Temporal composition and structure of post-beetle lodgepole pine stands: Regeneration, growth, economics, and harvest implications

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Mountain Pine Beetle Working Paper 2008-23

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MPBI Project # 8.59

Natural Resources Canada
Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria BC V8Z 1M5
2008

Library and Archives Canada Cataloguing in Publication

Temporal composition and structure of post-beetle lodgepole pine stands : regeneration, growth, economics and harvest implications / K. Runzer ... [et al.].

(Mountain pine beetle working paper ; 2008-23)
"MPBI Project # 8.59".
Includes bibliographical references: p.
Includes abstract in French.
ISBN 978-1-100-11413-2
Cat. no.: Fo143-3/2008-23E

1. Lodgepole pine--Diseases and pests--British Columbia--Prince George Region--Computer simulation. 2. Mountain pine beetle--Effect of forest management on--British Columbia--Prince George Region--Computer simulation. 3. Forest dynamics--British Columbia--Prince George Region--Computer simulation. 4. Silvicultural systems--Environmental aspects--British Columbia--Prince George Region--Computer simulation. I. Runzer, K II. Pacific Forestry Centre III. Series: Mountain Pine Beetle Initiative working paper 2008-23

SB945 M78 T45 2008 634.9'7516768 C2008-980394-9

Abstract

A recent survey of mountain pine beetle (MPB) attack in mature and immature pine leading stands indicated that attack rate was a function of tree size, age and stand density. However, the temporal dynamics of MPB attack in mature and immature stands, as well as the release of the regeneration layer or secondary structure under a dying canopy, are poorly understood. The primary objectives of this study were to i) investigate temporal and spatial aspects of MPB attack, ii) investigate regeneration dynamics (mortality and growth) of post-beetle attack, iii) model growth and yield with actual mortality and regeneration metrics, iv) describe economic opportunities of harvest scheduling with respect to post-MPB stand structure and v) develop improved management and regeneration options. The results have shown that attack rates are higher than anticipated and originally assumed by timber supply analysts, with attack rates in immature stands (except age class 1) ranging from 40% to 60% and exceeding 80% in mature stands. Almost all the pine were killed in mature stands. Although at the landscape level stands have considerable secondary structure, there is a need to quantify the release of secondary structure and competing shrubs in these stands. An accurate inventory of post-MPB stand attributes is also required to determine which stands could benefit from restoration activities. The forest simulator model SORTIE-ND was used to project the outcome of four management scenarios: 1) the base case – stand development without MPB attack (Base), 2) the result of MPB attack – attacked trees proportionally removed by 2 cm diameter at breast height (DBH) classes (MPB), 3) underplant the MPB attacked stand and allow the residual tree layer and secondary structure to develop (UPlant), and 4) clearcut the tree layer and replant with 800 sph of spruce and 800 sph of pine (Clear-Plant). The base case was modelled for comparison purposes. Concerns with the no treatment option (MPB) are fire hazard, species composition, rate of release of the secondary structure and stand density. Concerns with underplanting (UPlant) is that it is costly and has historically been unsuccessful due to abiotic and biotic agents. Concerns with the clear cut (Clear-Plant) scenario are that the stands will not contribute to mid-term timber supply and that structural and species diversity will be reduced. The scenarios and the modelling highlighted that the use of secondary stand structure may be the best option for designing cost-effective and environmentally sound management/restoration strategies/activities.

Keywords: mountain pine beetle, post-beetle landscapes, forest composition, regeneration.

Résumé

Une évaluation récente de l'infestation de dendroctone du pin ponderosa (DPP) dans des peuplements matures et immatures composés majoritairement de pin a révélé que le taux d'infestation est lié à la taille et à l'âge des arbres, et à la densité des peuplements. Cependant, la dynamique temporelle de l'attaque de DPP dans des peuplements matures et immatures et la réalisation d'une coupe de dégagement de la couche de régénération ou de la structure secondaire sous une couverture moribonde sont mal comprises. Les objectifs premiers de cette étude étaient les suivants : i) examiner les aspects spatiaux et temporels de l'infestation de DPP; ii) examiner la dynamique de régénération (mortalité et croissance) après une infestation de DPP; iii) modéliser la croissance et le rendement à l'aide des données réelles sur la mortalité et la régénération; iv) exposer les possibilités économiques d'un calendrier de récolte en ce qui concerne la structure des peuplements après infestation de DPP; v) élaborer des solutions en matière de régénération et de gestion améliorées. Les résultats ont montré que les taux d'infestation sont plus élevés que ce que prévoyaient les analystes des ressources en bois. Les taux d'infestation des peuplements immatures (à l'exception de la classe d'âge 1) oscillent entre 40 % et 60 %, et dépassent 80 % dans les peuplements matures. Presque tous les pins des peuplements matures ont été décimés. Bien que les peuplements aient une structure secondaire importante à l'échelle du paysage, il est nécessaire de quantifier le dégagement de structure secondaire et de la compétition arbustive. Un relevé précis des caractéristiques des peuplements ravagés par le DPP est également nécessaire afin de déterminer les peuplements qui pourraient profiter des activités de restauration. Le résultat des quatre scénarios de gestion suivants a été calculé à l'aide de SORTIE-ND : 1) le scénario de base – développement d'un peuplement sans infestation de DPP (base); 2) le résultat de l'infestation de DPP – les arbres infestés de DPP de la classe de diamètre de 2 cm à hauteur de poitrine sont proportionnellement éliminés (DHP); 3) planter en sousétage des peuplements infestés de DPP en permettant à la couche d'arbres résiduelle et à la structure secondaire de se développer (SOUS-É.); 4) la coupe à blanc de la strate d'arbres pour replanter avec des épinettes et des pins de 800 tph (COUPE-PLANTATION). Le scénario de base a été conçu aux fins de comparaison. Les préoccupations liées à l'absence de traitement sont les risques d'incendie, la composition des espèces, le taux de dégagement de la structure secondaire et la densité des peuplements. Les préoccupations liées à la plantation en sous-étage (SOUS-É.) sont le coût et les échecs par le passé en raison d'agents biotiques et abiotiques. Les préoccupations liées à la coupe à blanc (COUPE-PLANTATION) sont que les peuplements ne contribueront pas à l'approvisionnement forestier à moyen terme et que la diversité structurale et celle des espèces seront réduites. Les scénarios et les modèles laissent croire que l'utilisation de la structure secondaire de peuplement pourrait être la meilleure solution pour concevoir des activités et des stratégies de gestion et de restauration économiques et efficaces.

Mots-clés : dendroctone du pin ponderosa, paysages après infestation, composition de la forêt, régénération

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1 Introduction

Lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) and the mountain pine beetle (*Dendroctonus ponderosae* Hopkins, MPB) have "always co-existed as a natural part of the ecosystem in British Columbia's interior forests" (Ministry of Forests and Range 2008a). The MPB actively participates in the natural cycle of lodgepole pine forests by attacking older or weakened trees, providing an opportunity for the occurrence of natural regeneration (Ministry of Forests and Range 2003). Mountain pine beetle epidemics have occurred periodically and in British Columbia (BC) they have been recorded since 1910 (Taylor and Erickson 2007). Typically, MPB outbreaks show a decline over some period of time, generally attributed to adverse climatic conditions, wildfire and predation (Canadian Forest Service 2007a).

British Columbia's forests have been experiencing the largest recorded MPB outbreak. The current MPB epidemic in BC's central interior began in Tweedsmuir Provincial Park in 1993 (Canadian Forest Service 2007a). The epidemic has grown exponentially with a west-east expansion from the coastal mountains to Alberta, and a north-south expansion from the Williston Reservoir to the US border. Aerial overview surveys from 2007 estimated 10,051,919 hectares of lodgepole pine forests were affected by varying degrees of beetle attack. The area of immature pine stands (<60 years of age) affected was estimated as 157,360 hectares (Ministry of Forests and Range 2008b). It seems likely that the BC epidemic will end only when most of the mature pine has been infested (Ministry of Forests and Range 2007) along with a portion of immature pine.

1.1 Beetle biology and environmental factors with respect to the epidemic in BC

The current outbreak in the central BC interior has been attributed to i) increased annual temperatures of 1.1°C (Ministry of Water Land and Air Protection 2002), ii) absence of extreme winter temperatures which historically caused population collapse (Cayer 1988, Caroll et al. 2004) and iii) abundance of suitable host (age class 5 and older) - 1.2 billion m^3 of lodgepole pine on approximately 8.1 million ha (Eng et al. 2004, 2005). Amman (1978) suggested epidemic MPB populations develop when there is an expanse of mature pine greater than 80 years (age class 5), mean tree diameter at breast height are >20 cm, and significant numbers of trees have phloem thickness ≥2.5 mm.

Mature lodgepole pine trees (age class 5 to 8) are extremely susceptible to MPB attack, especially with favourable weather (Ministry of Forests and Range 2003). These large diameter pine trees are sought by beetles for the high quality food and larval habitat they provide, along with protection from both predators and extremes in climate. In addition, older trees have lower resistance to the blue-stain fungus which is inoculated by the beetle, and which spreads through the sapwood causing inhibition in the tree's defence response (Canadian Forest Service 2007b).

According to Cole and Amman (1969), the MPB is food-limited in its population growth within a given area. With a preference for large diameter trees, over the course of an outbreak there is ultimately a decrease in the food supply, which stimulates the beetle to either seek out new areas with suitable trees or attack smaller diameter trees. The MPB's host selection and food-limited population demonstrate the importance of a stand's proximity to active epidemic bark beetle populations (Shore and Safranyik 1992; Anhold and Long 1996; Shore et al. 2000; Caren et al. 2006). Previous studies have identified that a less susceptible stand may experience considerable MPB damage if there are large, active bark beetle populations (Shore and Safranyik 1992; Anhold and Long 1996; Caren et al. 2006). Proximity to active beetle populations may be considered the most important function/variable for explaining attack in immature stands within BC's central interior.

1.2 Immature attack and the predicted mid-term falldown

The timber supply analyses undertaken by both government and industry for various forest management units predict a significant mid-term falldown as a result of the current MPB epidemic (Pedersen 2004; Canadian Forest Products 2005; Nussbaum 2006). At the provincial level, the falldown in future harvest is likely to begin in approximately ten years and last for up to 50 years (Pousette and Hawkins 2006). An estimated 710 million m^3 of merchantable timber has been killed by the MPB (Ministry of Forests and Range 2008a). This number is greater than 15 years of normal harvest for the province's central and southern interior. It is predicted that 80% of the susceptible pine (age class 5 and older) will be killed by 2013 (Eng et al. 2005) and the Prince George Timber Supply Area (TSA) Annual Allowable Cut (AAC) will drop below 75% of the pre-MPB AAC (Eng et al. 2005; Pousette and Hawkins 2006).

The post-MPB epidemic estimated AAC is based on five assumptions: 1) oldest attacked stands are harvested first; 2) only mature stands are affected with attack rates of about 80% in age class 5 and older and attack rates of about 50% in age class 4; 3) there is no attack in age classes 1 to 3; 4) there is a regeneration delay of 15 years in areas not logged; and 5) a shelf life of ten years with five years for sawlogs (Eng et al. 2004, 2005). Mountain pine beetle induced mortality in immature lodgepole pine stands invalidates two of the timber supply assumptions and is not reflected in current timber supply analysis for the Prince George TSA (Pousette and Hawkins 2006). Immature mortality caused by the MPB will result in an extension, and possibly a deepening, of the mid-term fall down period beyond that which has been forecast in any provincial timber supply analysis to date (Pousette and Hawkins 2006).

1.3 Economic and environmental implications of the mountain pine beetle epidemic

The governments of British Columbia and Canada have recognized a need for active restoration of forest resources in areas affected by the epidemic (Burton 2006; Ministry of Forests and Range 2007). Characterizing stand dynamics and landscape patterns temporally and spatially across the affected area will provide the basis for developing cost-effective and ecologically sound restoration scenarios for different levels of MPB attack and advanced regeneration.

Restoration activities are problematic in immature stands. Firstly, the Ministry of Forests and Range is responsible for restoration activities since these stands have been declared free growing (Ministry of Forests and Range 2000). Secondly, the timber in immature stands will not be harvested (no revenue) due to its small size and poor wood quality: juvenile wood, large taper and branch size. Many restoration activities require clearing and reforestation. When clearing costs are coupled with reforestation costs many restoration activities become uneconomical especially when considering the size of the MPB-affected area. Other restoration activities such as underplanting are problematic due to biotic factors which include browsing and forest health agents. The development of alternative restoration strategies that balance the unique economical, ecological, and spatial aspects of MPB attack in immature stands is required. Recent studies target and recommend restoration activities that utilize residual stand structure and regeneration, and may offer the most economic and environmentally sound management strategies (Burton 2006; Coates et al. 2006).

1.4 Objectives

This project involved the study of mature and immature stands in the Prince George TSA affected by the MPB. The objectives were to quantify and map the composition and structure of forests in a post-MPB environment. Targeted objectives for both mature and immature stands were:

1. To examine the effects of spatial and temporal stand attributes on the severity of cumulative MPB damage at the stand and landscape level.
2. To develop informed regeneration and management strategies for post-MPB landscapes.
3. To identify potential economic opportunities associated with the harvest scheduling of post-MPB attacked stands.

2 Material and Methods

2.1 Study area

2.1.1 Study location and sampling areas

The Prince George TSA is found in BC's central interior. It is one of the largest TSAs in the province and is divided into three forest districts: Prince George, Vanderhoof, and Fort St. James. For this study, three areas were sampled over the course of three years. In 2005, sampling occurred in the Vanderhoof Forest District (VFD) and the south-western portion of the Prince George Forest District (PGFD) (Study Area 5). In 2006, sampling occurred in the southeast portion of the PGFD (Study Area 6). Sampling in the northwest portion of the PGFD and extreme south-eastern portion of the Fort St. James Forest District (FSJFD) occurred in 2007 (Study Area 7) (Figure 1).

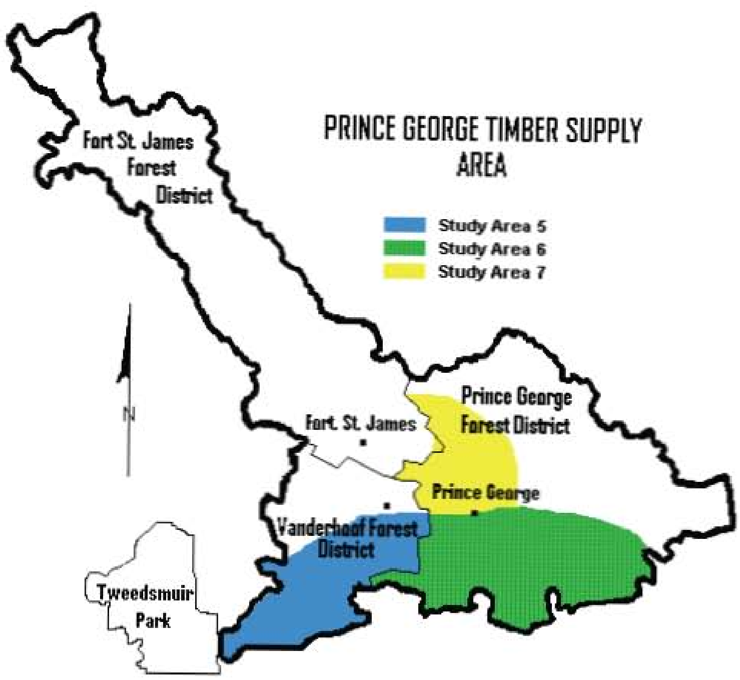


Figure 1. Prince George Timber Supply Area (TSA) and sampling areas

2.1.2 Mountain pine beetle epidemic time chronology of the study area

The current MPB epidemic spread westward from Tweedsmuir Provincial Park and, in 1999, light MPB attack was occurring in the VFD, extreme southwest portion of the PGFD, and southwest portion of the FSJFD (Ministry of Forests and Range 2008). By 2001, severe attack was found in the south-western portions of the VFD and the PGFD. Light to high attack was found throughout the rest of the VFD and south-western portion of the PGFD and FSJFD. For the next four years the epidemic spread east, north, and south to affect almost every lodgepole pine stand in the VDFD, PGFD, and southern portion of the FSJFD. At the onset of our research project in the summer of 2005, severe attack encompassed the entire VFD, western portion of the PGFD, and southern portion of the FSJFD. By 2006, severe attack spread further east, north, and south. Light to heavy attack had spread to almost all lodgepole pine stands, both immature and mature, in the PGFD and southern portion of the FSJFD. The MPB epidemic has continued to spread further east, north, and south. It currently affects lodgepole pine stands east of the Rocky Mountains and south of the Canadian/American border.

2.1.3 BEC subzone and variants

The Prince George TSA is predominantly a plateau landscape and is situated between the Coast Mountains to the west and the Rocky Mountains to the east (DeLong et al. 1993). It contains six biogeoclimatic subzones: boreal white and black spruce (BWBS), Engelmann spruce sub-alpine fir (ESSF), interior cedar hemlock (ICH), montane spruce (MS), sub-boreal pine spruce (SBPS), and sub-boreal spruce (SBS). All temporary sample plots are located within the SBS. The subzones sampled with in the SBS were the dry cool (dk), moist cold (mc), dry warm (dw), moist cool (mk), moist warm (mw), wet cool (wk) and very wet and cool (vk). The Prince George TSA contains approximately 3.7 million hectares of SBS which accounts for roughly 30% of the TSA’s land base (Holt 2001) and 78% of the timber-harvesting land base.

2.1.4 Disturbance history

2.1.4.1 Immature

A legacy of harvesting and silvicultural practices has created a large amount of managed age class 1 (zero to 20 years) and class 2 (21 to 40 years) lodgepole pine plantations on the landscape. Age class 1 and 2 stands were created by clear cut logging followed by planting mostly lodgepole pine. Mechanical site preparation and prescribed burning were widely used within the study area. Stand-tending activities such as brushing, weeding, fertilizing, and spacing were also applied to various age class 1 and 2 stands.

Age class 3 stands (41 to 60 years) surveyed in the study area are of fire origin. Lodgepole pine (Pl) and minor components of Black Cottonwood (Ac), Trembling Aspen (At), Sub-alpine Fir (Bl), Douglas Fir (Fd), Black Spruce (Sb), and interior Spruce (Sx) have naturally regenerated to produce high density pine leading stands. Juvenile spacing has been utilized throughout the Prince George TSA (but not in all stands).

2.1.4.2 Mature

Sampled stands greater than 80 years of age had no stand-tending practices. Most of the Pl leading stands are of fire origin and have all naturally regenerated. The mature tree layers of sampled stands are predominantly Pl and minor components of Ac, At, Bl, Fd, Sb, and Sx.

2.1.5 Polygon selection

During 2005, 2006, and 2007, temporary sample plot (TSP) establishment, candidate stands were identified from forest cover maps in the Prince George TSA. Reconnaissance was undertaken to determine if they met the criteria for sampling. These were defined as: lodgepole pine leading, age class 1–8 (Table 1), zero to nine years since green attack, SBS biogeoclimatic zone, less than 1 km from an access point, and on mesic and sub-mesic site series (Rakochy

2005). Seventy percent of stands were randomly selected and 30% were systematically selected to ensure complete coverage of age classes and various stand attributes.

Table 1. Age range associated with each age class.

Age class	Age range	Age class	Age range
1	1 – 20	5	81 – 100
2	21 – 40	6	101 – 120
3	41 – 60	7	121 – 140
4	61 – 80	8	141 – 250

2.1.6 Initial sampling

The sampling protocol commenced (POC) at least 50 m from polygon boundaries, roads or trails. Transects started at the POC and temporary sample plots with a 5.64 m radius (100 m^2) or a 3.99 m radius (50m^2) plot established every 50-100 m along the transect line. The smaller area plots were used in higher density stands. When atypical plot locations were encountered, such as areas with excessive windthrow or water, the plot was moved 25-50 m along the transect line. Polygon (stand) size and shape dictated the distance and orientation among plots. A minimum of five plots were established in a polygon and ten was the maximum. Forest cover polygon number, Global Positioning System (GPS) location, site series, site index, and macro aspect were used to identify and characterize each TSP. Data collected in each TSP were: crown closure using a spherical densitometer as described by Rakochy (2005), mature tree species (DBH at 1.37 m ≥7.5 cm), mature tree DBH, mature tree vigour or stage of MPB attack as described in Rakochy (2005), relative crown position (dominant, codominant, etc.), and wildlife-danger tree classification as detailed in Rakochy (2005). Height and one tree core was taken for the site tree in each plot. The tree cores were used to confirm stand age and calculate productivity (SI_{50}). SI_{50} was calculated using site index curve tables developed by Thrower et al. (1994).

A smaller 3.99 m radius (50 m^2) plot with the same plot center as the larger mature tree plot was used to collect regeneration or secondary structure (natural or artificial) information in each TSP – 1.78 m radius (10 m^2) plots were used where there were large amounts of regeneration. Seedlings were shorter than 1.37 m in height while saplings had a height ≥1.37 m and a DBH <7.5 cm. Regeneration was assessed as recently dead, healthy and moribund – not likely to survive to the next stage (seedlings to saplings or saplings to poles). The regeneration was categorized by quadrant (Q1=N to E, Q2=E to S, Q3=S to W, Q4=W to N) for stands initially sampled in 2007. This allows a spatial assessment of secondary stand structure. The species composition and percent cover of the shrub layer within the regeneration plot was described. A digital photograph of a randomly located 1 m by 1 m quadrant was taken to record the species composition of the forest floor. Species were identified either in the field (time permitting) or in the office from the photograph.

For initial stand assessment, project design was based on protocols and recommendations of Schreuder et al. (1993) and Rakochy (2005). Transect lines and circular plots are an acceptable form commonly used to sample forested stands (Anonymous 1998). Wildlife and danger tree assessments were completed for all mature trees using approved sampling methods developed and tested by the Wildlife Tree Committee and the Worker's Compensation Board of BC (Anonymous 2001, and used by Rakochy 2005). This methodology was augmented with protocols from Bate et al. (2002) and Manning et al. (2002). The use of photography to characterize vegetation was a technique adopted from Williston and Cichowski (2003).

2.1.6.1 Initial Stand Assessment Sampling Schedule

Initial stand assessment in the 2005, 2006, and 2007 study areas occurred from July 2005 to April 2006, July 2006 to March 2007, and July 2007 to November 2007, respectively. Sampling began in July to capture the current year beetle flight. Sampling was completed in late March or early April to avoid capture of next year's beetle flight. A summary of the amount of stands and TSPs sampled from 2005 to 2007 is found in Table 2. The sampling focus was age class 2 stands because of their problematic management issues.

Table 2. Total number of stands and TSPs sampled in each age class and BEC subzone and variant.

