Effects of salvage options for beetle-killed pine stands on ECA: December 2008 update

A synthesis of currently available data and uncertainties

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Updated – Dec. 2008

Summary

This project synthesizes currently available local data related to the effects of salvaging or not salvaging stands killed by mountain pine beetle on equivalent clearcut area (ECA) value of a stand. The current report examines four main aspects needed to predict the immediate and longer-term ECA effects of stand management options:

1) Relationships between the height and canopy cover of regenerating conifers and ECA,
2) Contributions from dead pines over time, including their fall rates and decreasing canopy cover,
3) Stand components expected to be unaffected by MPB – understory and non-pine overstory,
4) Expected growth and mortality of surviving non-pine canopy trees, saplings and seedlings, or planted seedlings, and natural ingress.

The contributions to reducing ECA from non-pine overstory, dead pine, saplings, seedlings and natural or planted regeneration are then combined to predict the ECA value of stands that are clearcut-salvaged and planted, partially salvaged and unsalvaged. ECA is calculated immediately after disturbance and through time subsequently, for three example stand types. Uncertainties associated with each parameter are estimated and followed through the analysis to determine the uncertainty associated with the ECA predictions.

As expected, unsalvaged stands have a lower ECA value than clearcut-salvaged stands initially, due mainly to non-pine canopy trees and the contributions of dead pine snags. However, the planted salvaged stands are expected to recover more quickly. Which option produces the least total ECA effect over time depends on many factors, but the amount of non-pine species in the canopy and growth rates had large effects in our analysis. ‘Partial salvage’ produces less ECA effect than clearcut salvage if planted trees grow as well, but somewhat greater total ECA if retention lowers growth rates considerably. The project will also look at how the stand-level comparisons roll-up into a watershed-level ECA value over time.

This project makes a number of assumptions and simplifications, and is intended to provide some quickly-available guidance for professional hydrologists and other decision-makers. Ongoing research and detailed stand and watershed modeling will provide better guidance when these are completed.

December 2008 update

This document was updated from the Dec. 2006 version by:

- Adding 2007 snow measurement results from Pierre Beaudry’s study in grey MPB-attacked stands. [Feb 2008 update]
- Adding initial results from Pat Teti’s snow and light studies in MPB stands. [Feb 2008 update]
- Adding results from Sarah Boon’s MPB snow study. [Feb 2008 update]
- Adding results from Buttle et al 2005 and Talbot and Plamondon 2002 on the relationship between tree height and ECA of regenerating stands. The curve of ECA versus tree height was also forced to remain at 100% ECA for 1m tall trees, which somewhat raised the ECA

curve at lower tree heights (i.e., delayed ECA recovery). The curve combining the 5 studies for an overall average relationship of ECA versus height weighted Winkler's local study twice as highly as each of the other studies. The result was that ECA remained somewhat higher as tree height increased in the updated analysis. [Dec 2008 update]

- Replacing the analysis of snag fall with the results from a more complete analysis done as part of an FSP synthesis of literature on deadwood rates. This revised curve of cumulative fall rates of snags over time produces a half-life of 13 years for 25-cm dbh snags (versus 10 years in the previous analysis, which included faster-falling ponderosa pine).
- Modifying the information on canopy loss in pine snags, based on a review of 4 studies of decay in pine snags and work by Dave Coates and Erin Hall. [Feb 2008 update]. Together with the moderately slower rate of snag fall, this change extended the predicted contribution of dead pine to reducing ECA by about 40%.
- A number of studies are measuring snow accumulation and ablation in stands affected by MPB. Rita Winkler provided a tabulation of their results for maximum snow water accumulation (tabulation of ablation still in progress). However, unavoidable limitations in the design of these studies make it difficult to calculate ECA values for red- or grey-attacked stands. The main problem is lack of simultaneous comparison with similar green stands, which is needed to calculate ECA. Green stands are either young (<40yr) enough not to be attacked by beetles (Winkler in progress, Winkler 2008, Bewley 2008) but also potentially young enough not to represent hydrological recovery, or were measured in earlier years prior to beetle attack (Winkler in prog.) when overall snow levels differed. In the latter case, more years of measurement are needed before yearly variation in accumulation can be averaged out. Another study (Dobson 2007, 2008) uses burned stands, which appear to be structurally different from MPB stands. Results from new studies in MPB stands have therefore not been included in the current update. [Ignoring the apples-and-orange comparisons and simply averaging all results from MPB stands in Rita's summary, green stands reduce accumulation 31.8% compared to openings, red stands 18.4% and grey stands 22.2%, which would give red stands an ECA of 44% and grey stands 30%. The value for red stands is higher than the synthesis here would predict, while the value for grey stands is lower (and, of course, red stands should have a lower ECA than grey). Again, though, these values are not very informative compared to matched comparisons, and neither refute nor support the predictions from the synthesis.]

