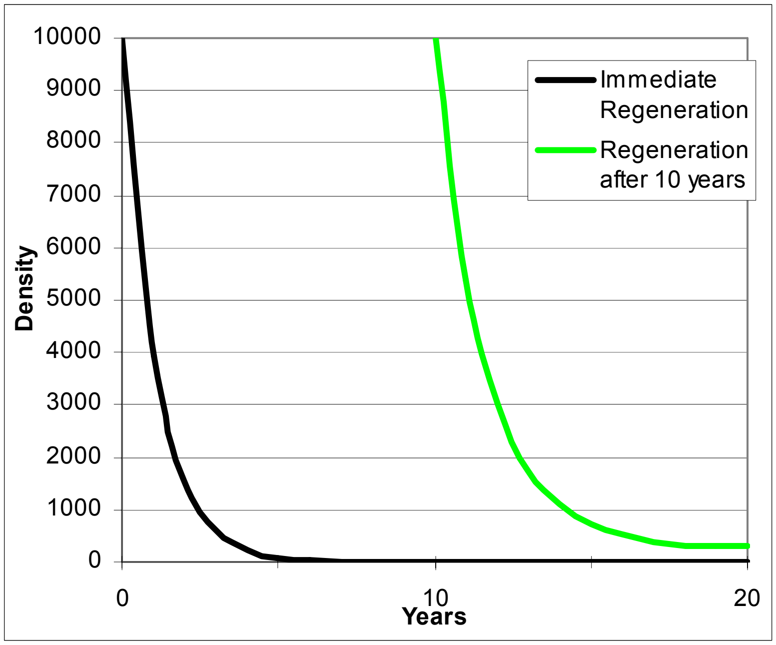


Figure 6. Survival of lodgepole pine regeneration under a MPB attacked pure pine stand. 10 000 stems/ha of natural regeneration were modelled 1 year and 10 years after MPB attack. Of the 10 000 stems/ha of natural regeneration originating 1 year post-MPB attack only 2 stems/ha were alive after 10 years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