Age Class	SBS Subzone and Variant																			
	dk		dw2		dw3		mc2		mc3		mk1		mw		vk		wk1		All	
	Stand	TSP	Stand	TSP	Stand	TSP	Stand	TSP	Stand	TSP	Stand	TSP	Stand	TSP	Stand	TSP	Stand	TSP	Stand	TSP
1	7	36	1	5	4	20	.	.	3	14	13	65	.	.	9	45	18	85	55	270
2	19	102	19	100	26	129	1	5	8	40	35	168	1	5	8	38	32	152	149	739
3	1	7	10	50	6	31	.	.	2	10	14	68	.	.	.	.	5	25	38	191
4	8	40	5	25	25	123	.	.	7	35	20	92	.	.	.	.	6	30	71	345
5	.	.	.	.	12	62	.	.	1	3	5	25	.	.	.	.	7	35	25	125
6	.	.	1	5	9	45	.	.	1	5	8	38	.	.	.	.	3	13	22	106
7	.	.	11	55	20	99	.	.	1	5	6	29	.	.	1	5	6	30	45	223
8	.	.	6	34	15	77	.	.	2	10	19	90	.	.	2	15	10	54	54	280
Total	35	185	53	274	117	586	1	5	25	122	120	575	1	5	20	103	87	424	459	2279

2.1.7 Re-measurement sampling

Re-measurements of temporary sample plots established in 2005 and 2006 commenced in July 2006 for 2005 TSP and again in July 2007 for 2005 and 2006 TSP. A complete re-measurement of age class 1 to 3 stands was attempted although a few stands were not re-measured due to access issues and logging. Almost all age classes 4 to 8 stands with live lodgepole pine in the mature tree layer (DBH >7.5 cm) were re-measured in 2006 and 2007. Stands that did not have any live lodgepole pine trees were not re-measured. Salvage harvesting limited the number of TSPs re-measured in mature age classes in Study Areas 5 and 6. Table 3 depicts the number of stands and TSPs that were re-measurements during the 2006 and 2007 re-measurement sampling years.

Table 3. Total number of stands and TSPs re-sampled in study areas 5 and 6.

	Study Area 5				Study Area 6		Combined	
	2006 Re-measure		2007 Re-measure		2007 Re-measure		2007 Re-measure	
Age Class	Stand	TSP	Stand	TSP	Stand	TSP	Stand	TSP
1	15	59	15	59	25	123	40	182
2	55	279	49	250	43	208	92	458
3	18	91	17	85	12	58	29	143
4	29	143	28	138	15	49	43	187
5	12	60	9	45	5	25	14	70
6	4	20	4	20	2	10	6	30
7	11	54	0	0	1	4	1	4
8	10	55	3	15	2	10	5	25

2.2 Data manipulation

All data collected during this study, first measurements and then re-measurements, were combined in Microsoft Excel spreadsheets. Age class files from each sampling year were combined after the 2007 initial plot establishment, and each data file contained a tree list and a secondary structure (advanced and seedling regeneration) list.

2.2.1 Tree list data files

The tree list data file has the following information: plot radius, plot multiplier, sample date, forest cover map sheet, polygon number, sampling year, road location, plot number, crown photograph, GPS coordinates, calculated site index, inventory site index, site tree identifier, crown closure, crown height, biogeoclimatic subzone and variant, moisture class code (site series), map age class, calculated age class, slope percent, slope aspect, tree number, tree species, DBH, MPB attack status, WCB code, tree description, crown class, basal area, DBH class, MPB affected code, site tree age, and mean polygon age.

Eight DBH classes with two different DBH ranges (2.5 cm and 5.0 cm) were established: 8.75 (7.50-10.0 cm), 11.25 (10.01-12.5 cm), 13.75 (12.51-15.0 cm), 17.5 (15.01-20.0 cm), etc. The smaller ranges in the low DBH classes were established to assist in better estimating MPB attack on smaller trees in all age classes. Basal Area (BA-m^2) was calculated for each tree using the formula: $BA = \pi * (DBH/200)^2$.

Mountain pine beetle affect code was added to the tree list data file for calculating MPB attack rates and pre- and post-MPB residual mature tree layer stocking. The tree list data sets will be used in i) growth and yield models SORTIE-ND and TASS 3 to project future stand yields and ii) model outputs used for economic analysis to direct post-attack harvest.

Other analyses are described in specific sections along with the results.

2.2.2 Regeneration list data files

The regeneration data files included the same parameters as the tree list. Basal area was calculated for each tree that was taller than 1.37 m.

The regeneration data sets will be used in i) growth and yield models SORTIE-ND and TASS 3 to project future stand yields; ii) post MPB regeneration descriptions (stand dynamics); iii) management scenarios for different levels of MPB attack and secondary structure in SBS sub-zones; and iv) cost-benefit analysis of various management scenarios in the SBS for different levels of MPB attack and secondary regeneration.

3 Results and Discussion

3.1 Mountain pine beetle attack and Lodgepole pine diameter

Mountain pine beetle attack rates increase with increasing DBH class (Figure 2).

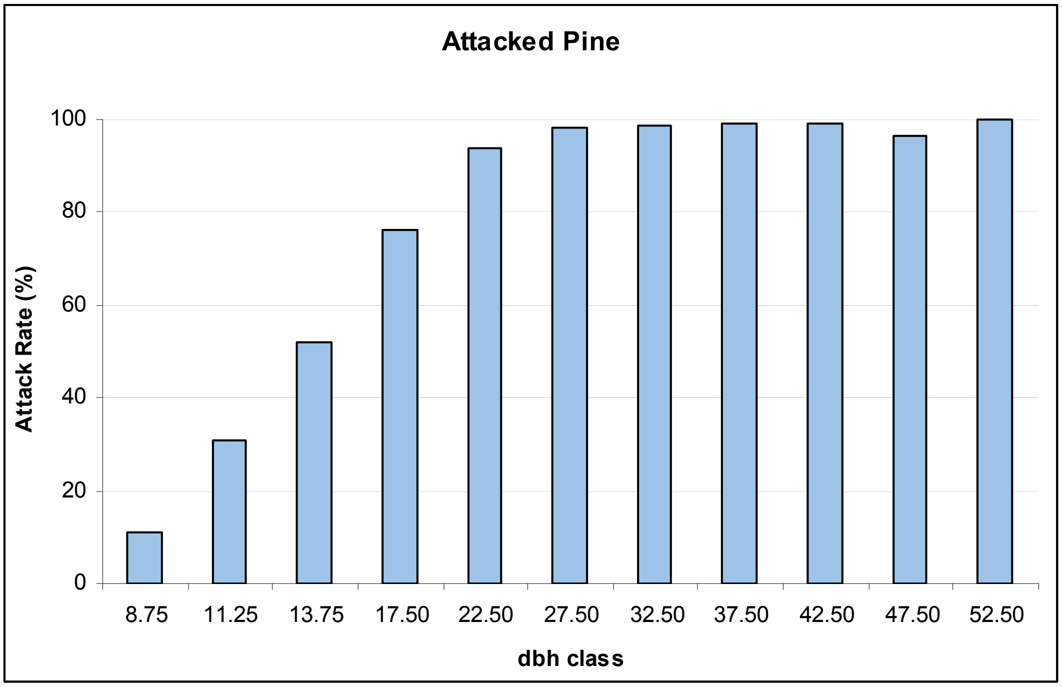


Figure 2. Percentage of mountain pine beetle-attacked pine by DBH class**.**

Except the two smaller DBH classes, all of the others presented MPB attack rates over 50%. This demonstrates the insects' preference for large diameter trees. MPB attacks and brood production are directly related to tree age and DBH (Cole and Amman 1969). Larger trees have thicker bark and phloem, offering more protection for the insects and larvae from natural enemies, extreme temperatures and sapwood drying.

3.2 Landscape level mountain pine beetle attack rates

Figure 3 shows the percentage of lodgepole pine trees attacked by the MPB for the Study Areas 5, 6 and 7 (see Figure 1). Standard deviations are not included because the analysis of attack rates has consistently shown considerable variation among variables analyzed, i.e., at landscape levels means and standard deviations are equal. Other than for age class 1 and 2, there was little difference in attack rates among the areas sampled.

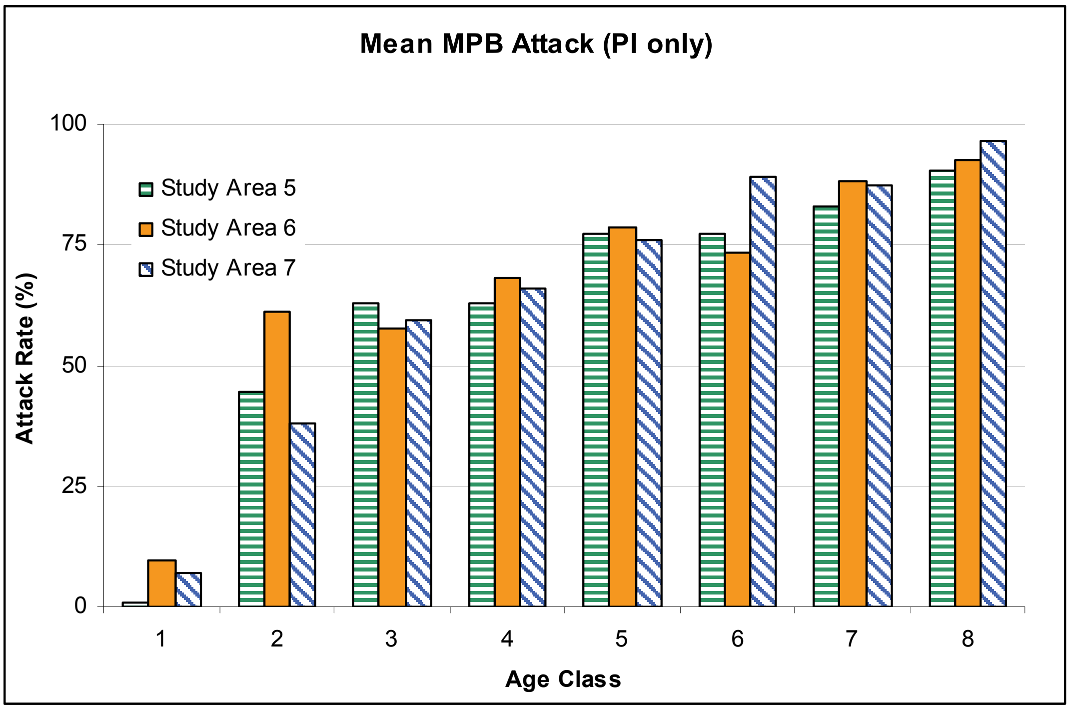


Figure 3. Mean mountain pine beetle attack rate in pine trees from study areas 5, 6 and 7.

For pine, mean DBH increases with age class (Figure 4).

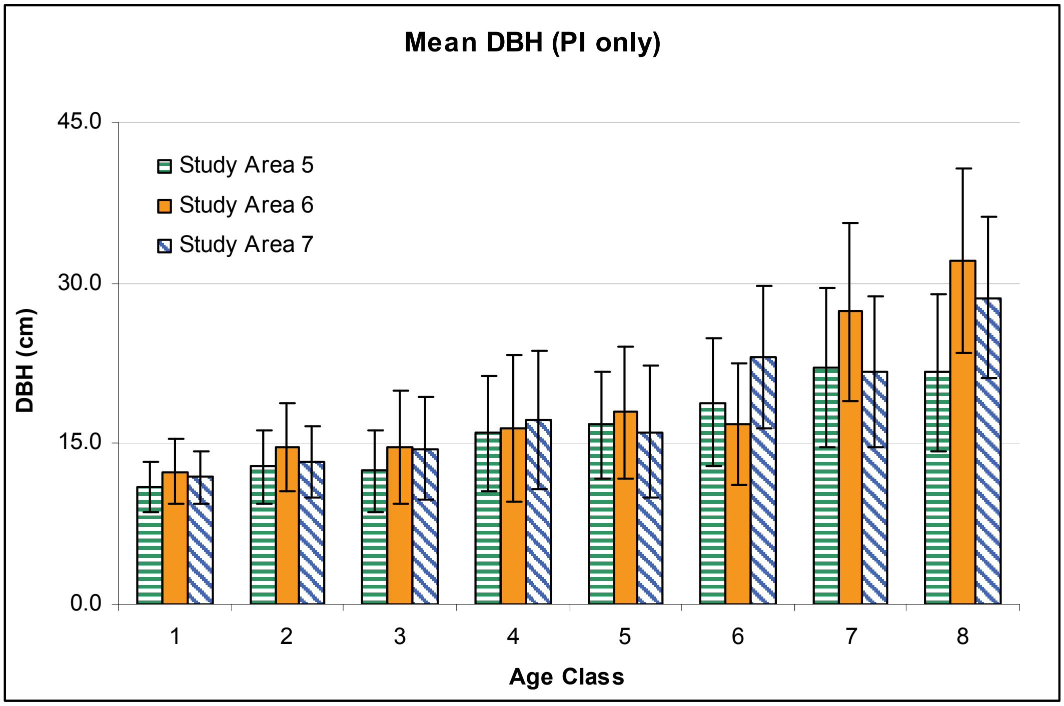


Figure 4. Mean diameter by age class in study areas 5, 6 and 7**.**

At the landscape level, attack increased with age class in all study areas, mean diameter increasing with stand age. This behaviour was expected as the MPB prefers to attack larger diameter hosts that are older or weakened (Canadian Forest Service 2007b). Older, mature, large diameter trees also have more bark fissures which can be used by the beetles to initiate entry holes. However, what is of interest and importance is the high levels of attack in age classes 2 and 3 given their small DBH.

When all species are considered, the attack rate decreased in older age classes (Figure 5).

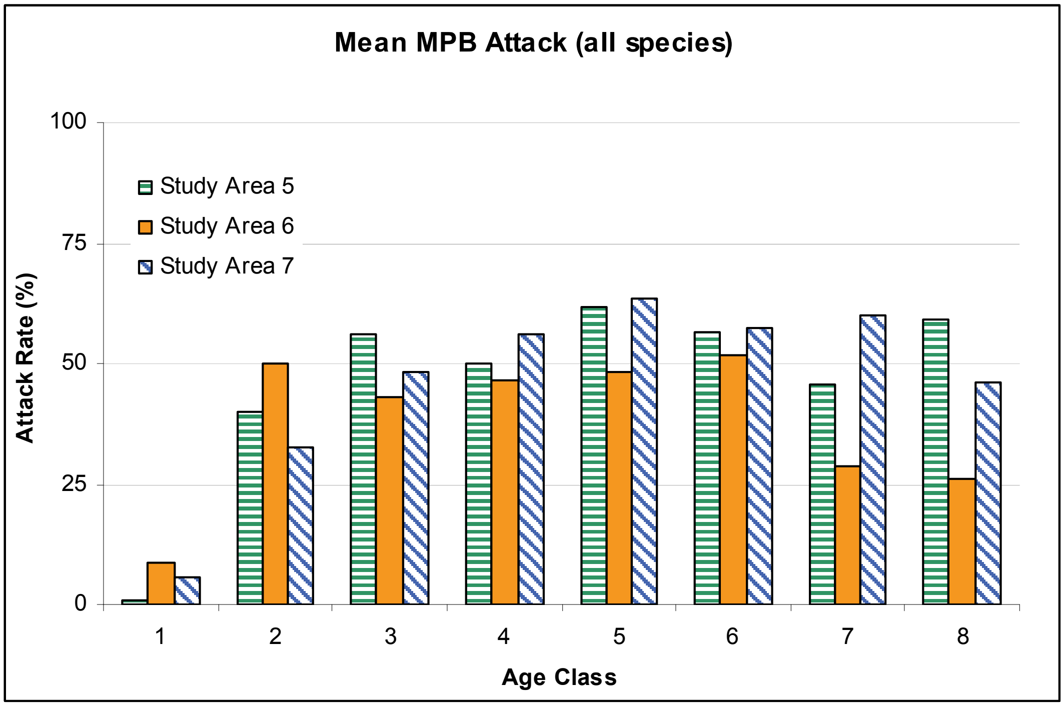


Figure 5. Mean mountain pine beetle attack rate for all tree species from study areas 5, 6 and 7.

The percentage of trees attacked by MPB, when considering all species, was significantly lower than those in Figure 3 (pine only). This occurs because mature stands have an increased amount of other species. The increase is primarily in sub-alpine fir, aspen and spruce. Generally, non-pine species were not attacked by the beetle. Black and interior spruce are the two exceptions but the attack rate is less than one percent for both species.

The increase in non-pine species with age class is consistent with the shift in BEC subzones and variants. Study Area 5 encompasses drier, warmer subzones than Study Area 6. With a decrease in temperature and an increase in moisture, species other than pine were found.

For age class 2 stands, the pine site index ranged from just under 20 in the mc2 to just under 23 in the wk1 subzones (Figure 6).

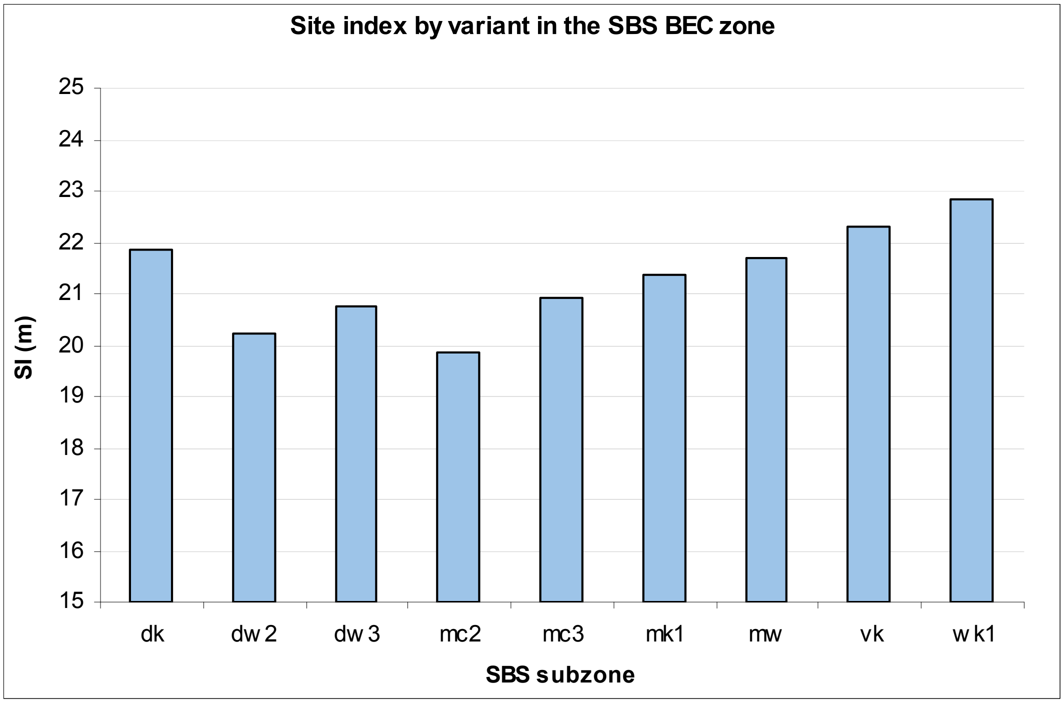


Figure 6. Site Index for age class 2 by SBS subzone for lodgepole pine trees**.**

There was no correlation of site index to the incidence of MPB, at least not in the current epidemic. Therefore, attack rates in age class 2 stands do not appear to be influenced by site productivity in the sampled areas. In endemic situations these results may vary but it is unlikely age class 2 stands would be attacked. Also, the calculated site index was generally larger than the site index from the forest inventory.

3.3 Basal area reduction

The basal area reduction refers to the difference between the basal area (m^2/ha) of the stands before and after the MPB infestation. All attacked lodgepole pine trees (including green attack lodgepole pine trees) were removed for the post MPB basal area calculation. Green attacked trees however, may not be killed by MPB, as was found in re-measurent assessments. Other than for age class 1, the basal area was markedly reduced as a result of MPB attack (Figure 7).

Figure 7. Mean Tree Basal Area by age class before and after the mountain pine beetle attacks, considering lodgepole pine only, in all study areas combined.

This illustrates the MPB's tendency to thin from above. The difference between the live basal areas before and after MPB attack started at age class 2 and increased significantly to age class 8. This difference between pre- and post-attack basal area in age classes 2 to 8 reflects the beetle preference for larger diameter trees as these are attacked first.

Mean basal area by age class pre- and post-beetle attack for all species and all study areas was also reduced (Figure 8).

Figure 8. Mean tree basal area by age class before and after mountain pine beetle attack, considering all species, in all study areas combined.

The live basal area for all species was higher than for lodgepole pine (Figure 7) and the same general trend was displayed. It indicates that other species compose, for instance, around 51.5% of the basal area in age class 4 before the attack. After attack, the basal area for the same age class is 62.6% greater for all species than just for pine.

Thus, for some stands, the mortality and loss of attacked pines would promote more light in the stand structure allowing the other species to release and develop. If left alone, these stands could contribute to the medium- and long-term wood supply.

3.4 Stand metrics which affect the amount of mountain pine beetle attack in pine-leading stands

Regression analyses were used to evaluate the importance of stand level variables (metrics) in the attack risk by MPB to lodgepole pine trees.

The scheme designed to analyze the stand metrics that affect MPB attack was defined based on age class, maturity of the stand and the biogeoclimatic subzone and variants in the study area. In each case, the analysis methodology adopted was a logistic (logit) regression because the measured attack in the field was a categorical value (attacked or not attacked) using SYSTAT v.11.

3.4.1 Age class analyses

The observed data were adjusted with logistic regressions. These data portray MPB attack in lodgepole pine trees (0 for live trees and 1 for dead trees) for different stand metrics. Figure 9 shows the distribution of attack intensity by DBH for all age classes.

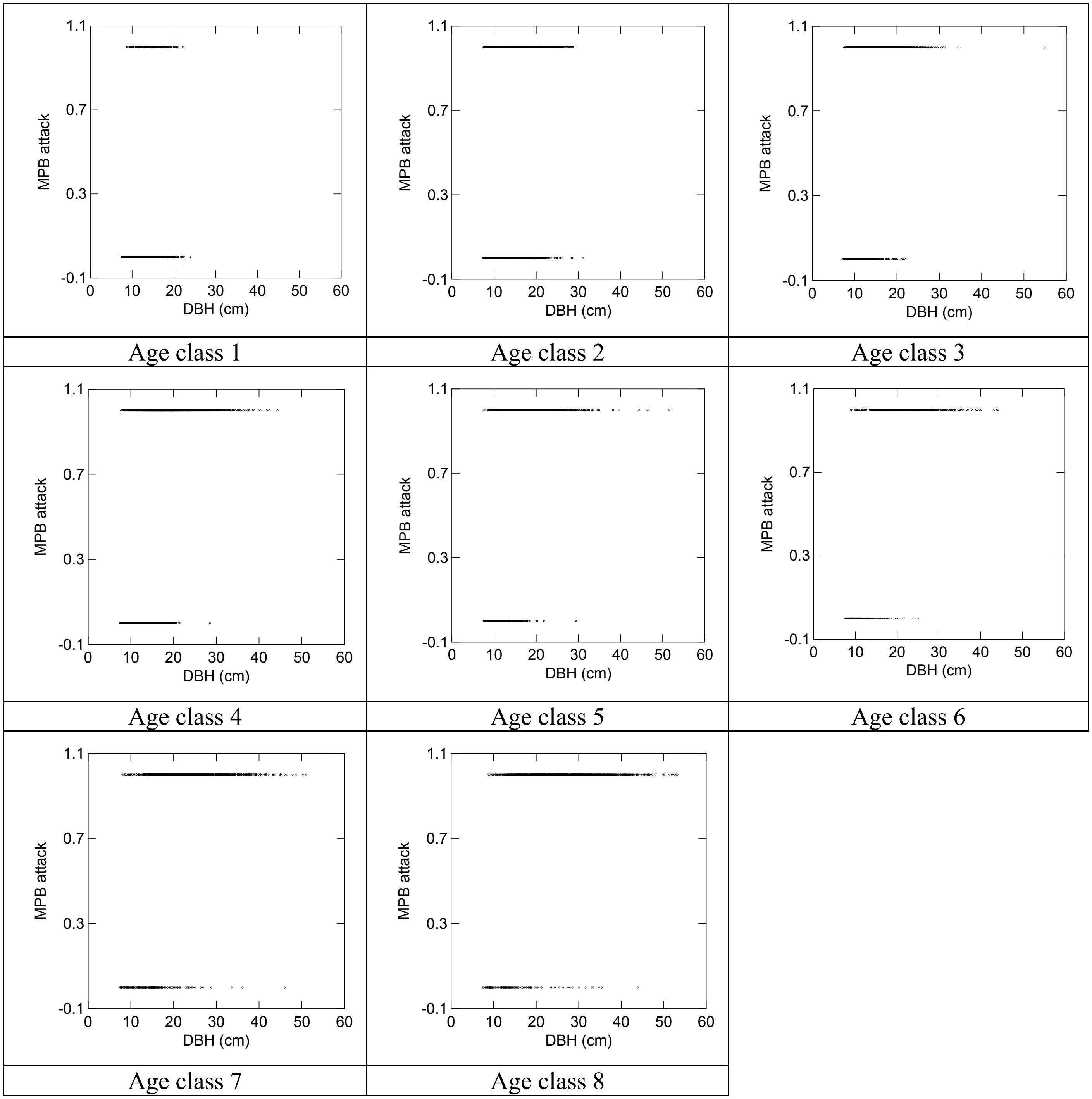


Figure 9. Distribution of observed MPB attack within age classes.