There have also been a number of direct hydrological modeling studies, by Markus Weiler, Younes Alila, Steve Chatwin and others, that will eventually supplant the need for ECA altogether (once the detailed models are operationally available to explore management scenarios in individual watersheds).

This document contains the following sections:

1. A background on the project from Doug Lewis
2. An overview “flow chart”, with explanatory notes (including aspects of the bigger picture that are not covered in this project)
3. A synthesis of ECA value as a function of tree height in regenerating stands, based on Hardy and Hensen-Bristow (1990), Hudson (2000), Winkler (2001), Talbot and Plamondon (2002) and Buttle et al. (2005).
4. Contributions expected from dead pine snags over time, based on a synthesis of their fall rates, loss of structure, and Beaudry's, Teti's and Boon's work on their ECA value. This section also includes a summary of the relationship between ECA and canopy closure, based on data provided by Winkler et al. (2004) from across southern BC.
5. A summary of immediate contributions to reducing ECA from live components of unsalvaged stands, based on survey results from Coates et al. (2006) and Vyse (in progress).

6. A simple model of expected change in the live components of unsalvaged stands over time, and their contributions to reducing ECA.
7. A combination of the different components to compare ECA values immediately after disturbance and over time for clearcut-salvaged, 'partial salvage' and unsalvaged stands, in 3 example stand types. This section also examines sensitivity of the results to some variations in parameter values suggested by reviewers of the initial draft.
8. Ideas about the next step of rolling up the results to the watershed level.

Important Note # 1 – ECA versus hydrology

This project examines the effects of different options for managing stands and watersheds affected by mountain pine beetle (MPB) on Equivalent Clearcut Area (ECA). The ECA concept was developed as an administrative tool to help guide assessments of watersheds by professional hydrologists. It is an indicator of the amount of forest disturbance in a watershed. The ECA value of a stand – e.g., a partial cut or a young regenerating stand – is assessed empirically by comparing its maximum snow accumulation and/or ablation[1] rate to values from clearcuts and mature stands. Although these are major components of the hydrology in the Interior, it is important to realize that there is no 1:1 relationship between ECA and the streamflow measures like peak flow, total yield or low flows that are the actual management concerns. Many factors beyond snow accumulation and ablation affect streamflow, and the empirical relationship between ECA and streamflow measures is highly variable. For these reasons, we avoid talking about "hydrological effects", "hydrological contributions" or "hydrological recovery", and instead present all results as "ECA value", "effects on ECA", "contribution to reducing ECA", "ECA returning to 0"[2], etc. The judgment of professional hydrologists is required to interpret how these ECA results relate to actual hydrological effects in a watershed, and how relevant ECA is for decisions affecting hydrological values.