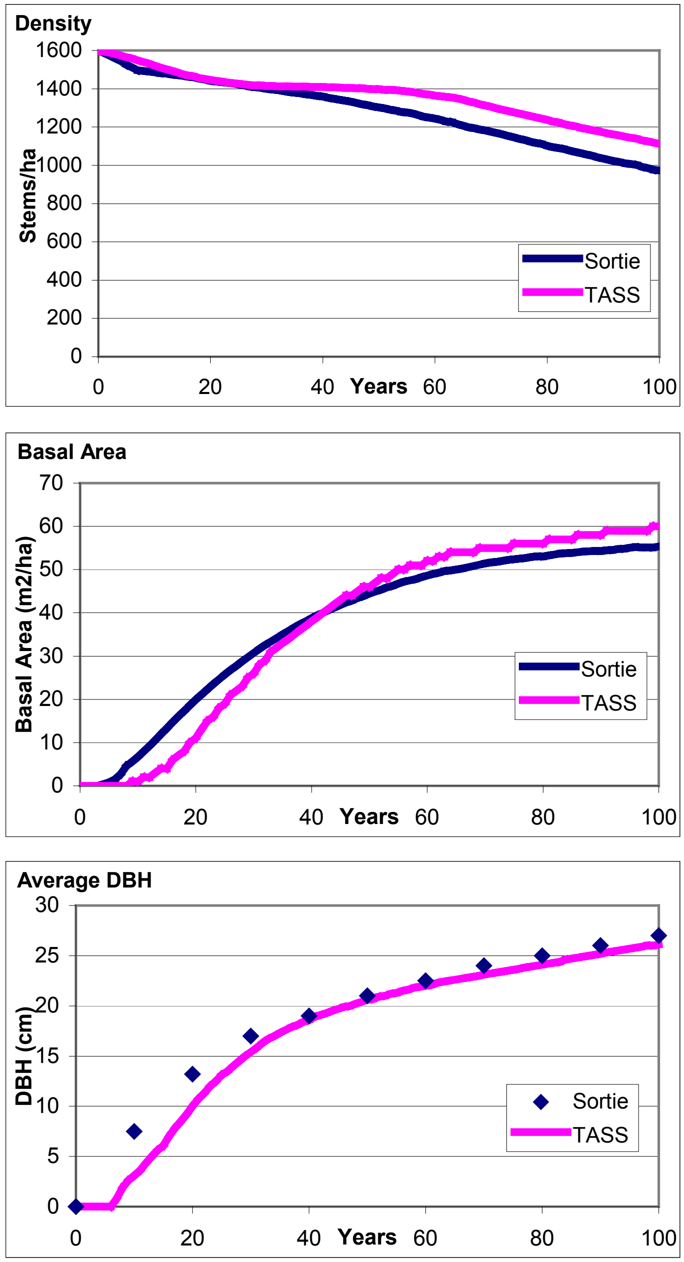


Figure 7a. Lodgepole Pine – Comparison of SORTIE-ND and TASS predictions of density, basal area, and average DBH for an even-aged lodgepole pine plantation with initial density of 1600 stems/ha. Over 100 years SORTIE-ND and TASS predictions of growth are similar.

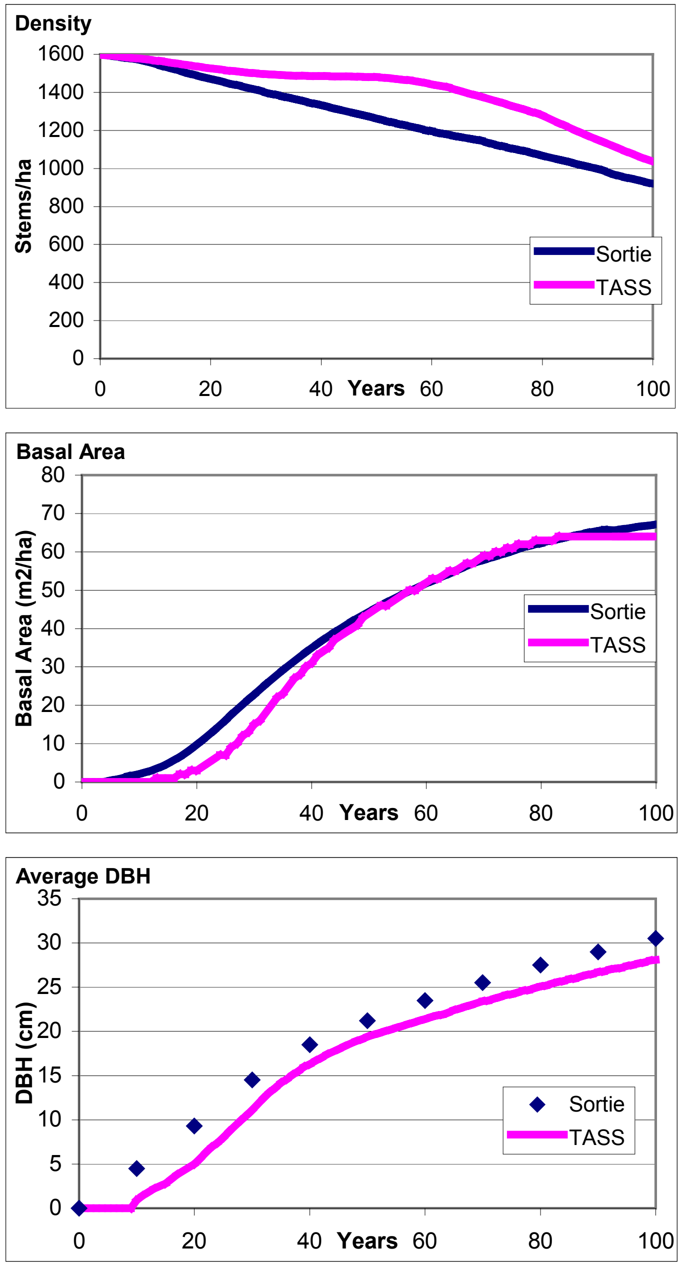


Figure 7b. Interior Spruce – Comparison of SORTIE-ND and TASS predictions of density, basal area, and average DBH for an even-aged interior spruce plantation with initial density of 1600 stems/ha. Over 100 years SORTIE-ND and TASS predictions of growth are similar.