Based on MPB attack, DBH and other stand metrics, regressions were made to estimate MPB attack risk. For each age class, a specific regression was constructed. Within these defined models, the observed data were used in the equation to generate a predicted behaviour for MPB attack (or MPB attack risk).

3.4.1.1 Age class 1

The adjusted logistical equation for age class 1 is as follows:

MPB = -14.48379 + 0.35899*DBH + 0.28618*SI – 0.00041*Pha + 0.00069*Tha

(McFadden's R-Squared = 0.20698 – Conf. Interv. = 95%) – number of samples: 3053

Where: MPB = mountain pine beetle attack rate (0 for live tree and 1 for dead tree);
DBH = diameter at breast height;
SI = site index (meters – at 50 years);
Pha = number of pine trees per hectare;
Tha = total number of trees per hectare (for all species present).

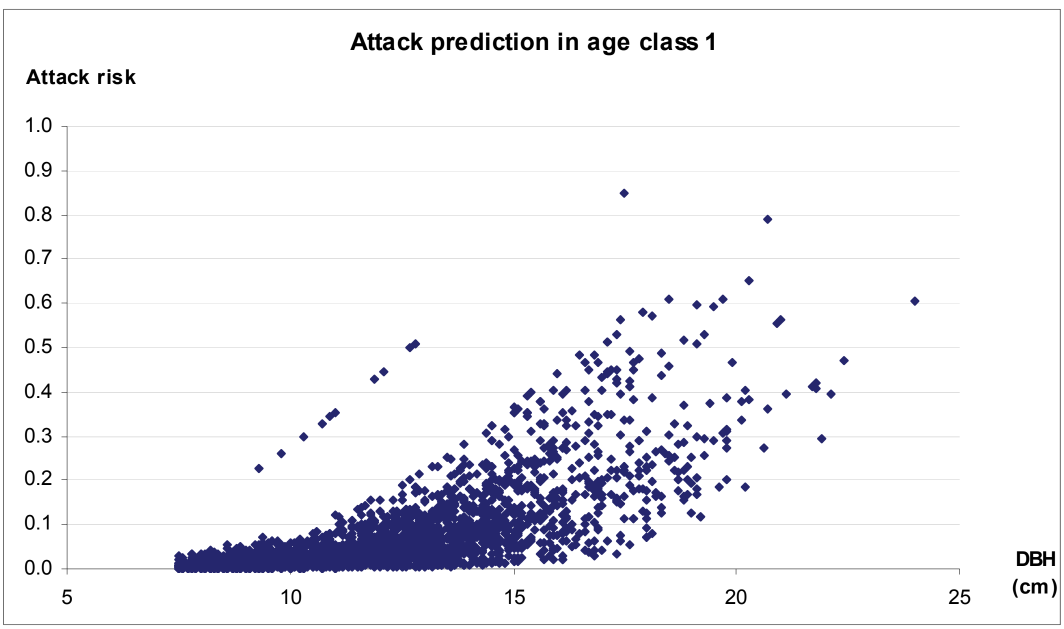


Figure 10. Distribution of predicted MPB attack risk in age class 1 using observed data in adjusted equation (Attack risk 0 for live tree, and 1 for dead tree).

3.4.1.2 Age class 2

The adjusted logistical equation for age class 2 is as follows:

MPB = - 6.56138 + 0.33978*DBH + 0.06972*SI + 0.00111*Pha - 0.00072*Tha

(McFadden's R-Squared = 0.19169 – Conf. Interv. = 95%) – number of samples: 8300

Where: MPB = mountain pine beetle attack rate (0 for live tree and 1 for dead tree);
DBH = diameter at breast height;
SI = site index (meters – at 50 years);
Pha = number of pine trees per hectare;
Tha = total number of trees per hectare (for all species present).

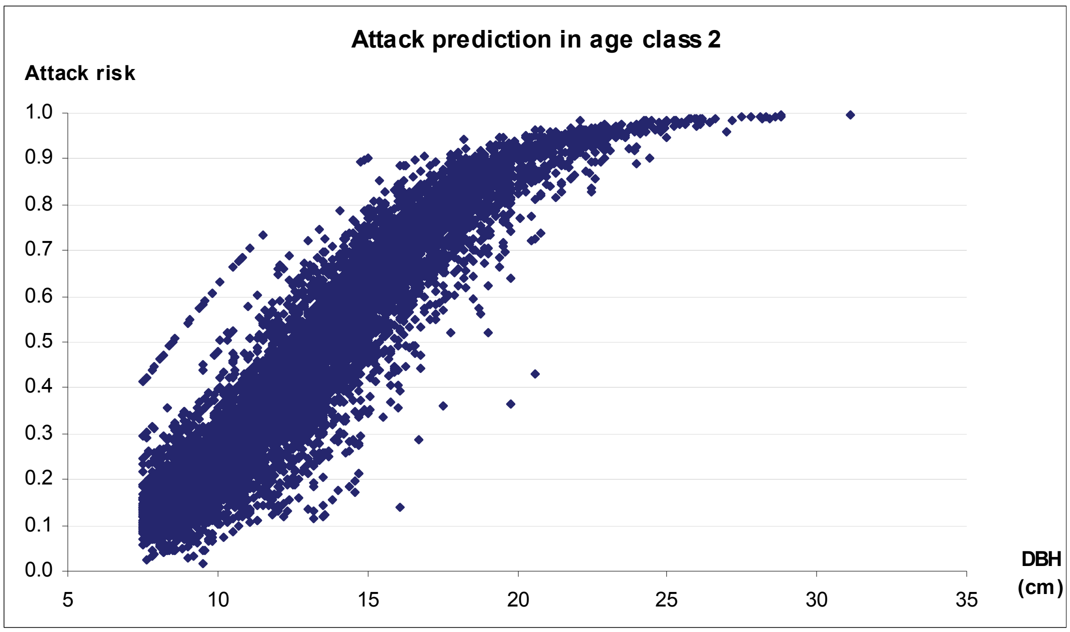


Figure 11. Distribution of predicted MPB attack risk in age class 2 using observed data in adjusted equation (attack risk 0 for live tree, and 1 for dead tree).

3.4.1.3 Age class 3

The adjusted logistical equation for age class 3 is as follows:

MPB = - 6.17504 + 0.55277*DBH - 0.04465*SI + 0.00016*Pha + 0.00009*Tha

(McFadden's R-Squared = 0.34256 – Conf. Interv. = 95%) – number of samples: 2281

Where: MPB = mountain pine beetle attack rate (0 for live tree and 1 for dead tree);
DBH = diameter at breast height;
SI = site index (meters – at 50 years);
Pha = number of pine trees per hectare;
Tha = total number of trees per hectare (for all species present).

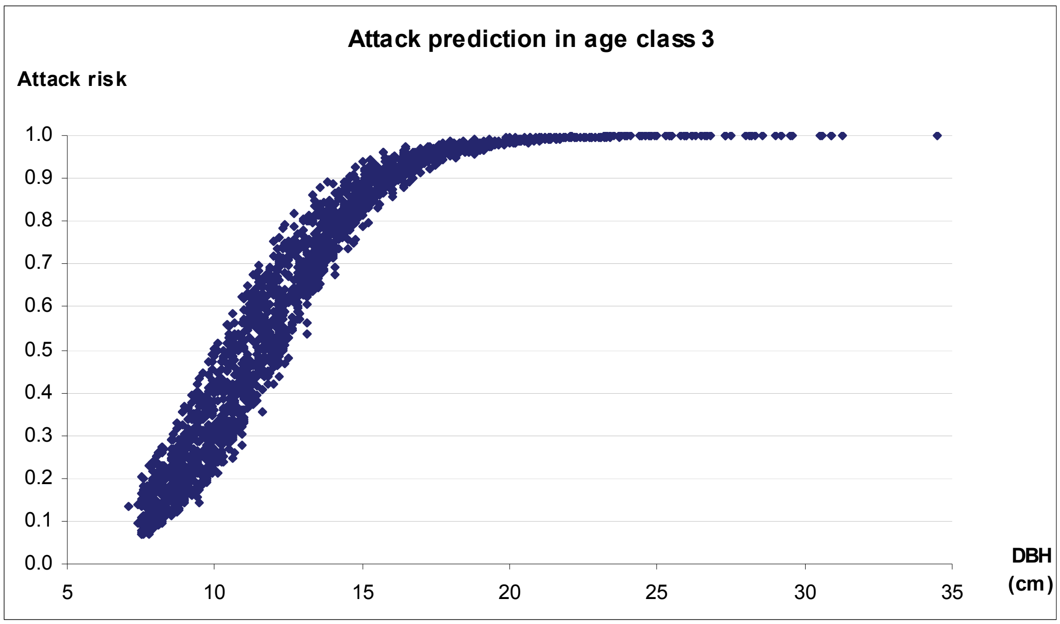


Figure 12. Distribution of predicted MPB attack risk in age class 3 using observed data in adjusted equation (attack risk 0 for live tree, and 1 for dead tree).

The reduction in the spread of the response between age class 2 and 3 demonstrates the MPB's affinity for stands with more trees with large DBH. This can also be seen with the plots of the older age classes.

3.4.1.4 Age class 4

The adjusted logistical equation for age class 4 is as follows:

MPB = - 6.46880 + 0.42291*DBH + 0.03636*SI + 0.00037*Pha - 0.00015*Tha

(McFadden's R-Squared = 0.36972 – Conf. Interv. = 95%) – number of samples: 3381

Where: MPB = mountain pine beetle attack rate (0 for live tree and 1 for dead tree);
DBH = diameter at breast height;
SI = site index (meters – at 50 years);
Pha = number of pine trees per hectare;
Tha = total number of trees per hectare (for all species present).

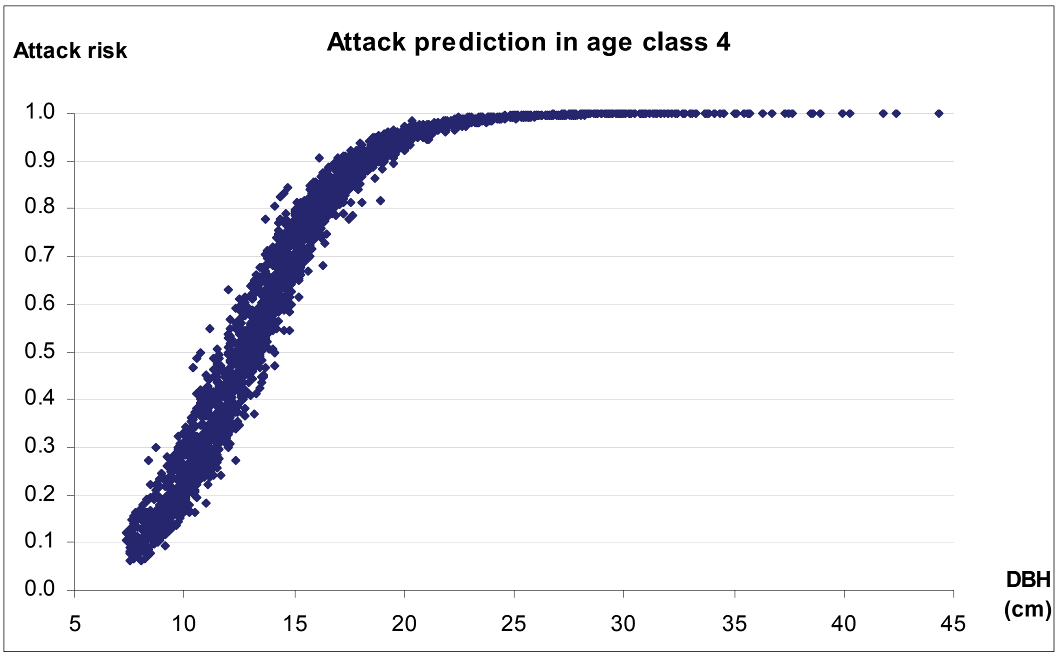


Figure 13. Distribution of predicted MPB attack risk in age class 4 using observed data in adjusted equation (Attack risk 0 for live tree, and 1 for dead tree).

3.4.1.5 Age class 5

In age classes 5 through 8, due to the low influence of the number of stems per hectare for prediction significance, the number of pine trees and the total number of trees per hectare were not included.

The adjusted logistical equation for age class 5 is as follows:

MPB = - 3.64198 + 0.46034*DBH - 0.11193*SI

(McFadden's R-Squared = 0.34246 – Conf. Interv. = 95%) – number of samples: 1140

Where: MPB = mountain pine beetle attack rate (0 for live tree and 1 for dead tree);
DBH = diameter at breast height;
SI = site index (meters – at 50 years).

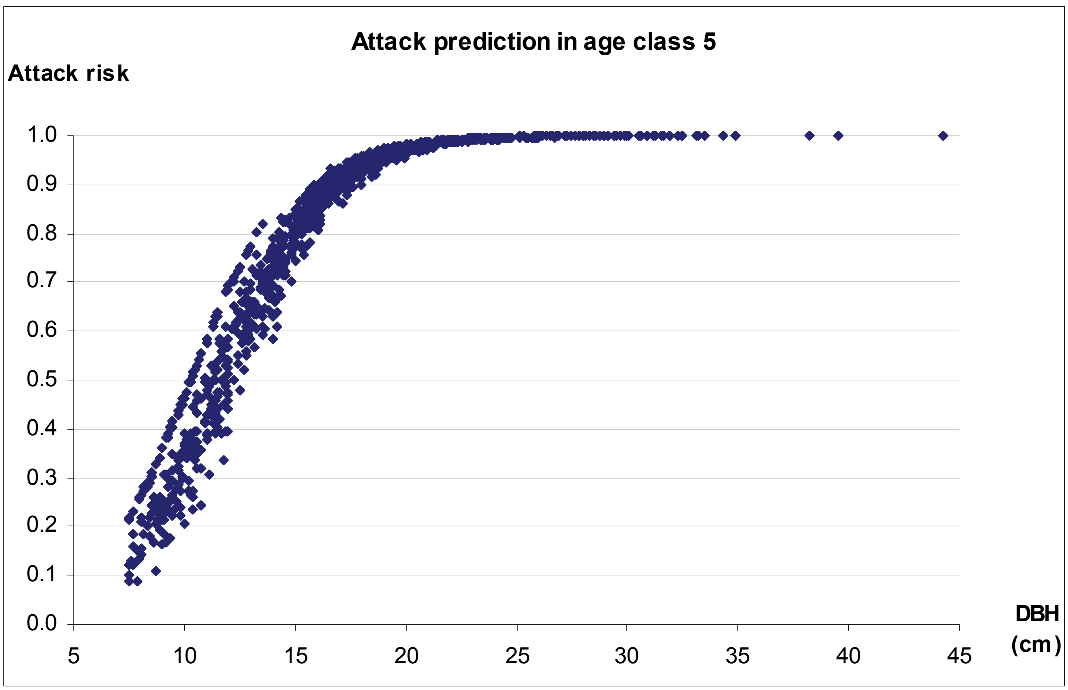


Figure 14. Distribution of predicted MPB attack risk in age class 5 using observed data in adjusted equation (Attack risk 0 for live tree, and 1 for dead tree).

3.4.1.6 Age class 6

The adjusted logistical equation for age class 6 is as follows:

MPB = - 8.94326 + 0.47442*DBH + 0.17640*SI

(McFadden's R-Squared = 0.48668 – Conf. Interv. = 95%) – number of samples: 743

Where: MPB = mountain pine beetle attack rate (0 for live tree and 1 for dead tree);
DBH = diameter at breast height;
SI = site index (meters – at 50 years).

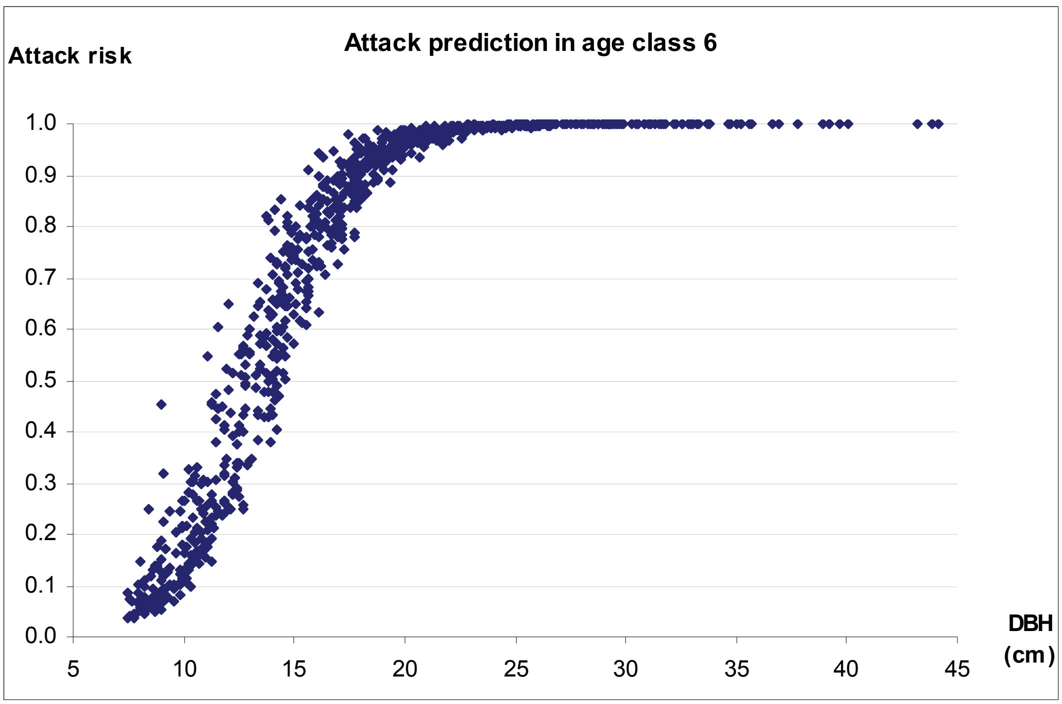


Figure 15. Distribution of predicted MPB attack risk in age class 6 using observed data in adjusted equation (Attack risk 0 for live tree, and 1 for dead tree).

3.4.1.7 Age class 7

The adjusted logistical equation for age class 7 is as follows:

MPB = - 2.54788 + 0.27637*DBH - 0.06013*SI

(McFadden's R-Squared = 0.29113 – Conf. Interv. = 95%) – number of samples: 1175

Where: MPB = mountain pine beetle attack rate (0 for live tree and 1 for dead tree);
DBH = diameter at breast height;
SI = site index (meters – at 50 years).

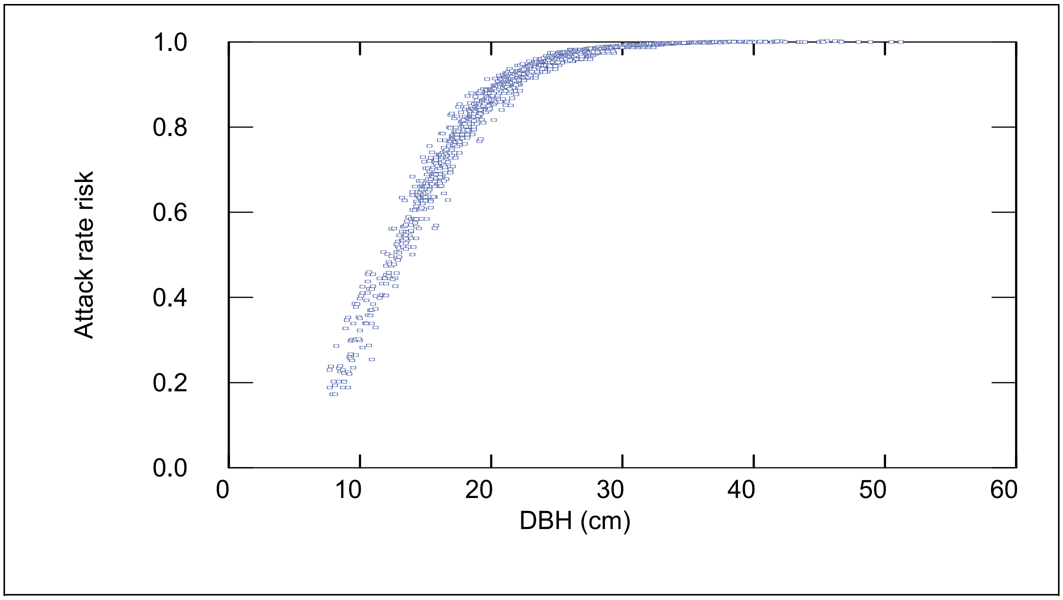


Figure 16. Distribution of predicted MPB attack risk in age class 7 using observed data in adjusted equation (Attack risk 0 for live tree, and 1 for dead tree).

3.4.1.8 Age class 8

The adjusted logistical equation for age class 8 is as follows:

MPB = - 1.59091 + 0.25746*DBH - 0.06671*SI

(McFadden's R-Squared = 0.26752 – Conf. Interv. = 95%) – number of samples: 1448

Where: MPB = mountain pine beetle attack rate (0 for live tree and 1 for dead tree);
DBH = diameter at breast height;
SI = site index (meters – at 50 years).