Important Note # 2 – Types of 'uncertainty'

An important aspect of this project is to assess the uncertainty involved in putting together many components of a stand and watershed to project the ECA effects of different management options. However, we can only deal with one aspect of uncertainty – the uncertainty arising from the fact that parameters and relationships used in our analysis have been estimated from limited field data. This is called "statistical uncertainty", and there are formal techniques available to estimate it and incorporate it into results. There is an additional, different type of uncertainty, due to all the factors that we cannot consider in our analysis, including all the different assumptions that we could have used. The world will always be more complex and uncertain than any simplified model used in an analysis, and there is no way to measure this inherent "model uncertainty". The confidence intervals we present therefore reflect only the statistical uncertainty in our results. True uncertainty is greater – probably much greater – because our analysis necessarily omits much of the complexity of the real world.

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[1] "Ablation" refers to snow loss from melt, sublimation and wind scour.

[2] "Hydrological recovery" does not necessarily occur when the ECA value of a regenerating stand returns to 0. Actual effects on streamflow may have disappeared before that point (at an ECA>0), or hydrological effects may continue after the ECA is 0 (for example, because of roads, or effects not related to snow accumulation and ablation, such as rain-on-snow events or summer storms).

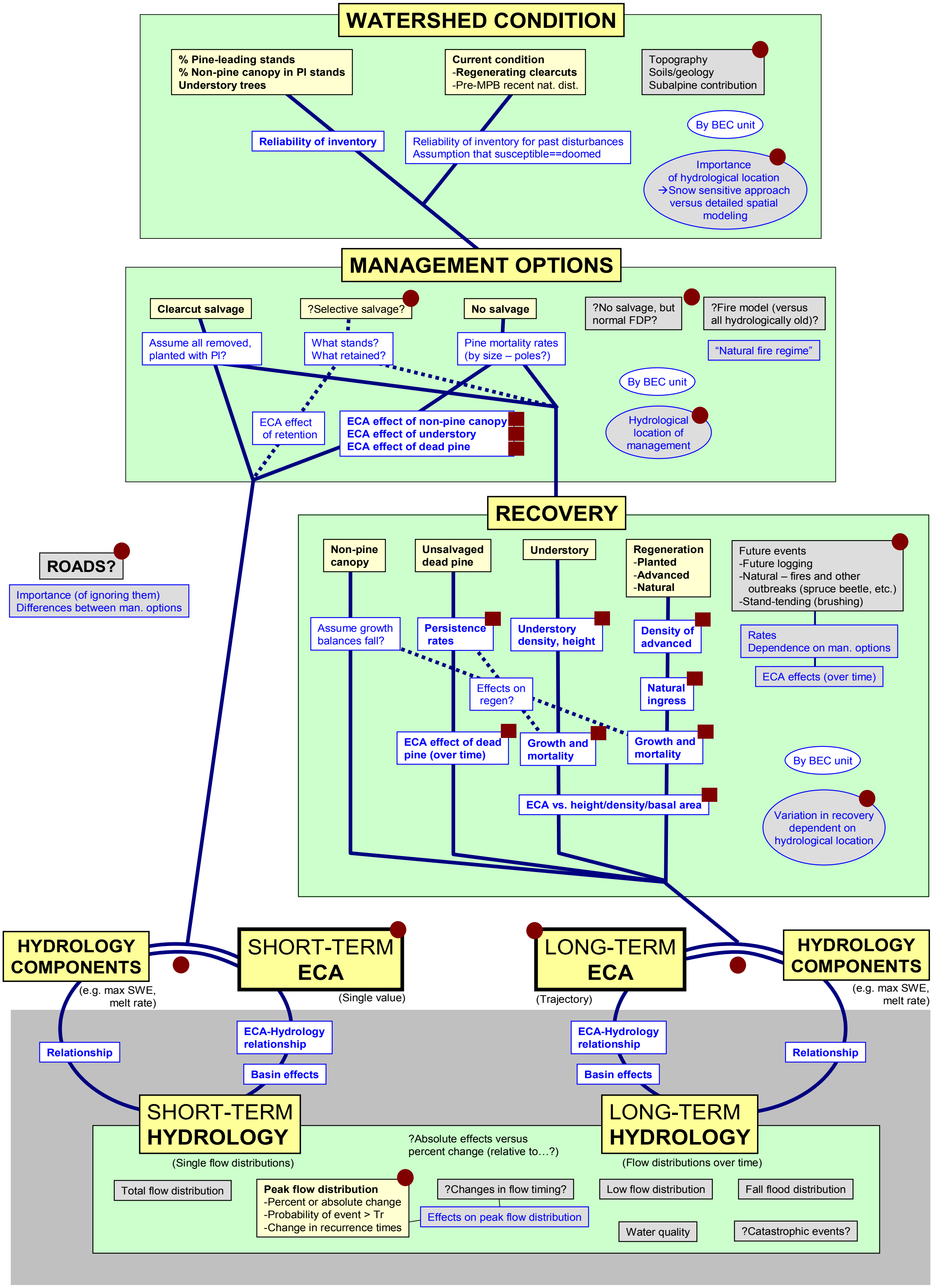
1. Background

Watersheds in the interior of British Columbia with a large component of mature lodgepole pine leading forests may experience significant impacts to hydrology due to tree mortality resulting from the current mountain pine beetle infestation. Key to this problem is debate about the relative hydrologic value of dead pine forest, both short and long term, compared to a salvage harvested stand and artificial regeneration. Significant uncertainty, primarily due to a lack of existing scientific information on the subject, exists regarding the hydrologic value of MPB killed stands related to non-pine overstory and understory forest structure, an intact shrub and ground layer, a lack of roads or logging related disturbances and the rate and quality of natural regeneration. Thus, forest managers are currently faced with difficult decisions to proceed with aggressive salvage harvest of MPB killed forests and risk