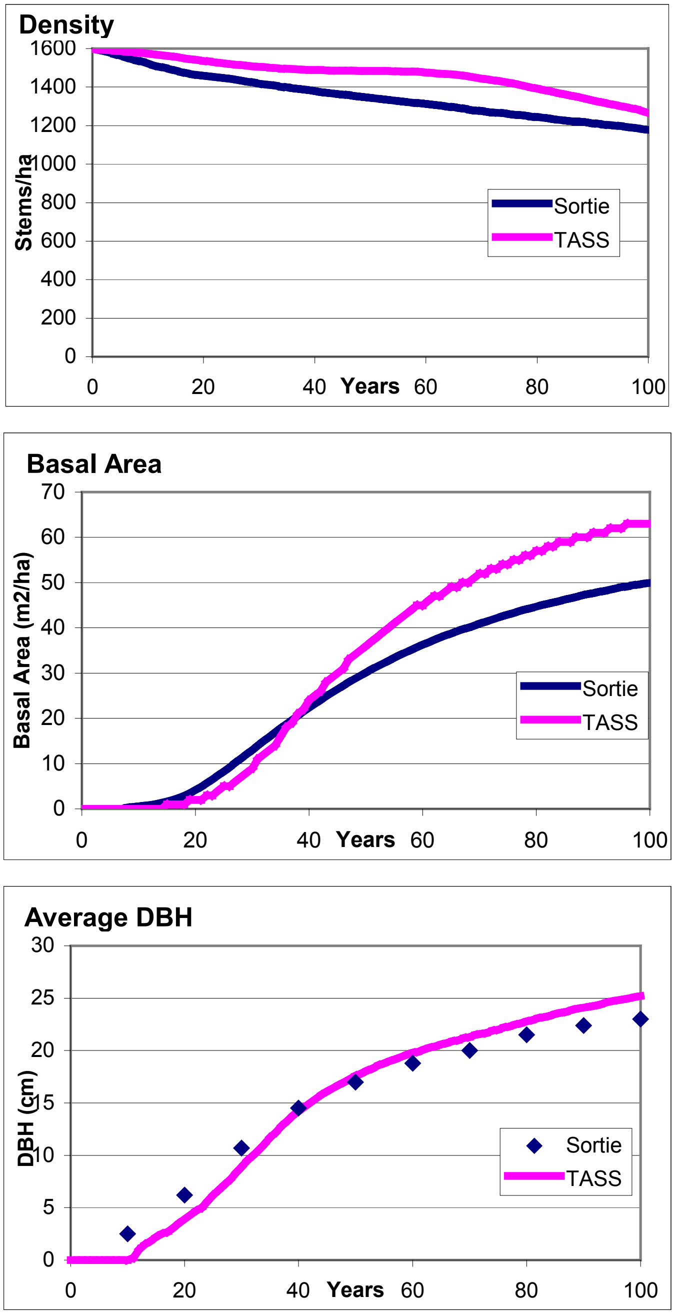


Figure 7c. Subalpine Fir - Comparison of SORTIE-ND and TASS predictions of density, basal area, and average DBH for an even-aged subalpine fir plantation with initial density of 1600 stems/ha. Using SORTIE-ND the growth rates of subalpine fir are lower over a 100 year period.