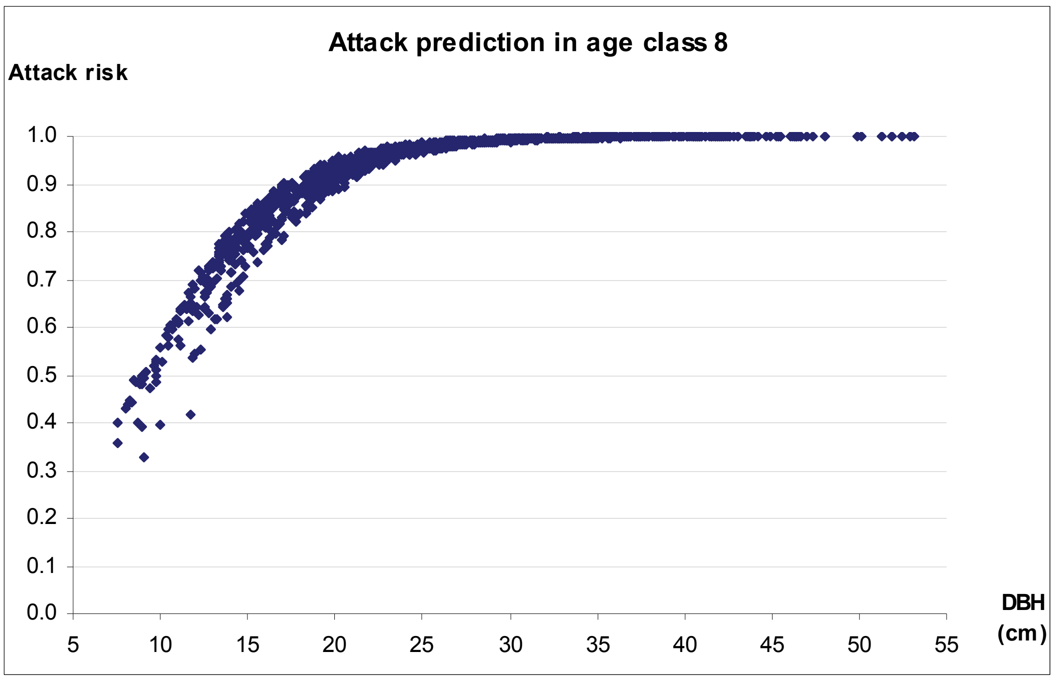


Figure 17. Distribution of predicted MPB attack risk in age class 8 using observed data in adjusted equation (Attack risk 0 for live tree, and 1 for dead tree).

3.4.1.9 Age class discussion

In general, diameter (based on DBH) is the variable that displayed the greatest relationship with MPB attack (Anhold and Long 1996; Shore et al. 2000). However, other variables, such as site index and stand density, help to refine predictions about risk of attack in pine-leading stands. Stand density contributes to the prediction of MPB attack risk in age classes 1 to 4.

When age classes are analyzed separately, the McFadden's R-squared index, which gives goodness of fit measures for nonlinear estimators, shows that stand metrics better explain MPB risk of attack for certain age classes (Figure 18).

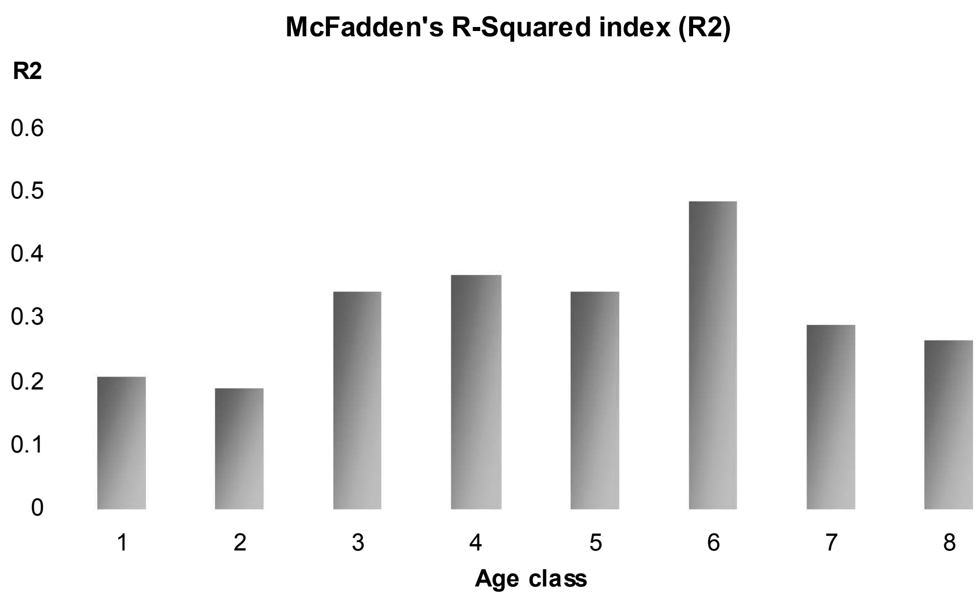


Figure 18. Tendency of McFaddens R-squared index within age classes**.**

The better model fit for age classes 3 to 6 is possibly due to increasing DBH with age class. The drop after age class 6 could result from natural stand processes: increased natural mortality (stand break-up) in pine stands, and recruitment of other tree species. The lower value for age class 1 and 2 reflects the high variability of attack associated with this age class as well as their smaller DBH. Another reason is that the epidemic condition makes the insects less selective for host trees, attacking large and small pine and, to a small degree, spruce.

Other stand characteristics just refine the analysis. According to Amman (1978), this is not the expected behaviour in endemic states, where the stress carried by trees influences the healthy tree condition.

3.4.2 Stand maturity

Stand maturity is divided into two sections: immature (age class 1 to 4) and mature (age class 5 to 8) stands.

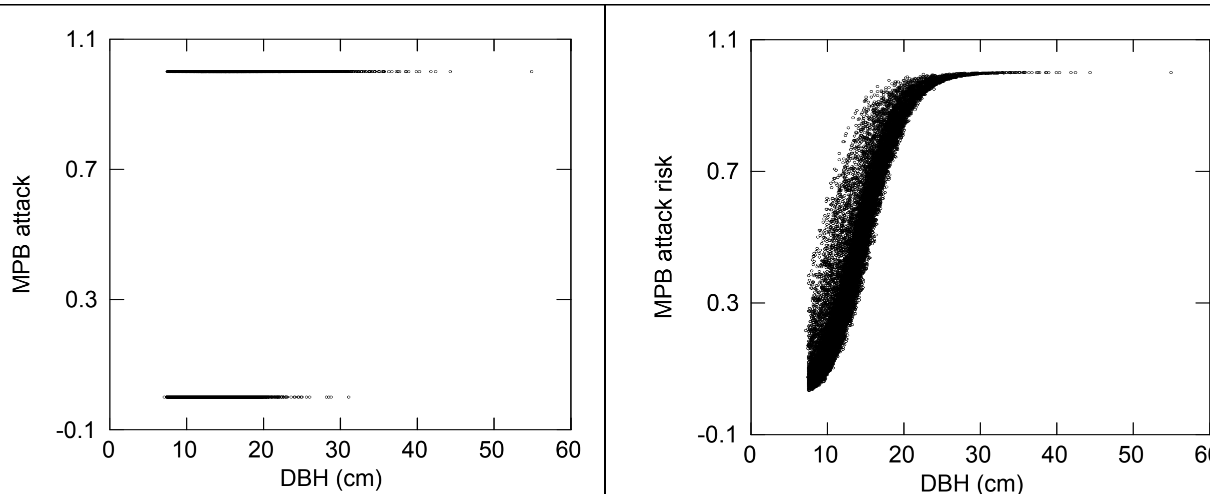
3.4.2.1 Immature stands

The adjusted logistical equation for immature stands (Figure 19) is as follows:

MPB = - 6.21851 + 0.39947*DBH - 0.01449*SI + 0.00059*Pha - 0.00004*Tha

(McFadden's R-Squared = 0.26355 – Conf. Interv. = 95%) – number of samples: 17015

Where: MPB = mountain pine beetle attack rate (0 for live tree and 1 for dead tree);
DBH = diameter at breast height;
SI = site index (meters – at 50 years);
Pha = number of pine trees per hectare;
Tha = total number of trees per hectare (for all species present).



Distribution of observed MPB attack in immature stands (MPB attack for live tree and 1 for dead tree).

Distribution of predicted MPB attack rate risk in immature stands using observed data in adjusted equation (MPB attack risk 0 for live tree and 1 for dead tree).

Figure 19. Observed MPB attack and predicted MPB attack risk in immature stands.

3.4.2.2 Mature stands

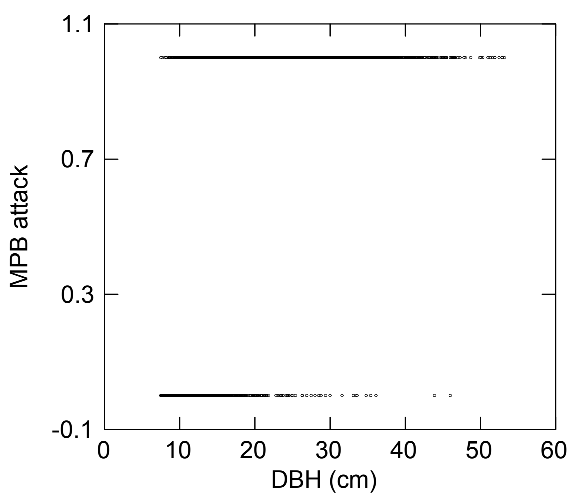
Because stand density had little influence on the prediction significance for mature stands, the number of pine trees and total number of trees per hectare were not included in the model (Figure 20).

The adjusted logistical equation for age class 6 is as follows:

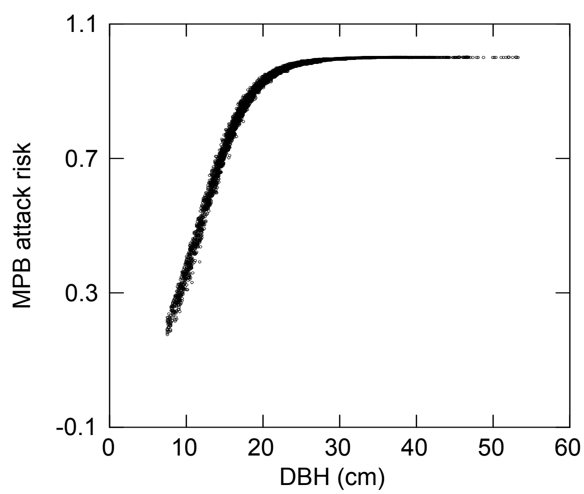
MPB = - 3.32236 + 0.32482*DBH - 0.03479*SI

(McFadden's R-Squared = 0.33569 – Conf. Interv. = 95%) – number of samples: 4506

Where: MPB = mountain pine beetle attack rate (0 for live tree and 1 for dead tree);
DBH = diameter at breast height;
SI = site index (meters – at 50 years).



Distribution of observed MPB attack in mature stands (MPB attack for live tree and 1 for dead tree).



Distribution of predicted MPB attack rate risk in mature stands using observed data in adjusted equation (MPB attack risk 0 for live tree and 1 for dead tree).

Figure 20. Observed MPB attack and predicted MPB attack risk in mature stands.

3.4.2.3 Stand maturity discussion

In both immature and mature stands, the relatively low R^2 for the adjusted equations can be attributed to the large number of attacked trees with small diameters and some non-attacked trees with larger diameters. The larger non-attacked trees may have genetic resistance to MPB attack.

3.4.3 Predictors by biogeoclimatic zone

In this section, biogeoclimatic zones were set as statistical treatments for regression. Within the study area, ten BEC subzones with pine-leading stands were sampled.

The observed data were adjusted with logistic regressions. These data describe MPB attack in lodgepole pine trees (0 for live trees and 1 for dead trees) with different stand metrics. Figure 21 shows the distribution of attack intensity by DBH for each of the studied BEC zones.

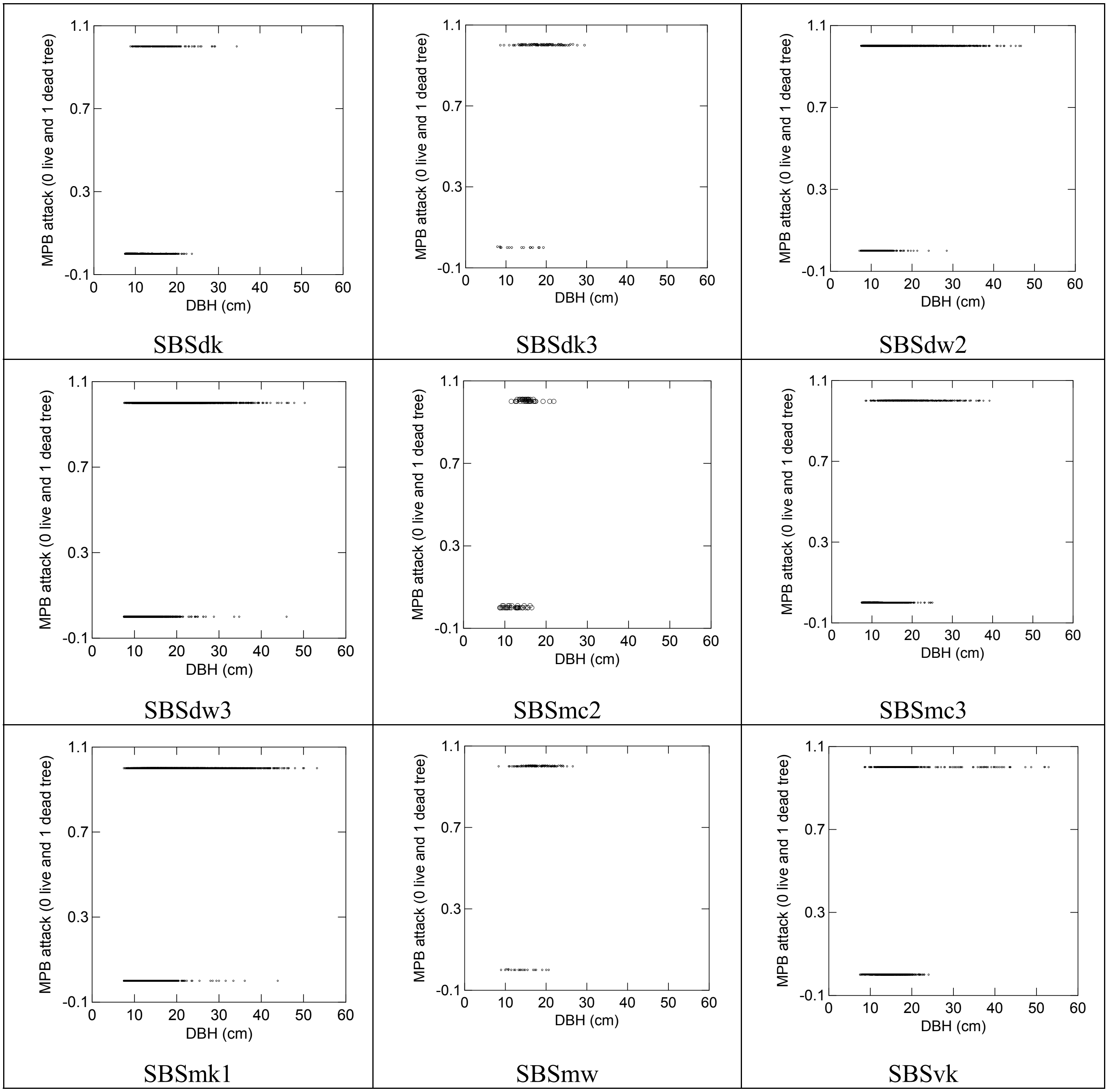


Figure 21. Distribution of observed MPB attack by BEC zone (continued on next page).

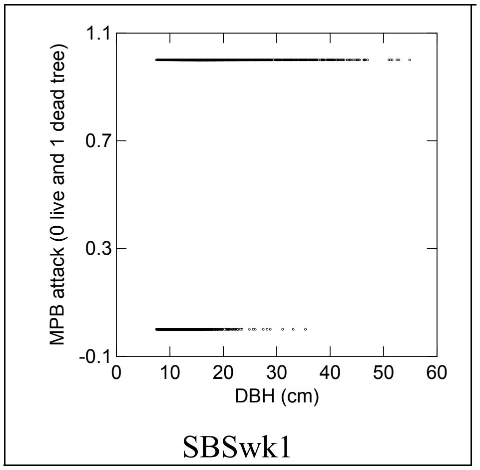


Figure 21. Distribution of observed MPB attack by BEC zone (continued from previous page).

Based on MPB attack, DBH and other stand metrics, a logistic regression was estimated for each BEC subzone a different regression was estimated (Table 4).

3.4.3.1 Adjusted equations for MPB attack risk by biogeoclimatic zone

Table 4. Adjusted equations for MPB attack risk by biogeoclimatic zone.

BECzone	Adjusted equation	McFadden's R-Squared	Number of samples
SBSdk	MPB = -5.72315 + 0.34084*DBH – 0.05093*SI	0.19270	1676
SBSdk3	MPB = 1.86167 + 0.33267*DBH – 0.32481*SI	0.25929	101
SBSdw2	MPB = -6.00110 + 0.56724*DBH – 0.00257*SI	0.34036	3028
SBSdw3	MPB = -4.90515 + 0.39536*DBH + 0.00065*SI	0.32498	4847
SBSmc2	MPB = -47.55395 + 1.26770*DBH + 1.57984*SI	0.48339	73
SBSmc3	MPB = -3.55499 + 0.42132*DBH – 0.18544*SI	0.39592	1211
SBSmk1	MPB = -3.26936 + 0.41497*DBH – 0.13541*SI	0.38129	5487
SBSmw	MPB = -12.04439 + 0.36996*DBH + 0.34052*SI	0.19164	122
SBSvk	MPB = -5.21205 + 0.24039*DBH + 0.04331*SI	0.16093	950
SBSwk1	MPB = -5.15148 + 0.42210*DBH – 0.03640*SI	0.36260	4019

Where: MPB = mountain pine beetle attack rate (0 is alive tree and 1 is dead tree);
DBH = diameter at breast height;
SI = site index (meters – at 50 years).

3.4.4 Discussion of the predictors by biogeoclimatic zone

The distribution of R-squared for the adjusted equations in each BEC subzone are variable (Figure 22). It is possible to detect better predictability in some subzones. Generally, these are the subzones with larger sample sizes. The predictability of MPB attack risk by BEC subzones does not appear to be directly related to potential productivity.

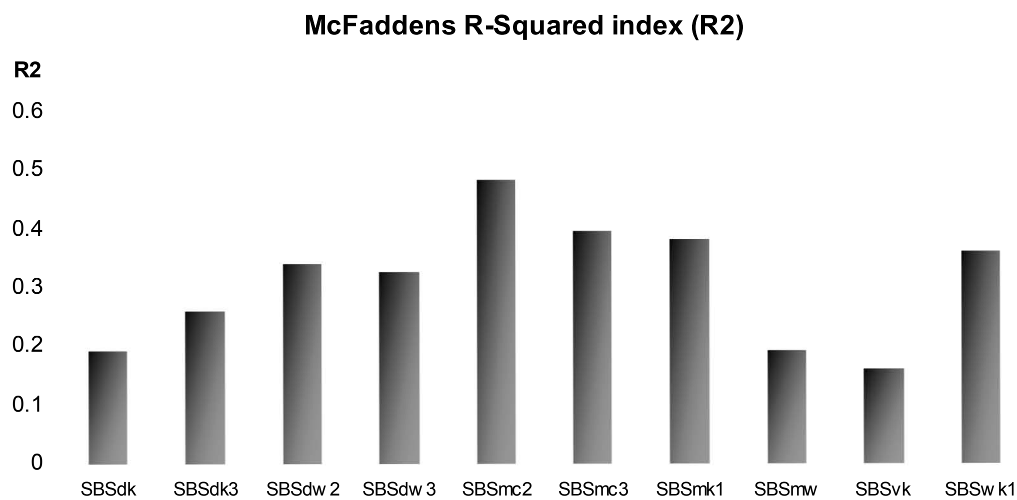


Figure 22. Tendency of McFaddens R-squared index within BEC zones (for all age classes).

3.4.5 Residual stand structure

Table 5 depicts the amount of advanced and seedling regeneration in each plot by density (sph) class. Sph classes were: 200 (100 to 300 sph), 400 (301 to 500), and so on.

Table 5. Total number and percent of plots containing advanced and seedling regeneration by stems per hectare class.

	SPH CLASS																					
Age Class	No Regen		200		400		600		800		1000		1200		1400		1600		1800		>2000	
	#	%	#	%	#	%	#	%	#	%	#	%	#	%	#	%	#	%	#	%	#	%
1	13	4.8	14	5.2	14	5.2	18	6.7	26	9.7	11	4.1	16	5.9	13	4.8	15	5.6	5	1.9	124	46.1
2	63	8.5	59	8.0	58	7.8	49	6.6	45	6.1	41	5.5	53	7.2	30	4.1	33	4.5	31	4.2	277	37.5
3	20	10.6	11	5.8	14	7.4	11	5.8	5	2.6	7	3.7	2	1.1	11	5.8	8	4.2	4	2.1	96	50.8
4	45	12.9	35	10.0	34	9.7	17	4.9	23	6.6	19	5.4	9	2.6	15	4.3	10	2.9	14	4.0	129	36.9
5	20	15.9	12	9.5	3	2.4	8	6.3	11	8.7	6	4.8	4	3.2	4	3.2	3	2.4	6	4.8	49	38.9
6	14	13.2	5	4.7	5	4.7	5	4.7	4	3.8	7	6.6	4	3.8	5	4.7	3	2.8	2	1.9	52	49.1
7	22	9.8	21	9.3	15	6.7	8	3.6	14	6.2	7	3.1	11	4.9	7	3.1	6	2.7	8	3.6	106	47.1
8	25	9.0	15	5.4	24	8.6	10	3.6	9	3.2	12	4.3	11	4.0	3	1.1	15	5.4	6	2.2	148	53.2

Age class 1 to 3 stands have significant amounts of advanced and seedling regeneration. At the plot level, 85, 76, and 75% of TSPs (respectively) have greater than 600 sph of advanced and seedling regeneration. Only 4.8, 8.5, and 10.6% of TSPs (respectively) are void of regeneration. At the plot level, 67, 72, 77, 74, and 77% of age class 4 to 8 TSPs (respectively) have greater than 600 sph of advanced regeneration. In age class 4 through 8, 12.9, 15.9, 13.2, 9.8, and 9.0% of TSPs (respectively) are void of regeneration. At the landscape level, a higher percent of TSPs which are void of regeneration were found in mature than in immature age classes.

The majority of TSPs, in immature and mature stands, have adequate regeneration to be considered stocked even if all of the mature layer Pl were to succumb to MPB and other forest health agents (Ministry of Forests and Range 2000). However, in some instances, regeneration would be mixed broadleaf-conifer rather than pure conifer stands. The density of regeneration at the landscape, stand, and plot level is highly variable. For example, an age class 8 stand in the SBSwk1 had 1000 sph of Bl regeneration in plot 1 and 6000 sph of Bl regeneration in plot 2.

Residual stand structure by age class is presented in Figure 23. The younger age classes (1 through 3) appear to be dominated by advanced regeneration and residual mature trees, whereas regeneration in the older age classes (5 through 8) appears to be largely seedlings. Age class 4 appears to be transitional between the two. The greater amount of residual trees in the younger age classes is likely due to the lower MPB attack rates.