future uncertain consequences (i.e. elevated peak flows, change in timing of peak flows, increased flood frequency, low flows, probability of erosion) associated with high levels of harvest, or to use a more precautionary approach to retain large tracts of MPB-killed pine forests, forfeiting short term economic gain from salvage, to obtain uncertain hydrologic benefits from the retained forest stands. To exacerbate this problem, the accelerated rate of MPB salvage operations to utilize the short shelf-life of dying pine will not allow managers sufficient time to incorporate research results prior to proceeding with salvage harvesting. Consequently, decisions on how much and where to proceed with harvesting must be made quickly, often within the next 2 years, without the benefit of improved information currently being collected by researchers throughout the province.

The goal of this project is to provide forest managers with some interim guidance on how to deal with uncertainty around the hydrologic value of dead pine when planning forest operations in watersheds. The project synthesizes existing research information, to explore how uncertainty around imperfect information, various assumptions around uncertain states of knowledge, and the values used in the assumptions could potentially influence stand-level Equivalent Clearcut Area (ECA) and hydrologic recovery of forests with a large amount of dead pine. This information will be critical for forest managers to consider the most appropriate management actions to balance resource objectives, particularly in watersheds with hydrologic concerns and high percentages of MPB-killed forests where minimizing watershed ECA has been a management priority. To emphasize these considerations, the project will use the Chase-Charcoal Creek watershed as a case study in order to compare and contrast how various assumptions and management actions utilizing retention of MPB-killed forests could potentially influence short and long term hydrology and affect other forest management objectives.

ECA uncertainty and MPB salvage options David Huggard Dec. 2008

2. Overview



WATERSHED CONDITION

% Pine-leading stands
% Non-pine canopy in Pl stands
Understory trees

Reliability of inventory

Current condition
-Regenerating clearcuts
-Pre-MPB recent nat. dist.

Reliability of inventory for past disturbances
Assumption that susceptible==doomed

Topography
Soils/geology
Subalpine contribution

By BEC unit

Importance
of hydrological location
→Snow sensitive approach
versus detailed spatial
modeling

MANAGEMENT OPTIONS

Clearcut salvage

Assume all removed,
planted with Pl?