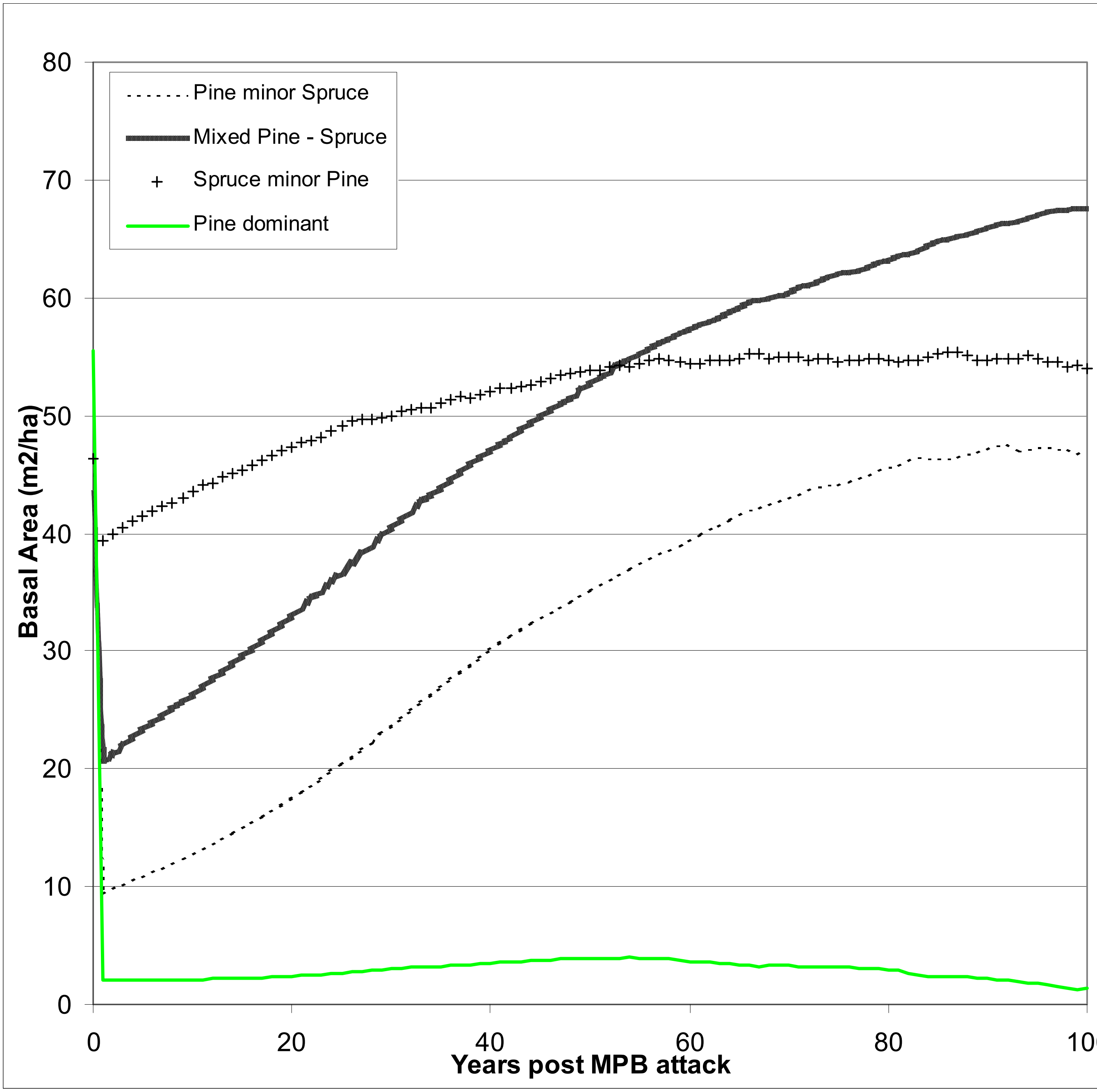


Figure 8a. Basal area growth of four stand types in the 100 years following severe mountain pine beetle attack. Stands with a spruce component recover reasonably well following MPB attack. The *Pine Dominant* stand lacking a spruce component does not recover within 100 years.