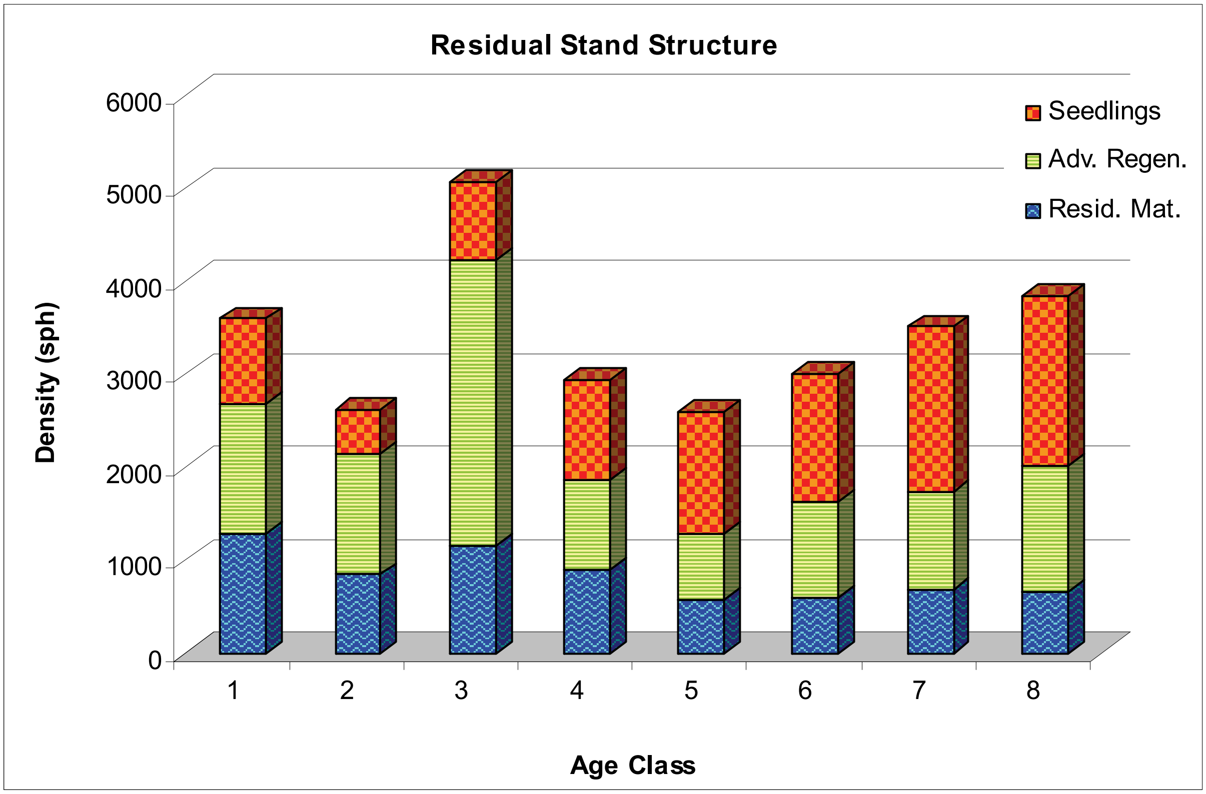


Figure 23. Residual stand structure (seedlings, advanced regeneration and residual mature) by age class.

There are no residual mature trees in the SBS mw (only one polygon was sampled) (Figure 24). There is considerable advanced regeneration in all of the SBS subzones. The SBS mc3, mk1, vk and wk1 have substantial seedling regeneration, whereas seedlings only make up a small component of the total regeneration in the remaining SBS subzones. Again, this suggests that barring the desirability of mixing species, there is adequate secondary structure in these subzones at the landscape level.

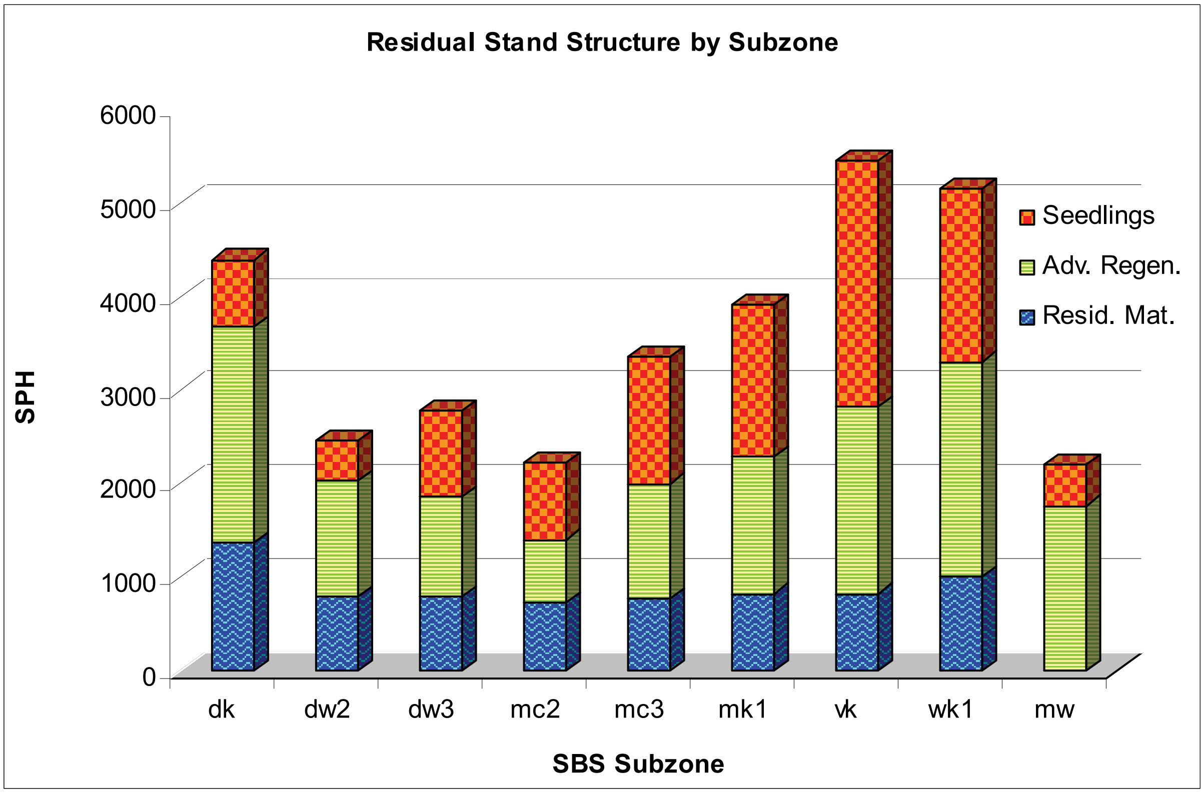


Figure 24. Residual stand structure (seedlings, advanced regeneration and residual mature) by SBS subzone.

Figure 25 shows residual mature species' composition by age class. Residual mature trees were classified as those trees DBH >7.5 cm. As expected, in the immature age classes (1 through 4), lodgepole pine, an early seral stage species, is the dominant species whereas in the mature age classes (5 through 8), there is a much greater diversity of species. The amount of spruce and sub-alpine fir increases with increased age class. In no age class is there an over- abundance of broadleaf species.

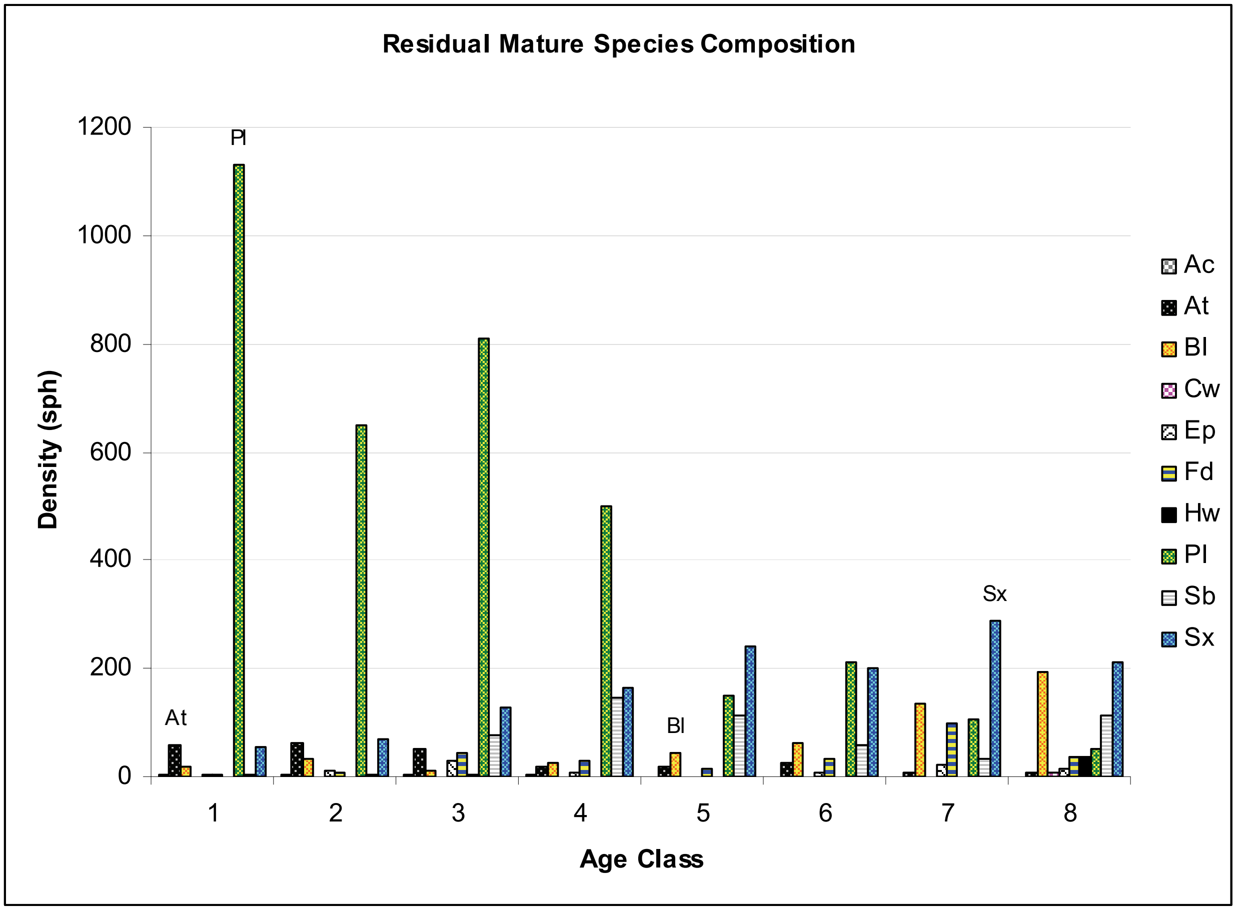


Figure 25. Residual mature species composition (Ac – black cottonwood; At – trembling aspen; Bl – subalpine fir; Ep – paper birch; Fd – Douglas-fir; Hw – western hemlock; Pl – lodgepole pine; Sb – black spruce; Sx – hybrid spruce; Cw – western red cedar) by age class.

There is a large mix of advanced regeneration species across all age classes (Figure 26). Advanced regeneration was classified as those trees greater than 1.37 m in height, but DBH <7.5 cm. Pine and spruce dominate in the younger age classes while spruce and other non- pine species dominate in the older age classes.

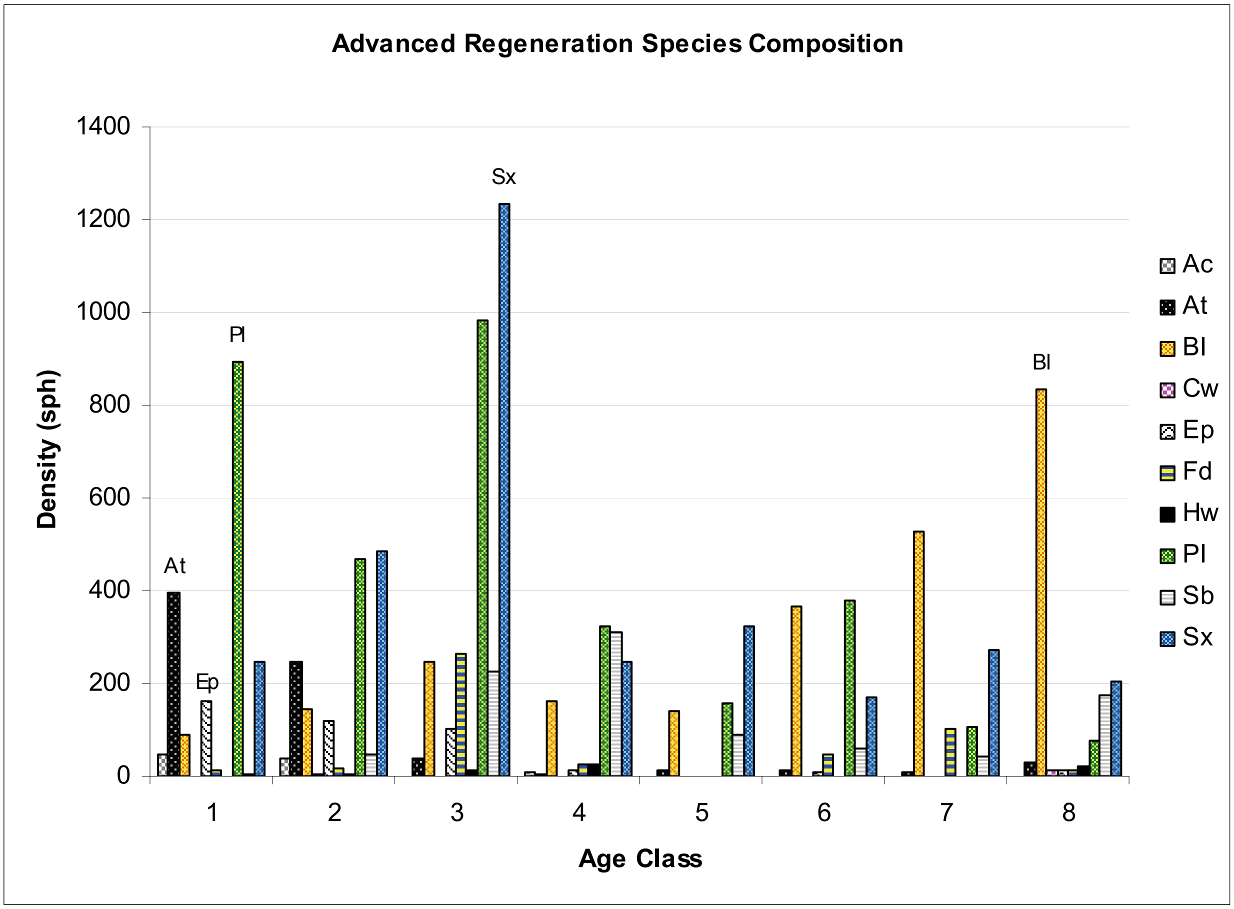


Figure 26. Advanced regeneration species composition (Bl – subalpine fir; Cw – western red cedar; Ep – paper birch; Fd – Douglas-fir; Hw – western hemlock; Pl – lodgepole pine; Sb – black spruce; Sx – hybrid spruce) by age class.

There is a large mix of seedling species across all age classes (Figure 27). Seedlings were classified as those trees smaller than 1.37 m in height. As expected, early seral stage species predominate in the younger age classes. Sub-alpine fir's presence increases with increased age class, particularly 7 and 8.

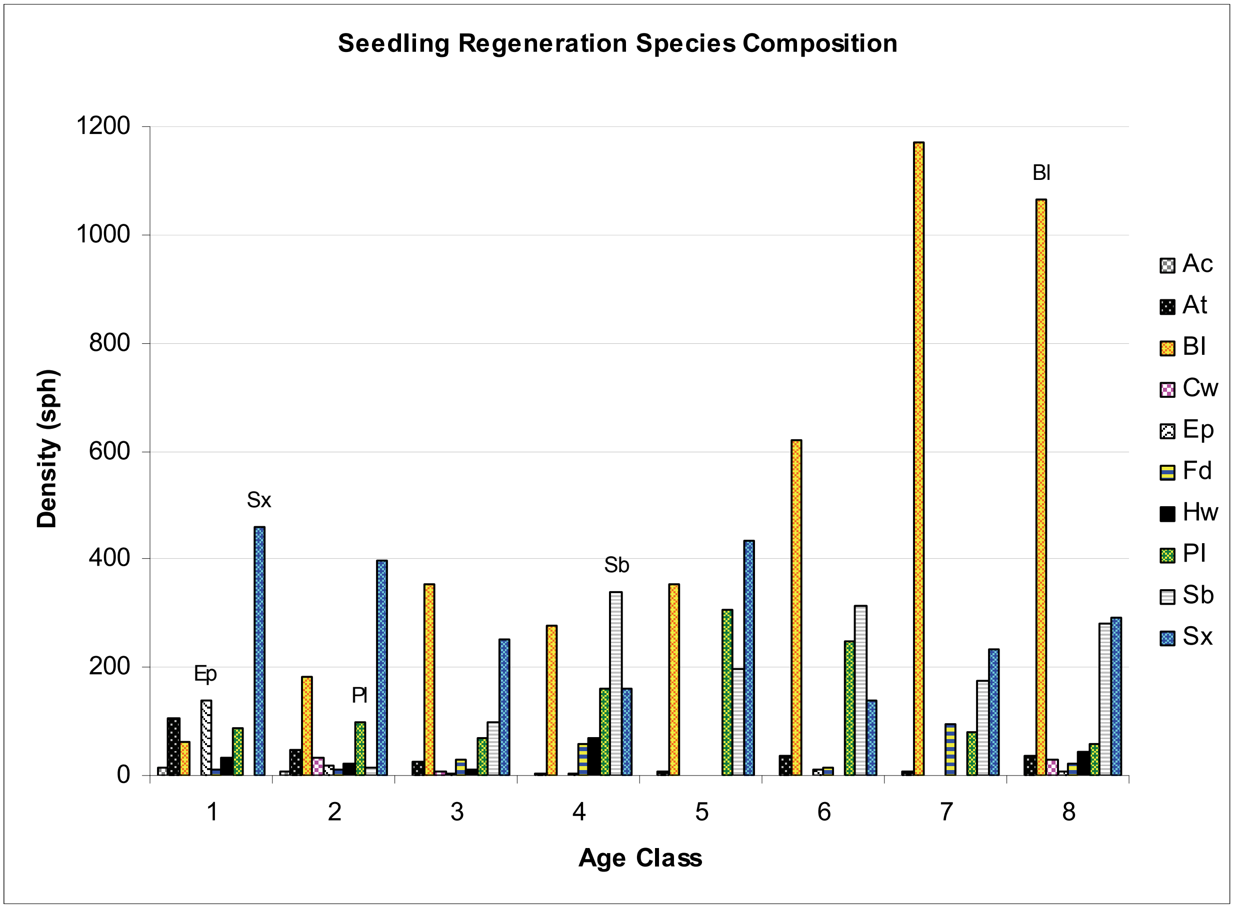


Figure 27. Seedling species composition (Ac – black cottonwood; At – trembling aspen; Bl – subalpine fir; Cw – western red cedar; Ep – paper birch; Fd – Douglas-fir; Hw – western hemlock; Pl – lodgepole pine; Sb – black spruce; Sx – hybrid spruce) by age class.

3.4.6 SORTIE-ND modelling: future forest condition

3.4.6.1 Immature stands

Six age class 2 polygons with a range (15%-96%) of MPB attack were (Table 6) were selected to be modeled in SORTIE-ND. As discussed earlier, age class 2 is the problematic immature age class from a management perspective. Age class 1 has ample time to recover prior to its expected harvest date while many age class 3 stands may be ready to log. Depending on attack levels in age class 2 stands, there are potentially several management scenarios. If attack rates are low, allow the stand to develop after MPB attack and log as planned at a rotation age of about 75 years. For moderate levels of attack, under-planting may be an option to raise yields for the planned harvest date. Finally, for extreme attack levels, the best option may be to clear the stand and start over again by planting.

Four scenarios were selected for each polygon: 1) the base case - stand development without MPB attack (Base); 2) the result of MPB attack - attacked trees proportionally removed by 2 cm DBH classes (MPB); 3) under-plant the MPB-attacked stand and allow the residual tree layer and secondary structure to develop (UPlant); and 4) clear cut the tree layer and replant with 800 sph of spruce and 800 sph of pine (Clear-Plant). Generally, there will be no revenue, only cost from the clearcut. This is the major difference between immature stands and mature stands. The assumptions for the age class 2 NPV were: a real interest rate of 3%, an initial stand establishment cost of $900 per ha, a clearing to plant cost of $1000 per ha, a planting after clearing cost of $1200 per ha, an under-planting cost of $450 per ha and stumpage as for age classes 4 to 6 (see below). For the clear cut of the immature stand, planting is an additional cost to the current stand as it has failed. Therefore, it is not charged against the future crop but is added to the cost of the stand being replaced.

Table 6. Age class 2 polygon attributes: stand age, sapling basal area, sapling and seedling sph, mature tree basal area lost to MPB, basal area lost as a percentage of total, percent MPB attack and years to projected rotation age (PRA).

Polygon	Stand age	Sapling BA m^2*	Sapling sph	Seedling sph	BA lost to MPB m^2	BA lost to MPB %	% MPB attack	PRA** years
59	32	0	160	120	7.0	16	15.1	43
528	26	0.18	280	1010	12.0	59	49.7	49
351	30	1.25	1500	800	14.0	78	55.8	45
1571	34	0.48	560	40	9.5	54	56.0	41
619	23	0.12	350	2000	10.5	84	81.2	52
235	29	0	160	445	11.7	98	96.3	46

* basal area
** time from present to projected rotation age of 75 years since establishment

The impact of low MPB attack levels (15%) has little impact on yield beyond 25 years (Figure 28). These types of stand will meet yield expectations at a projected rotation age (PRA) of 75 years which occurs in 43 years.

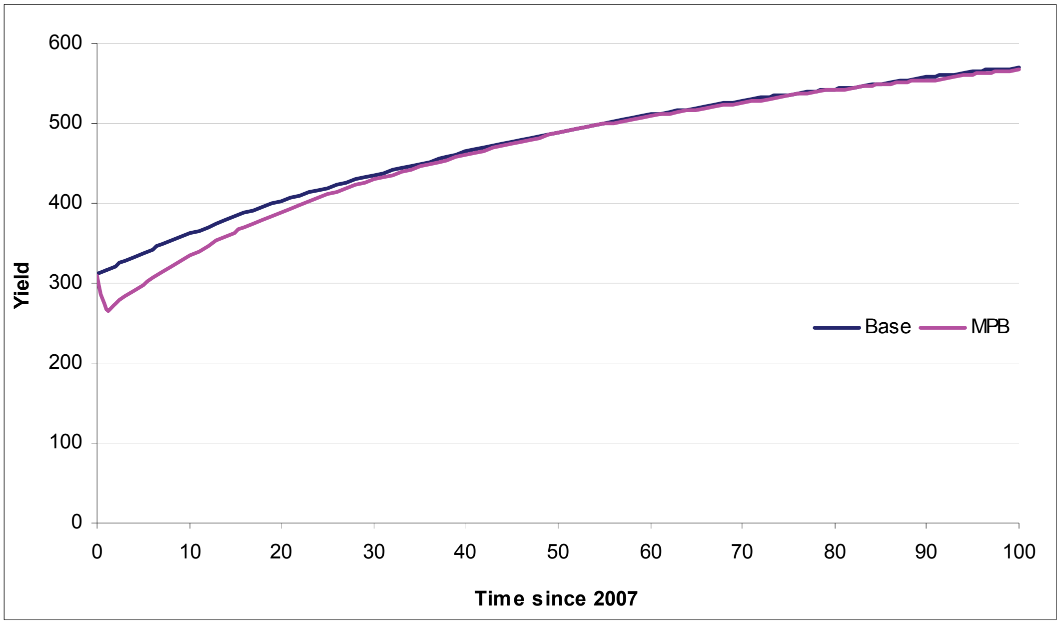


Figure 28. Projected yields for age class 2 polygon 59: MPB attack 15.1%.