?Selective salvage?

What stands?
What retained?

ECA effect
of retention

No salvage

Pine mortality rates
(by size – poles?)

ECA effect of non-pine canopy
ECA effect of understory
ECA effect of dead pine

?No salvage, but
normal FDP?

?Fire model (versus
all hydrologically old)?

"Natural fire regime"

By BEC unit

Hydrological
location of
management

ROADS?

Importance (of ignoring them)
Differences between man. options

RECOVERY

Non-pine
canopy

Assume growth
balances fall?

Unsalvaged
dead pine

Persistence
rates

Effects on
regen?

ECA effect of dead
pine (over time)

Understory

Understory
density, height

Growth and
mortality

Regeneration
-Planted
-Advanced
-Natural

Density of
advanced

Natural
ingress

Growth and
mortality

ECA vs. height/density/basal area

Future events
-Future logging
-Natural – fires and other
outbreaks (spruce beetle, etc.)
-Stand-tending (brushing)

Rates
Dependence on man. options

ECA effects (over time)

By BEC unit

Variation in recovery
dependent on
hydrological location

HYDROLOGY
COMPONENTS
(e.g. max SWE,
melt rate)

Relationship

SHORT-TERM
ECA
(Single value)

ECA-Hydrology
relationship

Basin effects

SHORT-TERM
HYDROLOGY
(Single flow distributions)

LONG-TERM
ECA
(Trajectory)

ECA-Hydrology
relationship

Basin effects

HYDROLOGY
COMPONENTS
(e.g. max SWE,
melt rate)

Relationship

LONG-TERM
HYDROLOGY
(Flow distributions over time)

?Absolute effects versus
percent change (relative to…?)

Total flow distribution

Peak flow distribution
-Percent or absolute change
-Probability of event > Tr
-Change in recurrence times

?Changes in flow timing?

Effects on peak flow distribution

Low flow distribution

Fall flood distribution

Water quality

?Catastrophic events?

Notes on MPB-ECA uncertainty flowchart

Main analysis components are in yellow boxes. Sources of uncertainty are in blue, with uncertainties that seem most important in bold. We do not deal with the aspects that are in grey boxes, including the relationship between ECA and actual streamflow hydrology. The letters refer to comments below, with squares indicating components that were analysed and summarized in following sections.

A. The immediate goal of this project is to examine uncertainty in ECA values. This includes ECA values of individual stands managed under different options (salvaged versus unsalvaged), and how this scales up to whole watersheds. Short-term ECA refers to the immediate post-harvest conditions, before any recovery. This is one value (plus uncertainty) for a stand or watershed. Long-term ECA is the trajectory of ECA values through time, as disturbed stands recover and, potentially, other stands in a watershed undergo disturbance.

ECA is the immediate focus, because it is the tool used to make management decisions. However, the true concern is for the actual hydrological events, particularly peak flows. ECA is just a practical indicator of amount of forest disturbance. Unfortunately, the relationship between ECA and peak flow is not very clear, or is at least highly variable in empirical measurements. Some thought has gone into how the available information might be used to refine relationships between ECA and peak flow (or other hydrological variables), but this work is currently considered beyond the immediate scope of this project. The relationship between ECA and actual hydrological values will remain a major source of uncertainty in the application of this project's results.

B. These loops of ECA-hydrology components-hydrology values are meant to symbolize the assumption that ECA value is directly related to specific measurable hydrological components, especially maximum snow water-equivalence (SWE) and maximum melt (ablation) rates. Measurements of SWE and ablation in various stand types are the main way that trees retained or regenerating in stands are converted to an ECA value.