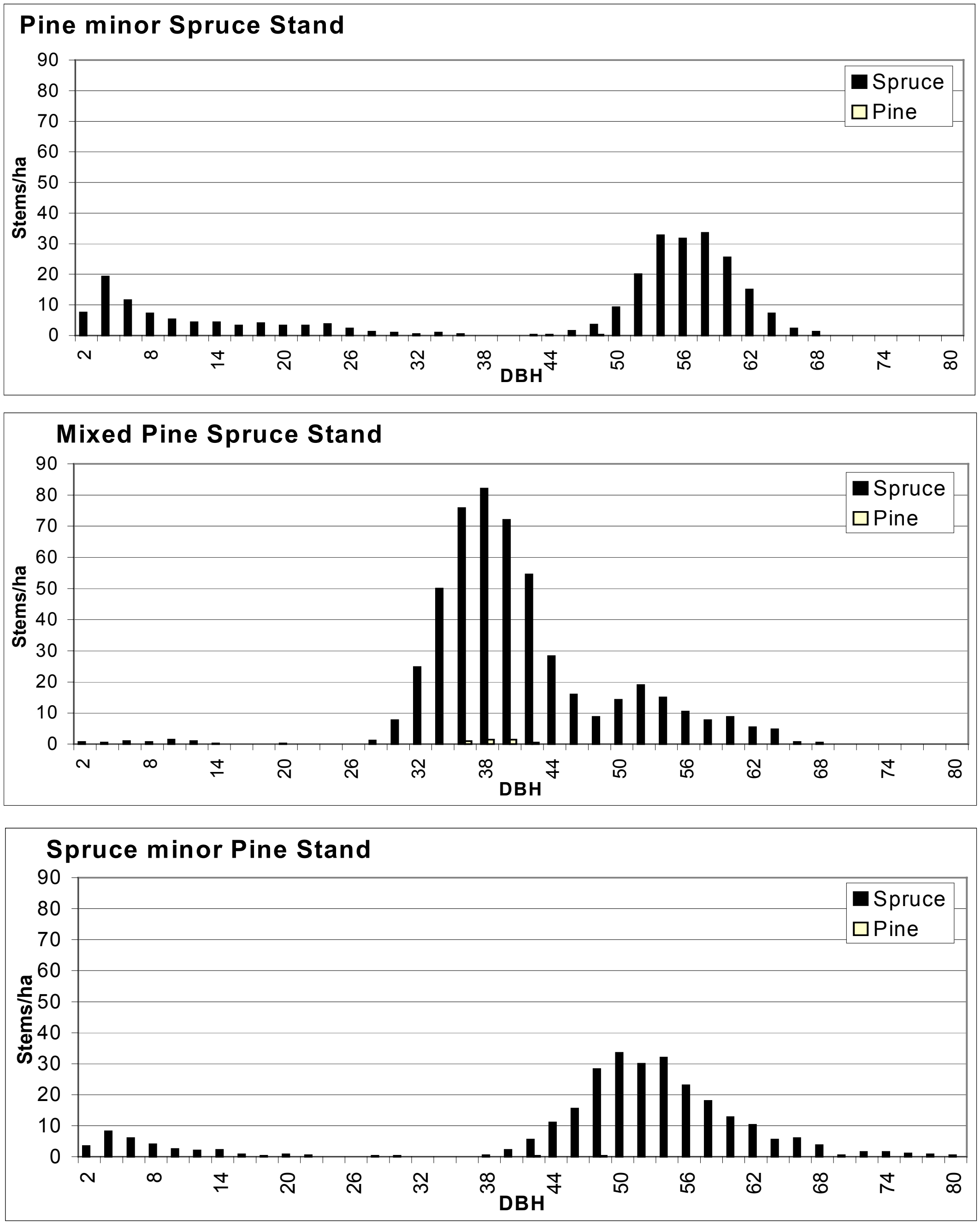
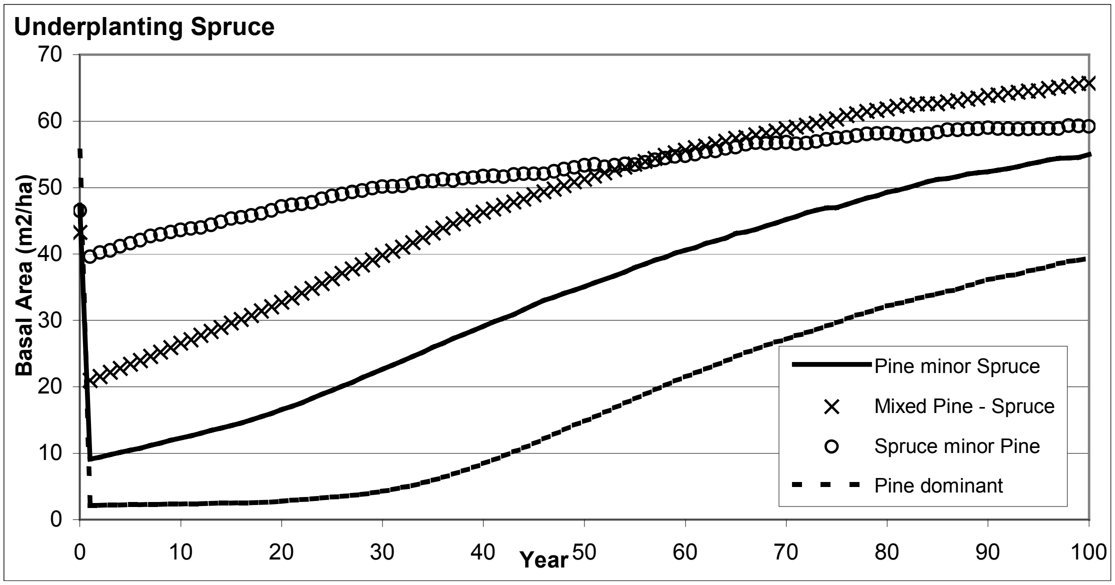