At 50% MPB attack levels, the loss to MPB is about 70 m^3 at PRA in about 49 years (Figure 29). Under-planting or clearing and planting does not bring yields similar to that of the base case for about 100 years.

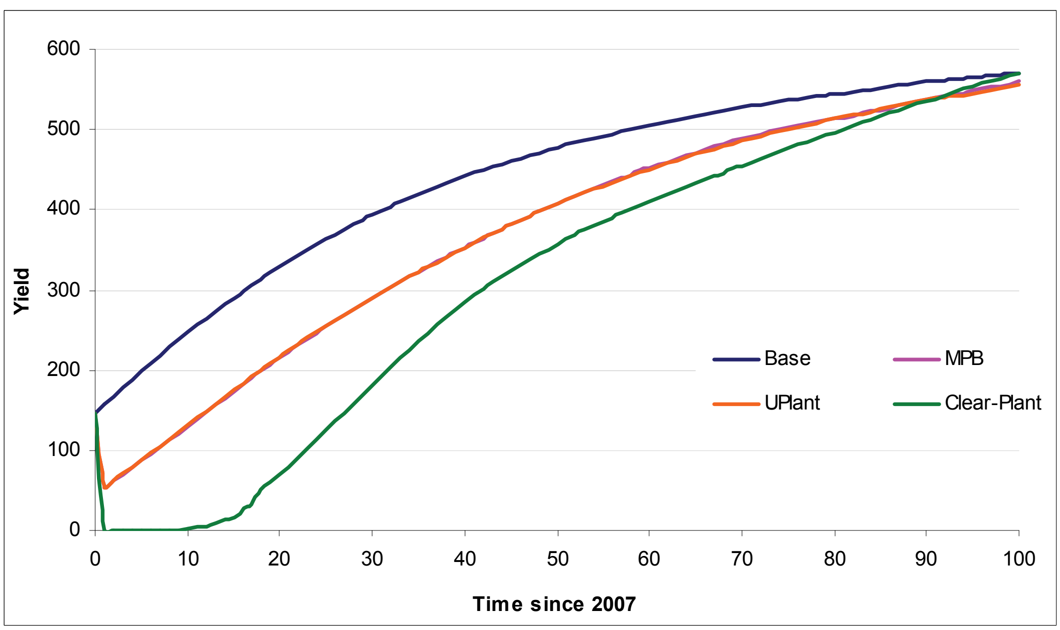


Figure 29. Projected yields for age class 2 polygon 528: MPB attack 49.7%.

Projected rotation age for polygon 351 is in 45 years and yield loss due to an MPB attack of 55% is small, about 25 m^3 (Figure 30). Within 60 years, yield from the MPB attack exceeds that of the base case as does the underplant. On the other hand, clearing and planting does not enhance yield in the time frame examined. For this polygon, likely the best management regime is to allow the stand to develop without intervention.

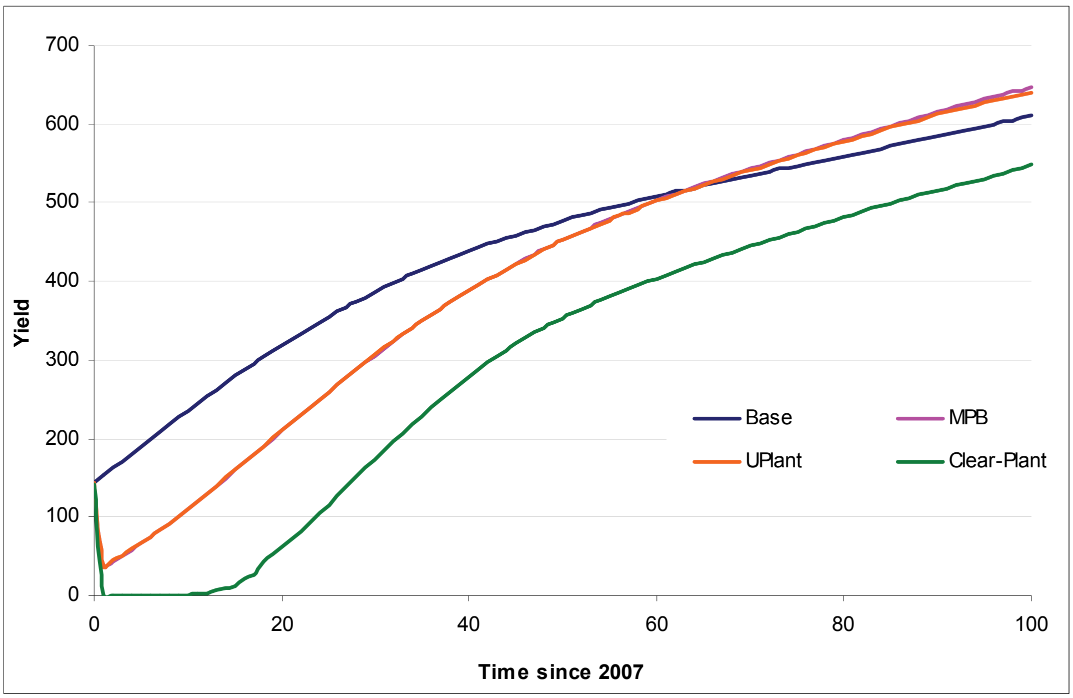


Figure 30. Projected yields for age class 2 polygon 351: MPB attack 55.8%.

The response of polygon 1571 to an MPB attack rate of 56% is similar to that of polygon 351 with a 55% attack rate (Figure 31). The two major differences are being that MPB-attacked yields take about 80 years to exceed those of the base case, and clearing and planting results in similar yields after 100 years. The accelerated development in 351 may be due to the greater number of saplings at the time of MPB attack: 1500 sph versus 560 sph in polygon 1571.

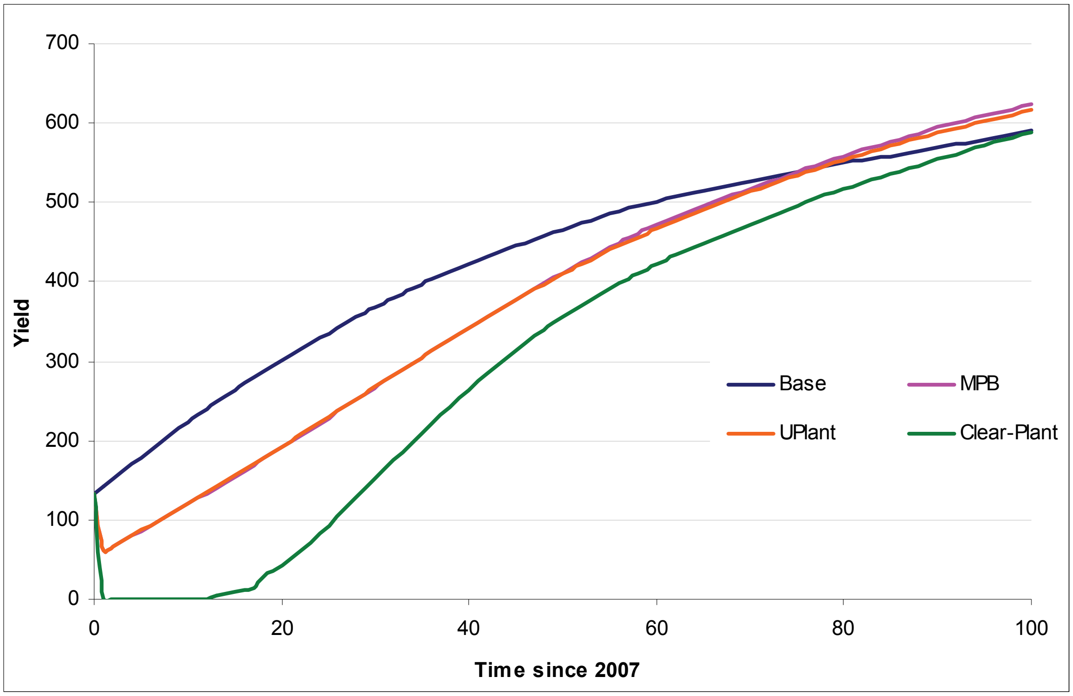


Figure 31. Projected yields for age class 2 polygon 1571: MPB attack 56.0%.

Yield for polygon 619 with an 81% MPB attack rate has been significantly reduced, particularly in the mid-term (Figure 32). Projected rotation age is in about 50 years and yields are down by about 150 m^3, but still exceed 300 m^3 for all scenarios. There is not a large difference among the three MPB management scenarios, possibly because of the small number of saplings present at the time of attack.

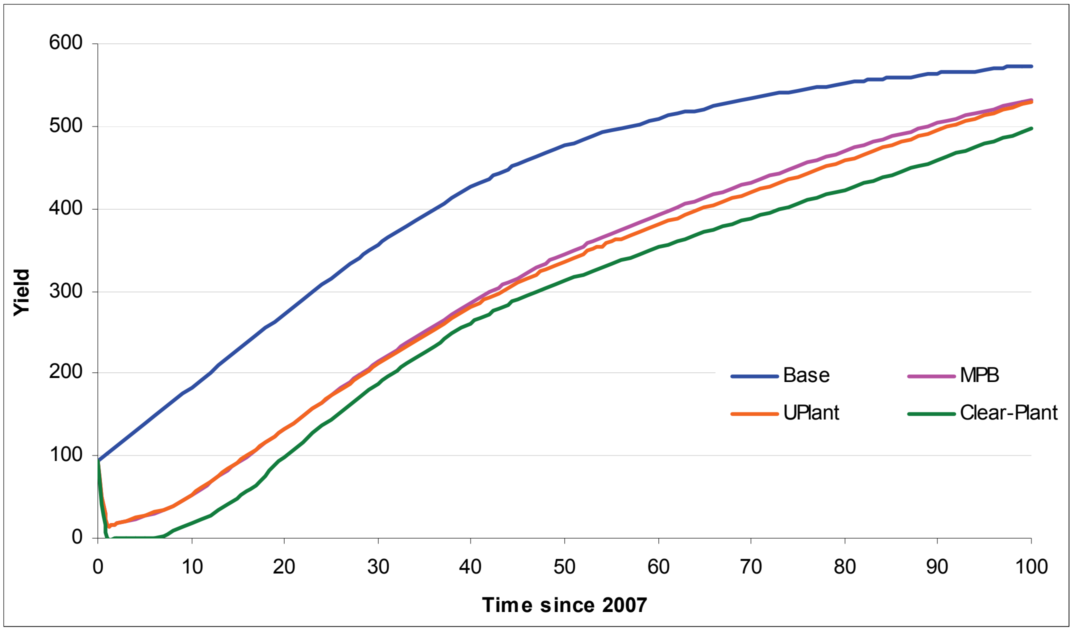


Figure 32. Projected yields for age class 2 polygon 619: MPB attack 81.2%.

Almost the entire pine layer was killed by the MPB in polygon 235: attack 96% (Figure 33). At PRA in 46 years, clearing and planting and underplanting both have significantly greater yields than allowing the MPB-attacked stand to develop without intervention. The best yield enhancement appears to be underplanting followed by clearing and planting: both yields exceed that of the base case by about 65 years.

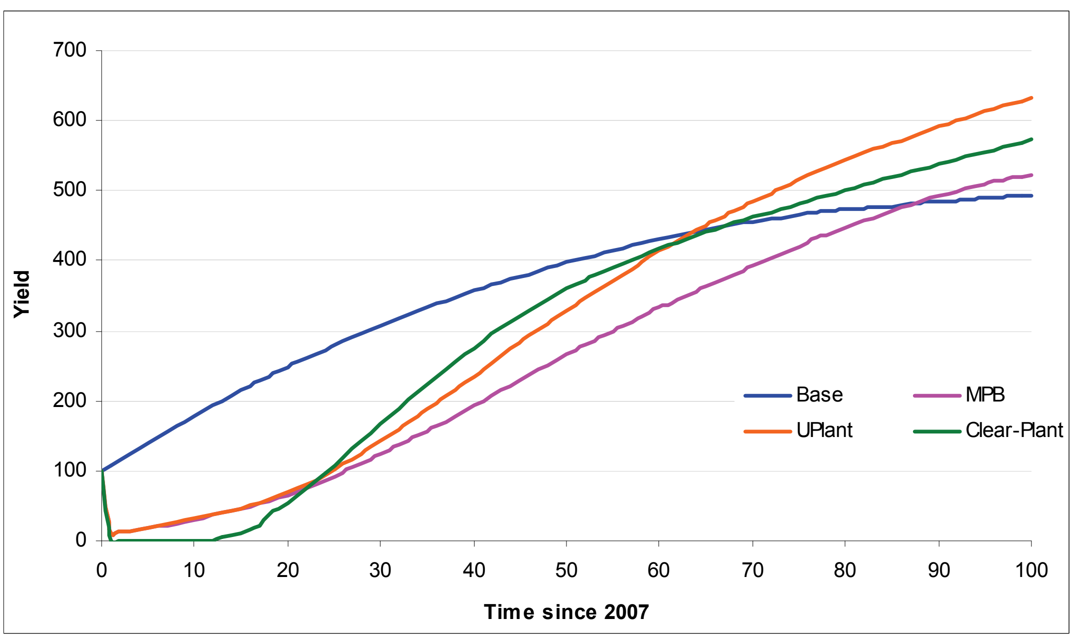


Figure 33. Projected yields for age class 2 polygon 235: MPB attack 96.3%.

As with yield, there is no impact on net present value (NPV) as a result of low MPB attack by PRA (Figure 34). For low levels of attack, allowing the stand to develop without intervention appears to be a prudent, low risk management approach.

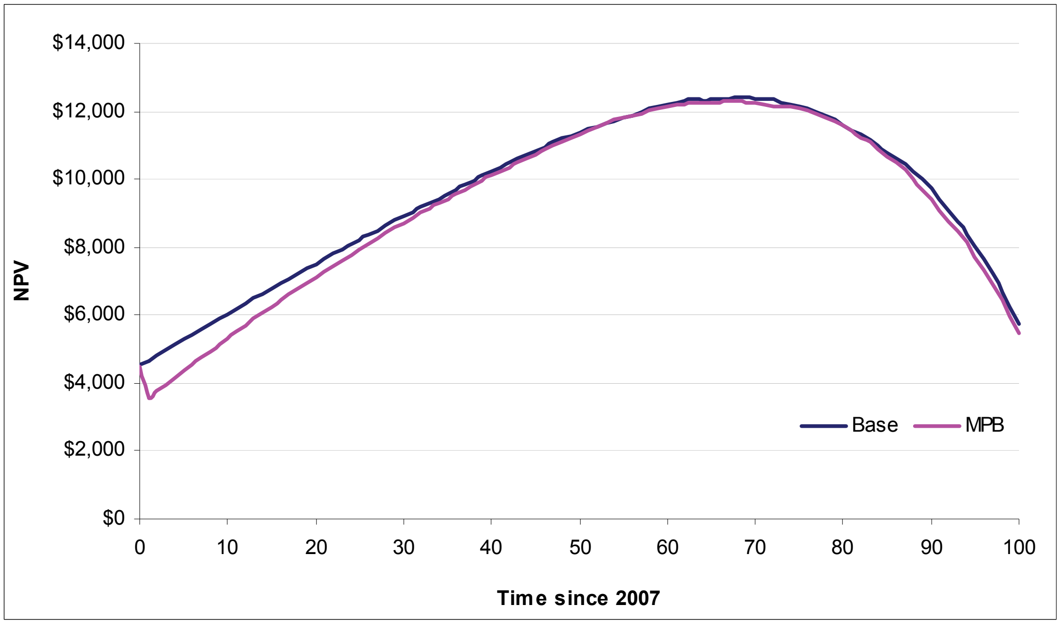


Figure 34. Projected NPV for age class 2 polygon 59: MPB attack 15.1%.

The NPV of polygon 528 for the MPB scenario exceeds that of the base by about 70 years (Figure 35). However at PRA in 49 years, MPB attack has reduced the value of the stand by about $1500 per ha. Still, allowing the stand to develop is the most cost-effective approach for this stand even though attack rates were 50%. Clearing and planting did have a positive NPV from 45 to 80 years but it was much lower than the other management options.

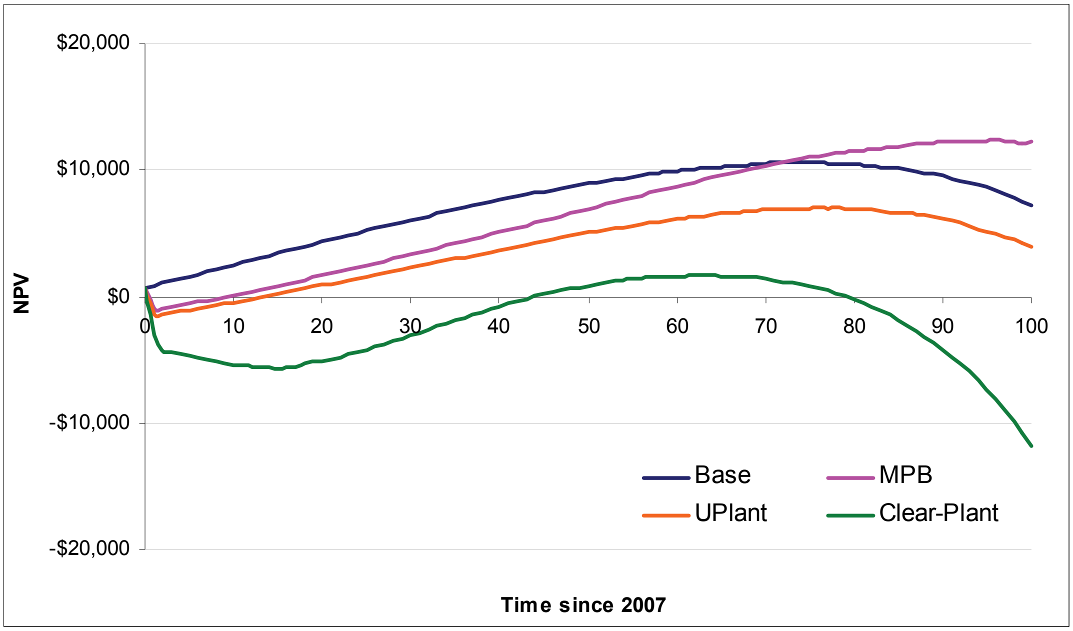


Figure 35. Projected NPV for age class 2 polygon 528: MPB attack 49.7%.

At PRA in 45 years for polygon 351, the best NPV is for the MPB scenario with 55% attack: allow the beetle-attacked stand to develop without management intervention (Figure 36). In this case, clearing and planting never results in a positive NPV while the MPB NPV greatly exceeds that of the base case.

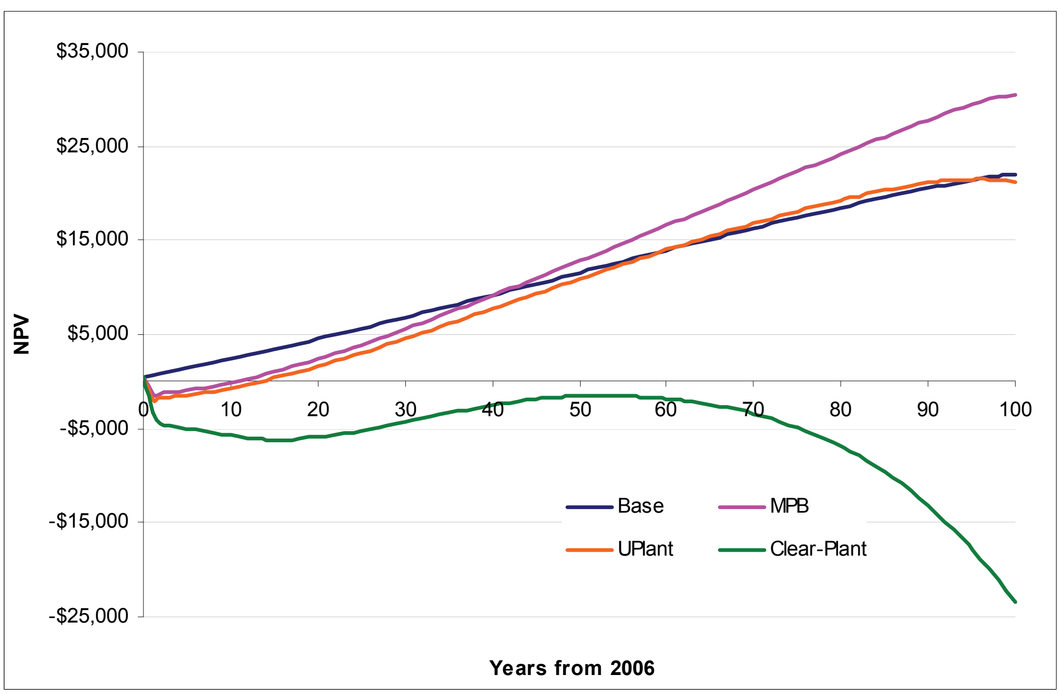


Figure 36. Projected NPV for age class 2 polygon 351: MPB attack 55.8%.

Polygon 1571 with fewer saplings than polygon 351 (which had a similar attack level) has a small economic loss as a result of the beetle at PRA (41 years) (Figure 37). However, in 50 years the best NPV is again seen with the MPB scenario – no management intervention. Clearing and planting never resulted in a positive NPV while at 70 years the underplant exceeded the NPV of the base case.