C. One step in the analysis is to summarize available information on trees that are expected to survive MPB in pine-leading stand – non-pine overstory, understory (including pines that are too small for MPB attack) and seedlings. Survey information was summarized from by Coates et al (2006) for SBS stands, and Alan Vyse (ongoing project) for pine-leading stands in the Kamloops Region. **Section 5.**

D. Another analysis step examined the expected hydrological contribution of MPB-killed pine trees over time. This included a synthesis of information on fall rates of beetle-killed pine based on several studies, and a summary of Beaudry's (2006) results on the ECA values of different stages and densities of MPB-killed pine combined with Winkler et al. (2004) data on ECA versus canopy closure. **Section 4.**

E. An important step in the analysis was to synthesize information that related height and canopy cover of regenerating stands to their ECA values. This analysis used results from Winkler's (2001) study in the southern Interior, Hudson's (2000) results from coastal BC and Hardy and Hansen-Bristow's (1990) results from Montana. The relationship of ECA to height (and to canopy closure that is also related to height) is an important link between the stand components and their ECA values. **Section 3.**

F. Projecting stands over time requires modeling of growth and mortality of retained trees, and rates and growth of natural ingress. Detailed stand modeling was beyond the scope of this project and is being conducted by others (Coates et al 2006). Instead, a simpler projection approach was used that tries to capture the main processes occurring in regenerating stands. Because this step relied less directly on empirical results, it is a main place to examine how different people's assumptions about stand regeneration will affect predicted hydrological contributions. **Section 6.**

G. Clearly, many watershed characteristics besides stand management are important for hydrology - topography, soils, contribution from subalpine areas, and "hydrological location" of disturbed stands (e.g., in riparian versus upland areas, or in different elevation or slope classes). However, examining these factors requires detailed spatial modeling of hydrology in watersheds. This was also well beyond the scope of this project, though again work on this topic is ongoing by others. This detailed hydrological modeling will help test and go beyond the simple operational use of ECA as the basis of management decisions.

H. The three main management options being examined are salvaging MPB-affected stands with clearcutting and replanting, 'partial salvage' (removal of dead pine, with some operational loss of non-pine canopy and understory) and no salvage. However, partial salvage is also possible at the watershed scale, by only salvaging a subset of MPB stands that would minimize any negative ECA effects. This option can be examined to some extent when the watershed roll-up is done later in this project. Again, however, the detailed hydrological modeling of watersheds needed to fully predict low sensitivity stands, and the detailed stand modeling to predict the response to selective salvage within a stand, are both beyond the scope of this project.

I. These are just hypothetical comparisons that might provide some context for the results. The Forest Development Plan scenario would indicate what conditions would have been expected if MPB hadn't happened. This was presumably an "acceptable" level of disturbance. The non-MPB natural disturbance scenario (e.g. fire-dominated) is mentioned to point out that the ECA concept implicitly compares with a hydrologically undisturbed watershed. But Interior watersheds would naturally have had an ECA>0 because of recent fires. These 2 scenarios will not explicitly be examined here, but are meant as reminders of some context for interpreting results.

J. Roads have well-known local hydrological effects, and the amount and location of roads will differ in the different management scenarios. However, there are no obvious ways to deal with the basin-level hydrological effects of roads in the ECA approach. Detailed spatial modeling of watershed hydrology is again needed. The issue is only important if different management options generate different levels (or locations) of roads, which may not be the case in a watershed that is already highly developed.

K. Watershed-level projections of ECA over time generally ignore the possibility of unexpected future events, such as fires or outbreaks of other insects or diseases. This may be important in assessing how different current management options contribute to risk. Again, though, this is not a current focus of this project, because it would require more detailed landscape-level modeling (including how risk of future disturbances is affected by current options of salvaging or not).