Figure 8b. Stand composition of the three stand types with spruce components 100 years after MPB attack. These stands have recovered well and the spruce have grown to a merchantable size. Note that the *Pine Minor Spruce* stand has higher levels of natural regeneration in the understory than the other 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.



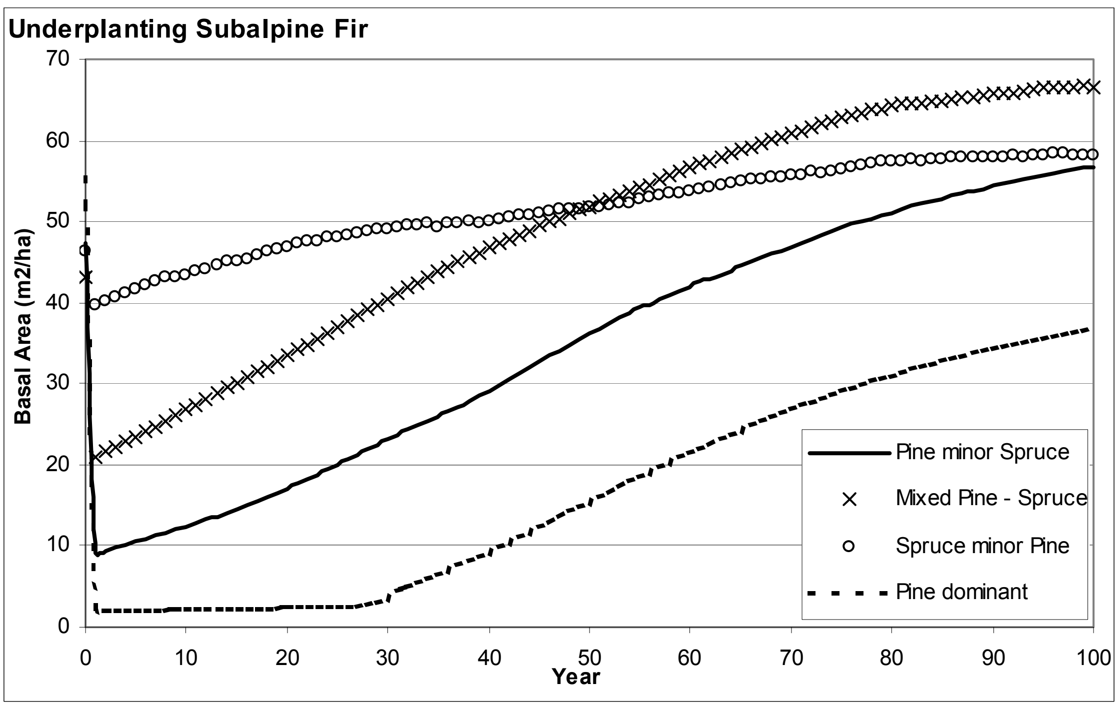


Figure 9. Yield, in terms of basal area, resulting from underplanting the four major stand types with spruce or subalpine fir. Underplanting improves the yield of three of the four major stand types; yield of the *Mixed Pine – Spruce* stand is not significantly changed. Although all of the stand types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