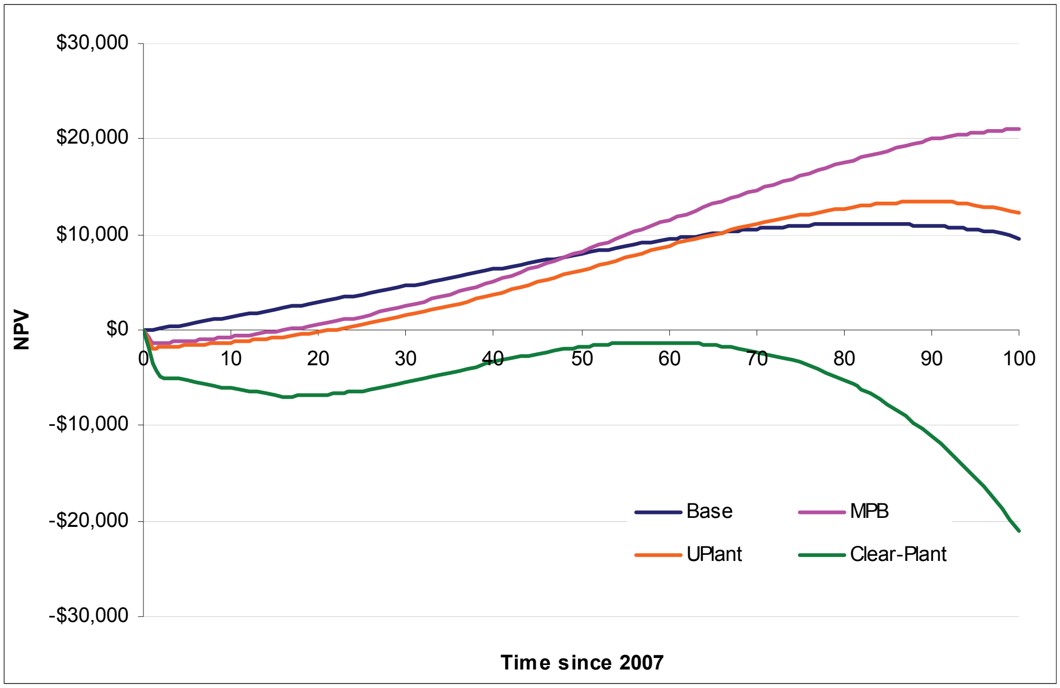


Figure 37. Projected NPV for age class 2 polygon 1571: MPB attack 56.0%.

At 81% MPB attack, polygon 619 had a large NPV reduction from the base case for all scenarios (Figure 38). However, at PRA (52 years), the NPV of both MPB and underplant were positive. This likely is because the yield at that time exceeded 300 m^3 per ha. Again, clearing and planting did not result in a positive NPV. Even for very high levels of MPB attack, the MPB scenario, allowing the stand to develop without intervention may be the best management strategy.

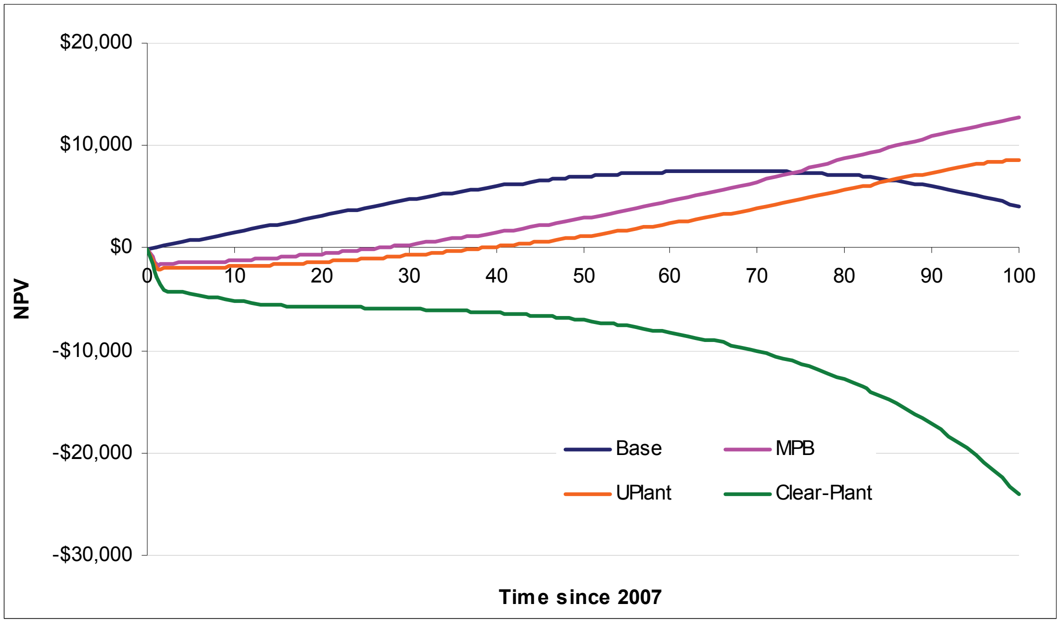


Figure 38. Projected NPV for age class 2 polygon 619: MPB attack 81.2%.

Even though clearing and planting had the best yield for polygon 235, it has the poorest NPV: it is never positive (Figure 39). The NPV of the underplant is almost at base levels at PRA (46 years) and exceeds that of the base by 55 years. Even the MPB scenario NPV exceeds that of the base by about 65 years. Again, even at extreme levels of MPB attack it is questionable whether clearing and planting is the best management strategy. However, in some recent underplanting trials, there was significant browse and mortality of the underplanted stock, suggesting this may not be a viable management strategy. To minimize future risk, some management activity is likely needed for stands with attributes similar to polygon 235.

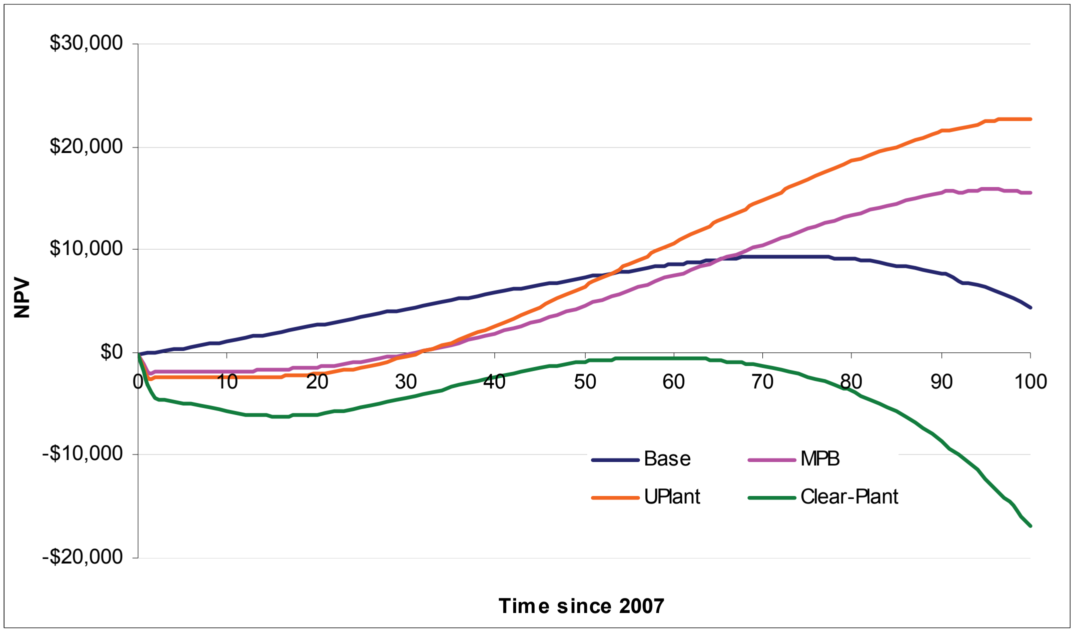


Figure 39. Projected NPV for age class 2 polygon 235: MPB attack 96.3%.

The MPB had little impact on age class 2 stand yield at low or moderate levels of attack but at high levels of attack yield was significantly reduced at PRA. However, even in the extreme cases, the projected yield at PRA exceeded the minimum harvest level for the Prince George TSA (Ministry of Forests and Range 2004). That is, it would be economically feasible to log these stands at PRA.

In no instance was the clear and plant scenario the best investment even though in one instance it resulted in a greater yield at PRA. This recognizes the fact that a significant investment has already been made in the stand up to the time of the MPB attacks and it is lost (no revenue generation) with stand clearing. In general, it appears the best management option may be to allow natural stand dynamics to proceed rather than setting the stand age back to zero. Overall, the findings are dependent on the SORTIE-ND projections used for the scenarios and the assumptions inherent within the model.

In mature stands, MPB attack has resulted in release of the residual trees (Heath and Alfaro 1990; Veblen et al. 1991). However, the rates of release and associated stand dynamics are not understood for immature pine leading stands (Veblen et al. 1991, Stockdale et al. 2004). However, an understanding of how the attacked stands change (develop) over time is requisite for developing management strategies and assessing the impending impacts on stand dynamics and potential mid-term timber supply.

It appears that in age class 2 stands for most levels of attack, the best economic management strategy is to let stand dynamics proceed without intervention and harvest at the original PRA.

3.4.6.2 Mature stands

Representative age class 4, 5 and 6 polygon (Table 7) tree lists were run for 100 years from today in SORTIE-ND. Four SORTIE-ND scenarios were run for each polygon: the base case – stand development without MPB attack (Base), the result of MPB attack – attacked trees proportionally removed by 2 cm DBH classes (MPB), remove all pine larger than 16 cm and leave the remainder of the stand to develop (Partial), and clearcut the mature layer and replant with 800 sph of spruce and 800 sph of pine (Clear-Plant).

Table 7. Age class 4, 5 and 6 polygons modeled in SORTIE-ND.

Polygon	Locale	Age	MPB attack*	Mature sph	Secondary sph seedling + sapling sph
423	Teardrop	56	27.4%	1820	21,200 + 3400
1662	Telegraph	93	94.2%	1625	1600 + 240
253	Vama	101	70.0%	2060	4360 +240

* attack for pine only

As these stands were naturally regenerated (stand replacing disturbances), there was no establishment cost. The NPV is viewed from the Crown's perspective: stumpage is revenue and any expenses to clear or plant a site are a cost. For all age classes it is assumed the cost to partial cut is about $500 per hectare over and above the revenues captured through stumpage, i.e. an incentive is required to partial cut. The clearcut is assumed to be at no cost to the Crown. As NPV are being compared, the future cost of planting is charged to the current stand rather than the future stand which is the conventional approach. The assumptions for the NPV calculations are a real interest rate 3% (Hawkins et al. 2006); a partial cut incentive $500 per hectare; an age class 4 partial cut stumpage $5 per m^3 (reduced because of small piece size); and regular stumpage per m^3 for spruce, pine, sub-alpine fir and aspen, respectively, are $30, $18, $5 and $1 (these are based on scaled averages determined for Prince George Forest District).

Yields for the four scenarios and three polygons are in Figures 40 to 42. Stocking for the four scenarios and three polygons are in Figures 43 to 45 while NPV are in Figures 46 to 48.

Short-term (25-50 years from now) yield is best in the MPB scenario (Figure 40). This is not a productive site so all yields are low. Long-term yield (50 to 100 years from now) is best in the clear and plant (start over). This stand likely will be logged in 10 to 15 years.

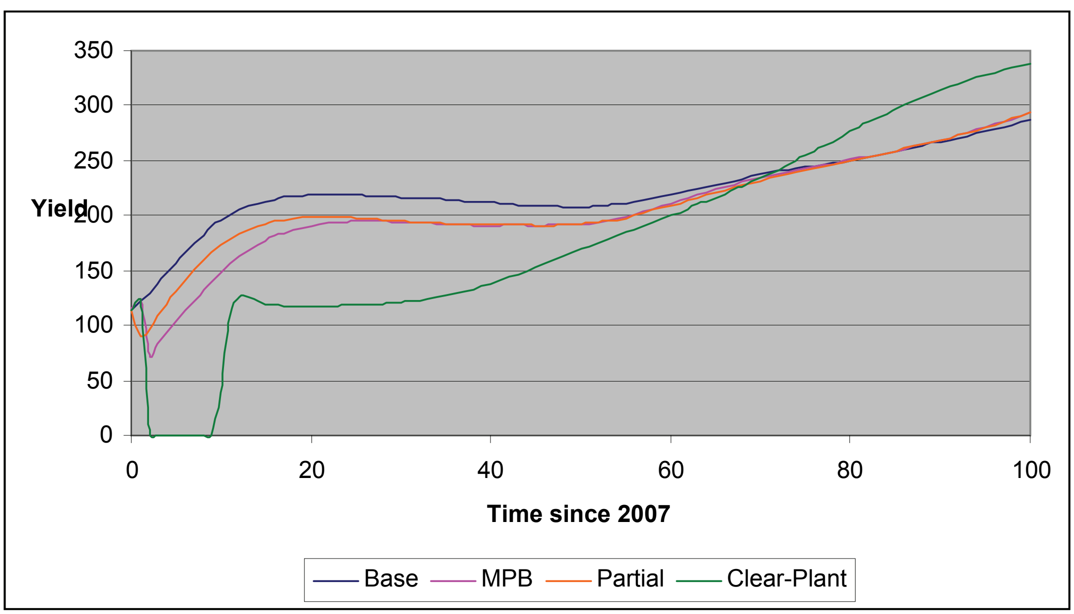


Figure 40. Yield scenarios for polygon 423 – age class 4. Abbreviations as in text.

Short-term yield (25 to 50 years from now) is best in the partial-cut scenario for the age class 5 stand (Figure 41). This is a much better site than 423 so even the MPB yield exceeds 400 m^3 at 45 years. Long-term yield (50 to 100 years from now) is best in the MPB scenario: effectively, this is a thinning from above. With the MPB scenario, this stand could contribute to the mid-term timber supply, albeit at a reduced level, in 30 years.

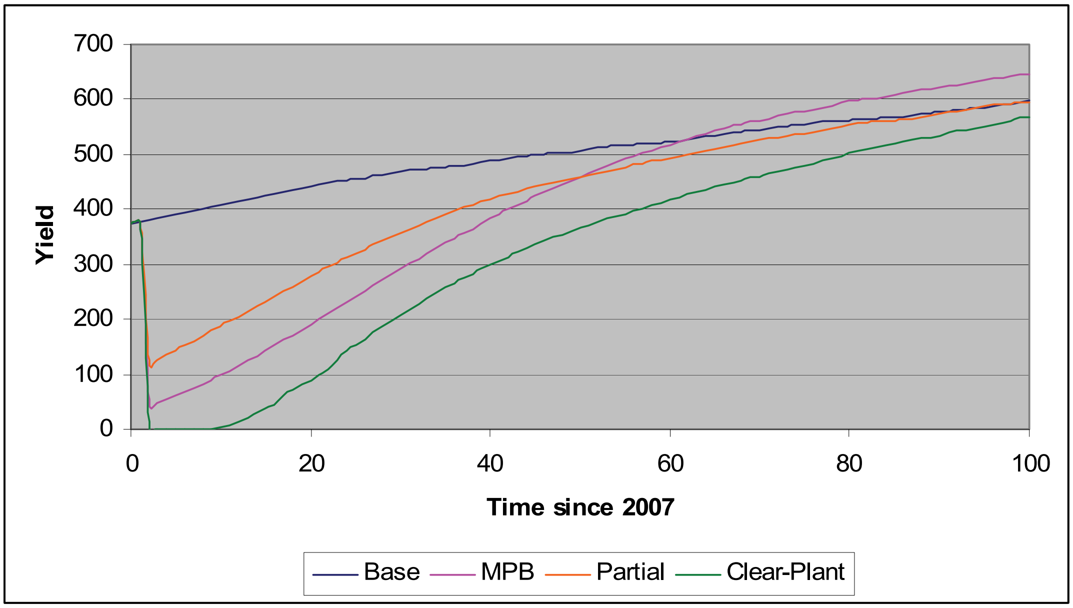


Figure 41. Yield scenario for polygon 1662 – age class 5. Abbreviations as in text.

Short-term yield (25 to 50 years from now) is best in the partial-cut scenario for the age class 6 stand (Figure 42). MPB yield exceeds 400 m^3 at 45 years. Long-term yield (50 to 100 years from now) is best in the partial-cut scenario. Even without management, this stand could contribute to the mid-term timber supply in 25 years.

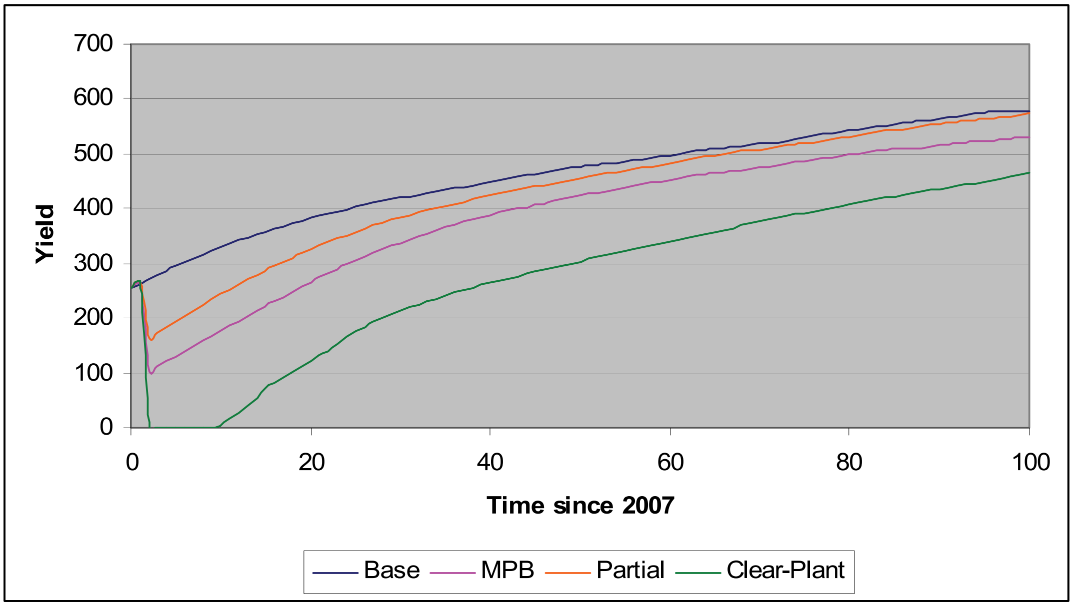


Figure 42. Yield scenario for polygon 253 – age class 6. Abbreviations as in text.

There is little difference from base level mid-term stocking for MPB or partial-cut scenarios in polygon 423 (Figure 43). The clear cut and plant results in greater mid-term stocking.

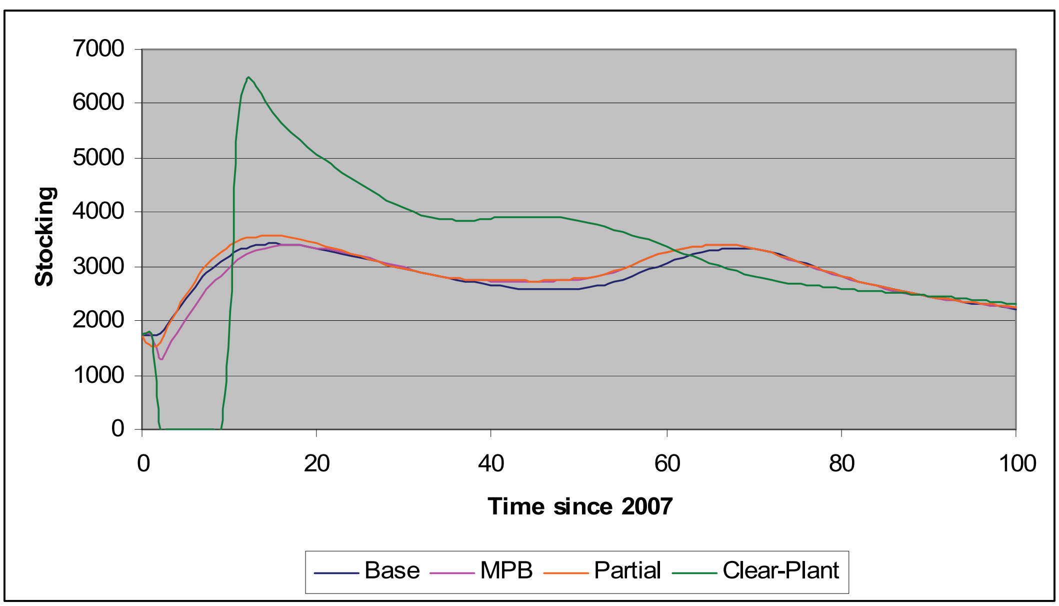


Figure 43. Stocking scenario for polygon 423 – age class 4. Abbreviations as in text.

Mountain pine beetle stocking is not different from base level long-term stocking in polygon 1662 (Figure 44). The partial cut appears to have the best mid-term stocking while the clear cut has the best long-term stocking.

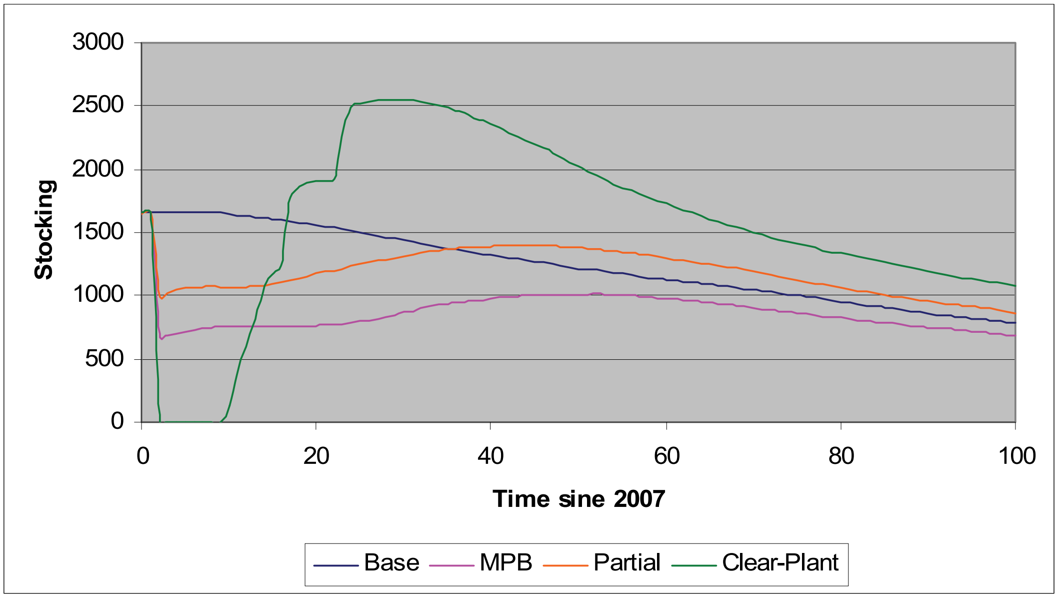


Figure 44. Stocking scenario for polygon 1662 – age class 5. Abbreviations as in text.

Mountain pine beetle stocking is best in the mid-term in polygon 253 (Figure 45). The clear cut has the best long-term stocking.

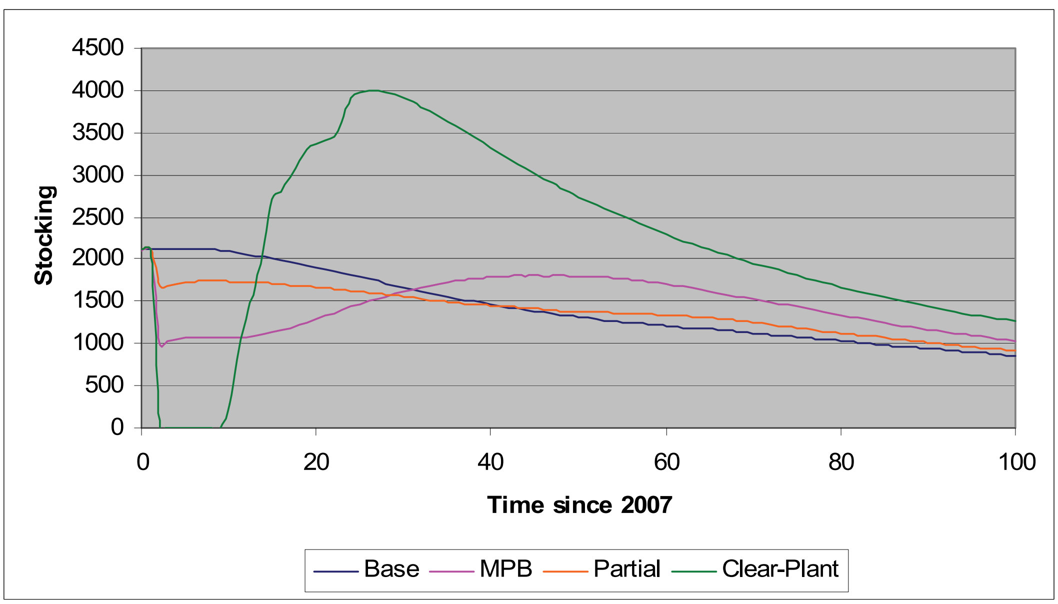


Figure 45. Stocking scenario for polygon 253 – age class 6. Abbreviations as in text.

The best NPV in the age class 4 stand, except for a brief period of about 15 years, is the MPB scenario (Figure 46). This suggests the better management option for this stand is to let it develop from existing secondary structure after MPB attack and harvest it in about 20 to 25 years.

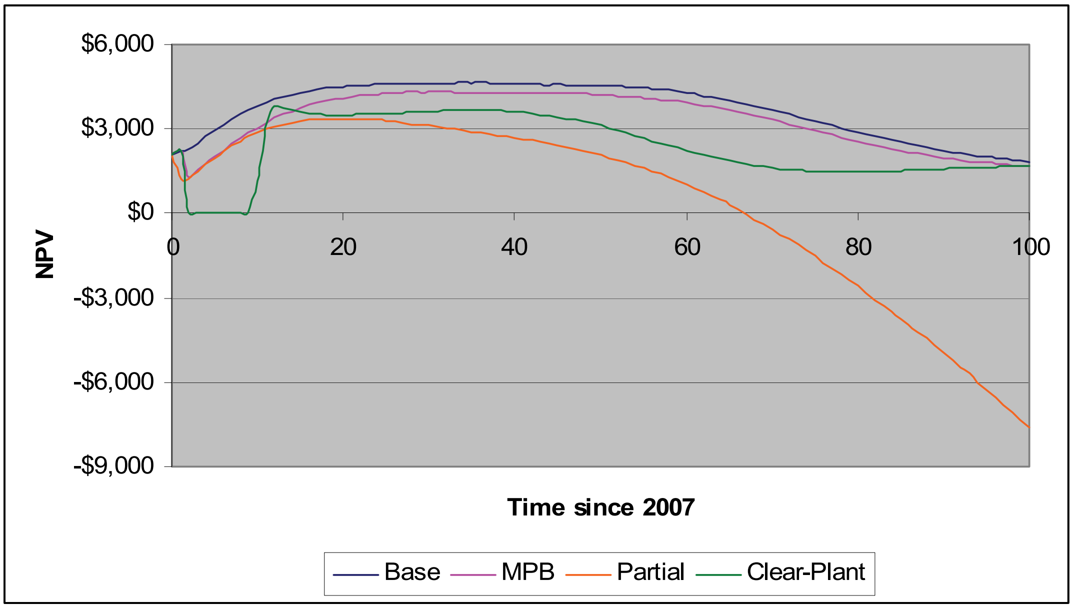


Figure 46. Economic scenario for polygon 423 – age class 4. Abbreviations as in text.

The best NPV for the mid-term is the post-MPB release scenario in polygon 1662 (Figure 47). The MPB scenario is also best for the long-term but it is followed closely by the clear cut option. Before selecting a management option, species mixes and log quality in the long-term would also need to be considered. The MPB scenario does have the greatest yield in the long-term. For stands like this, they can either be logged now or left to contribute to the mid-term timber supply,

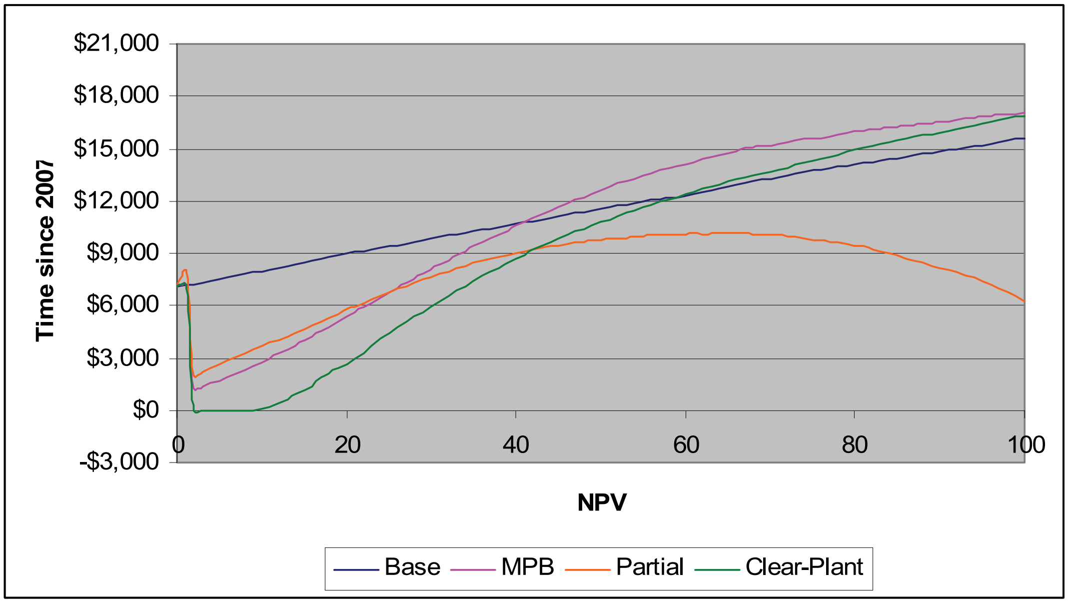


Figure 47. Economic scenario for polygon 1662 – age class 5. Abbreviations as in text.

The best NPV in the age class 6 stand for the mid-term is the post-MPB release scenario (Figure 48). The MPB scenario is also best for the long-term but the clear cut option is gaining on it by 100 years. This is the only scenario where the MPB has significantly reduced long-term NPV. Likely the best approach for stands like this is to log now and expect it to contribute to long-term timber supply.

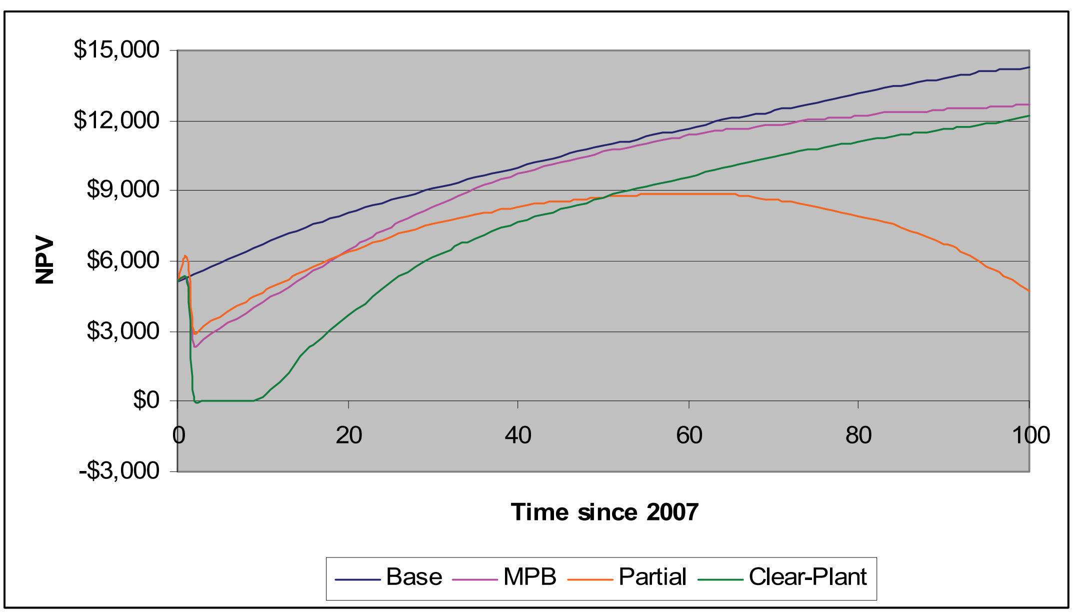


Figure 48. Economic scenario for polygon 253 – age class 6. Abbreviations as in text.

Age class 5 and 6 stands have the potential to contribute to the mid-term timber supply in 25 to 30 years when yields from MPB-attacked stands will exceed 300 m^3 per ha. On the other hand, they also could contribute to today's cut. In 25 years, the yield reduction in age class 4 is small, about 25 m^3 below the base case. Therefore, it appears that many attacked stands are suitable candidates to contribute to the mid-term timber supply. However, the threat of fires, blow down, and mortality of the residual trees due to insects or diseases must be considered before leaving these stands.

The best early mid-term NPV of the non-base case scenarios for all age classes is allowing the stand to develop without intervention: the MPB scenario. The partial cut appears to be the least desirable approach economically. Both from a biologic and an economic perspective, it appears that leaving the MPB-attacked stands to develop for 25 to 35 years and contribute to the mid-term timber supply is a reasonable management approach. However, it must be kept in mind that the model output is highly dependent upon the assumptions incorporated into SORTIE-ND.

While we have a high level of confidence in the modeled release of the mature tree layer (Heath and Alfaro 1990; Veblen et al. 1991) we are less sure of the modeled release of secondary structure and competing shrub layer. Actual release of secondary structure in MPB-attacked stands, both immature and mature, needs to be quantified (Veblen et al. 1991; Stockdale et al. 2004) in order to accurately project post-MPB attack stand growth in SORTIE-ND.

Part of the reason for the enhanced NPV as a result of beetle attack in both immature and mature stands is the MPB-induced species shift from pine leading to spruce leading. Spruce is more valuable to the Crown than pine by about $12 per m^3 and therefore the species conversion is economically favourable even if total yields are reduced.

4 Conclusions

It is generally accepted that MPB attack rates are largely influenced by diameter (DBH). However, epidemic conditions and a stand's proximity to active beetle populations weaken the diameter-attack relationship. Although the relationship improves with the inclusion of other stand attributes, such as stand density index (SDI), site index (SI_{50}), subzone, site series and basal area, the variability of stand characteristics and MPB attack limit the ability of diameter to predict or explain attack rates at the landscape, stand or plot level. Our repeat survey data has shown that attack surges when the population arrives; it then spreads into adjacent immature stands which ends the outbreak in that local area.

Mountain pine beetle attack in age classes 2, 3 and 4 is much higher than originally anticipated and assumed in the Prince George TSA timber supply review (Pousette and Hawkins 2006). Immature stands still have a significant amount of suitable host and the attack of younger age class stands will further exacerbate the mid-term timber supply fall down referred to by the Chief Forester. In order to mitigate or reduce the mid-term timber supply fall down, it will be imperative to capture the growth of the existing secondary stand structure in these young age classes as well as in mature age classes (5 through 8).

Although the majority of mature and immature stands at the landscape level have adequate secondary structure to be considered stocked, some of these stands may result in mixed broadleaf-conifer forests. Our SORTIE-ND modeling scenarios suggest that the best option for extant mature stands would be to allow the stand to develop naturally without intervention and harvest them to assist with mid-term timber supply. Also, immature stands may benefit from underplanting or a similar restoration activity that protects the secondary structure. Due to highly variable stand characteristics found in our study, restoration activities and/or management strategies that are cost-effective and environmentally sound should be selected on a stand by stand basis. However, based on our modeling exercises, it appears the best management strategy for immature MPB-attacked stands is to allow them to develop without intervention and harvest at planned rotation age. In order to support the model, there is a need to quantify the release of secondary structure and competing shrubs in these stands. An accurate inventory of post-MPB stand attributes is also required to determine which stands could benefit from restoration activities.

Clearly, mature stands can be logged and planted today. However, there are mature stands, particularly age class 4 to 6 which, if left after MPB attack, can contribute significantly to the mid-term timber supply in 25 to 50 years. Basically, we allow the residual tree layer and secondary structure to develop. Age class 3 likely either needs to be harvested when planned with yields being reduced or possibly cleared with the fiber used for bio-energy and then planted. For most age class 2 stands types examined, there appears to be adequate secondary structure and residual tree layer so that the best economic based management decision is to allow the stands to develop and harvest as planned in the original silviculture prescription.

5 Acknowledgements

This project was funded by the Government of Canada through the Mountain Pine Beetle Initiative, a program administered by Natural Resources Canada, Canadian Forest Service. Publication does not necessarily signify that the contents of this report reflect the views or policies of Natural Resources Canada – Canadian Forest Service.

6 Literature Cited

Amman, G.D. 1978. Biology, ecology, and causes of outbreaks of the mountain pine beetle in lodgepole pine forests. Pages 39-53 *in* D.L. Kibbee, A.A. Berryman, G.D. Amman, and R.W. Stark (editors). Symposium proceedings for theory and practice of mountain pine beetle management in lodgepole pine forests. Held at Washington State University, Pullman, Washington, 25-27 April 1978.

Anhold, J.A.; Long, J.N. 1996. Management of Lodgepole Pine Stand Density to Reduce Susceptibility to Mountain Pine Beetle Attack. Western Journal of Applied Forestry 11(2): 50-53.

Anonymous. 1998 Land management handbook 25 ISSN: 0229-1622 B.B. Ministry of Environment, Lands and Parks, Ministry of Forests and Range, Victoria, BC.

Anonymous. 2001. Wildlife/Danger tree assessor's course workbook. Forest harvesting and silviculture module. Workers' Compensation Goard of British Columbia. Ministry of Water, Land and Air Protection.

Bate, L.J.; Garton, E.O.; Wisdom, M.J. 2002. Sampling methods for snags and large trees important to wildlife. USDA Forest Service GTR PSW-GTR-181.

Burton, P.J. 2006. Restoration of forests attacked by mountain pine beetle: misnomer, misdirected, or must-do? BC Journal of Ecosystems and Management 7(2):1-10. <http://www.forrex.org/publications/jem/ISS35/vol7_no2_art1.pdf> Accessed Nov. 18, 2008.

Canadian Forest Products Ltd. 2005. Prince George sustainable forest management plan. <http://www.canfor.ca/_resources/sustainability/SFM_Plan_PrinceGeorge_October_2005.pdf> Accessed Nov. 18, 2008.

Canadian Forest Service. 2007a. Mountain pine beetle program. Natural Resources Canada, Victoria, BC. 10 p. Available at <http://warehouse.pfc.forestry.ca/HQ/27367.pdf> Accessed Nov. 18, 2008.

Canadian Forest Service. 2007b. Mountain pine beetle home page. Mar. 2008. Natural Resources Canada, Victoria, BC. <http://cfs.nrcan.gc.ca/subsite/mpb/home-accueil> Accessed Nov. 18, 2008.

Caren, C.D.; Wulder, M.A.; Shore, T.L.; Nelson, T.; Boots, B.; Riel, B.G. 2006. Evaluation of risk assessment of mountain pine beetle infestations. Western Journal of Applied Forestry 21(1):5-13.

Carroll, A.L.; Taylor, S.W.; Regniere, J.; Safranyik, L. 2004. Effects of climate change on range expansion by the mountain pine beetle in British Columbia. Pages 223-232 *in* T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Mountain Pine Beetle Symposium: Challenges and Solutions. Held in Kelowna B.C. 30-31 October 2003. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC, Canada. Information Report BC-X-399. 298 p.

Cayer, L. 1988. The mountain pine beetle story in the Cariboo Forest Region: 1972-1988. BC Ministry of Forests, Victoria, British Columbia.

Coates, K.D.; DeLong, C.; Burton, P.J.; Sachs, D.L. 2006. Abundance of secondary structure in lodgepole pine stands affected by the mountain pine beetle. Report for the Chief Forester, Ministry of Forests and Range, Victoria, BC. 17 p.

Cole, W.E.; Amman, G.D. 1969. Mountain pine beetle infestations in relation to lodgepole pine diameters. Research Note INT-95. Forest Service of the U.S. Department of Agriculture. Ogden, Utah, U.S.A. 8 p.

DeLong, C.; Tanner, D.; Jull, M.J. 1993. A Field Guide for Site Identification and Interpretation for the Southwest Portion of the Prince George Forest Region. Land Management Handbook #24. Ministry of Forests and Range, Victoria, BC. 294 p.

Eng, M.; Fall, A.; Hughes, J.; Shore, T; Riel, B.; Hall, P. 2004. Provincial level projection of the current mountain pine beetle outbreak: an overview of the model (BCMPB) and draft results of year 1 of the project. Canadian Forest Service and the BC. Forest Service, Victoria, BC.

Eng, M.; Fall, A.; Hughes, J.; Shore, T.; Riel, B.; Hall, P.; Walton, A. 2005. Provincial level projection of the current mountain pine beetle outbreak: an overview of the model (BCMPB v2) and results of year 2 of the project. Canadian Forest Service and the B.C. Forest Service, Victoria, BC.

Hawkins, C.D.B., T.W. Steele, and T. Letchford. 2006. The economics of site preparation and the impacts of current forest policy: evidence from central British Columbia. Can. J. For. Res. 36(2):482-494.

Heath, R. and R.I. Alfaro. 1990. Growth response in a Douglas-fir/lodgepole pine stand after thinning of lodgepole pine by mountain pine beetle. J. Entomol. Soc. Brit. Columbia, 87: 16-21.

Holt, R.F. 2001. Strategic Ecological Restoration Assessment (SERA) of the Prince George Forest Region. Results of a Workshop. Forest Renewal BC. Ministry of Environment Habitat Branch. 35 p. <http://www.llbc.leg.bc.ca/public/PubDocs/bcdocs/353008/pgeorge_terp.pdf> Accessed Nov. 18, 2008.

Manning, T.; Bradford, P.; White, G.; Rowe, D.; Densmore, N.; Guy, S. 2002. British Columbia's dangerous tree assessment process. USDA Forest Service GTR PWS-GTR-181.

Ministry of Forests and Range. 2000. Establishment to free growing guidebook. Prince George Forest Region. Rev. ed., Version 2.2. Forest Practices Branch, Ministry of Forests and Range, Victoria, BC. Forest Practices Code of British Columbia Guidebook.

Ministry of Forests and Range. 2003. Timber supply and the mountain pine beetle infestation in British Columbia. Forest Analysis Branch. 28 p.

Ministry of Forests and Range. 2004. Prince George, Lakes, and Quesnel Timber Supply Area Rationale for Allowable Annual Cut (AAC) Determination.

Ministry of Forests and Range. 2007. Mountain pine beetle action plan: Sustainable forests, sustainable communities. Annual Progress Report 2006/2007. Victoria, BC. 40 p.

Ministry of Forests and Range. 2008. Mountain pine beetle information maps. May 2005. <http://www.for.gov.bc.ca/hre/bcmpb/cumulative/2005.htm> Accessed Nov. 18., 2008.

Ministry of Forests and Range. 2008a. Mountain pine beetle. Mar. 2008. <http://www.for.gov.bc.ca/hfp/mountain_pine_beetle/> Accessed Nov. 18., 2008.

Ministry of Forests and Range. 2008b. 2007 Aerial overview summary table. Mar. 2008. <http://www.for.gov.bc.ca/hfp/health/overview/2007table.htm> Accessed Nov. 18., 2008.

Ministry of Water, Land and Air Protection. 2002. Indicators of climate change for British Columbia. Victoria, BC.

Nussbaum, A. 2006. Forecasting the effects of species choices on long-term harvest levels: Sub-component of the provincial mountain pine beetle analysis project. Presented at the Northern Silviculture Committee 2006 Winter Workshop. <http://www.unbc.ca/assets/conted/courses/nrme/nsc_presentations/anussbaum.pdf> Accessed Nov. 18, 2008.

Pedersen, L. 2004. Expedited timber supply review for the Lakes, Prince George, and Quesnel Timber Supply Areas. B.C. Ministry of Forests and Range, Victoria, B.C. Public Discussion Paper. <http://www.for.gov.bc.ca/hts/tsa/PDP_TSAs_14-24-26.pdf> Accessed Nov. 18, 2008.

Pousette, J.; Hawkins, C.D.B. 2006. An assessment of critical assumptions supporting the timber supply modelling for mountains-pine-beetle-induced allowable annual cut uplift in the Prince George Timber Supply Area. BC Journal of Ecosystems and Management 7(2):93-104. <http://www.forrex.org/publications/jem/ISS35/vol7_no2_art10.pdf> Accessed Nov. 18, 2008.

Rakochy, P. 2005. Lodgepole pine stand dynamics as a result of mountain pine beetle attack in central British Columbia. M.Sc. Thesis. University of Northern British Columbia.

Schreuder, H.T.; Gregoire, T.G.; Wood, G.B. 1993. Sampling methods for multi-source forest inventory. Wiley, New York, 446 p.

Shore, T.L.; Safranyik, L. 1992. Susceptibility and risk rating systems for the mountain pine beetle in lodgepole pine stands. Forestry Canada, Pacific and Yukon Region, Pacific Forestry Centre, Victoria, BC. Information Report BC-X-336.

Shore, T.L.; Safranyik, L.; Lemieux, J.P. 2000. Susceptibility of lodgepole pine stands to the mountain pine beetle: testing of a rating system. Canadian Journal of Forest Research 30: 44-49.

Stockdale, C., S. Taylor, and B. Hawkes. 2004. Incorporating mountain pine beetle impacts on stand dynamics in stand and landscape models: a problem analysis. *In* Mountain pine beetle symposium: challenges and solutions. *Edited by* T.L. Shore, J.E. Brooks, and J.E. Stone. *Held in* Kelowna, BC. October 30-31, 2003. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC., Canada. Information Report BC-X-399. pp. 200-209.

Taylor, S.; Erickson, B. 2007. Historical mountain pine beetle activity. Feb 2008. Natural Resources Canada, Canadian Forest Service. <http://cfs.nrcan.gc.ca/subsite/mpb/historical-historique> Accessed Nov. 18, 2008.

Thrower, J.S.; Nussbaum, A.F.; Di Lucca, C.M. 1994. Site index curves and tables for British Columbia: Interior species.2nd ed. BC Land Management Field Guide Insert 6, Ministry of Forests and Range, Research Branch, Victoria, BC.

Veblen, T.T., K.S. Hadley, M. Reid, and A.J. Rebertus. 1991. The response of subalpine forests to spruce beetle outbreak in Colorado. Ecology, 72: 213-231.

Williston, P.; Cichowski, D. 2003. The response of caribou terrestrial forage lichens to forest harvesting and mountain pine beetles in the east Ootsa and Entiako areas. March 2003. Summary No. 15. <http://www.for.gov.bc.ca/hfd/library/FIA/HTML/FIA2008MR189.htm> Accessed Nov. 18, 2008.

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