3. ECA Value versus height of regenerating stands

This step examines the relationship between characteristics of regenerating stands and their ECA value. This is an important component of this overall study, because it determines the ECA values of regenerating existing clearcuts, salvaged MPB stands and the non-beetle-killed parts of unsalvaged MPB stands. The ECA value of a stand is indexed for snow-melt dominated systems by measuring the value of a stand's annual maximum snow water equivalent (SWE) accumulation or annual maximum rate of snow melt ("ablation") relative to accumulations or ablation rates in the open (100% ECA) and in mature stands (0% ECA). Two BC studies, one Montana study and two from the eastern Canadian boreal forest were used for this analysis:

- Hardy and Hansen-Bristow (1990) studied one young regenerating pine stand and one 35 year-old stand, along with a clearcut and mature forest, at high elevation in Montana.
- Hudson (2000) measured snow packs for 5 years in 9 regenerating stands, plus an uncut stand and an open area in the MH zone on the Sunshine coast. He presents results for the recovery (100%-ECA) values for accumulation and ablation for each of the 9 stands in each of the 5 years. These values are related to the average canopy height and the average canopy density (=canopy cover) of each stand in each year.
- Winkler (2001) presents maximum accumulations and ablation rates for 3 regenerating and 3 mature stands in the upper MS and lower ESSF zones in the southern Interior. She includes measurements of several stand characteristics, concluding that average crown length explains the most variation in accumulations among stands, and square-root basal area best explains variation in ablation rates. However, to be consistent with the variables presented by Hudson (2000) and to allow results to relate to more readily available inventory variables, the analysis here uses her measurements of average tree height and crown closure. In Winkler's analysis, these variables were not much poorer at explaining stand-level variation than the best variables, and with only 6 stands, the various stand measurements are quite highly correlated amongst themselves.
- Talbot and Plamondon (2002) present ECA recovery values based on ablation rates measured in 3 years at 11-13 stands dominated by balsam fir in boreal Quebec, ranging from recent clearcuts to mature stands. Maximum accumulation data were not presented.
- Buttle et al. (2005) measured accumulation and ablation in 2 clearcuts, 2 mature stands, 5 young clearcuts (≤3.3m tall) and 1 intermediate regenerating stand (6.9m) in 1 year. The limited measurements at each stand and the single stand at intermediate heights add considerable uncertainty to the height-recovery relationship from this study.

For the analysis, the original data were entered from the five publications. Because changes in the stand variables between years were reported in Hudson (2000), each year x stand value was entered, using linear interpolation within the reported range. Recognizing that the 5 measurements within a stand are not independent, the combination of the three studies' results (see below) doubled the confidence intervals estimated with separate year x stand results for Hudson's study. This is equivalent to an assumption that each set of 5 yearly measurements from a stand actually represent 1.25 (5/4) independent samples. Winkler (2001) did not report separate values of the stand-structure measurements for each year, so the analysis used a single value per stand, with the snow measurements averaged across the 3 years of the study[3]. Talbot and Plamondon (2002) apparently remeasured some stands in more than 1 year, but also add and removed some stands between years. Hardy and Hansen-Bristow (1990) and Buttle et al. (2005) report values from one year only. The raw data come from Tables 1-3 of Hardy and

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[3] Combining years is appropriate here, because the analysis is looking at overall average relationships, not trying to explain year-to-year variation. Yearly values were used for Hudson's study, because the trees showed substantial growth over the period of his snow measurements.

Hansen-Bristow (1990), Table 2 of Hudson (2000)[4], Table 5.3 and Figures 5.4 and 5.5 of Winkler (2001), Figure 3 of Talbot and Plamondon (2002) and Tables 1 and 3 and Figure 1 of Buttle et al. 2005.

The formula for ECA[5] was applied to Winkler's accumulation and ablation data, separately within her 2 sites. The mature forest at Mayson Lake was used as the 0% ECA value for calculating the ECA of the 2 juvenile stands at Mayson Lake. The average of the 2 mature stands at upper Penticton Creek was used for the 0% ECA value for the juvenile stand at upper Penticton Creek. The idea behind averaging the 2 mature stands for the comparison with the juvenile stand was that they might bracket typical mature forest types in that area, with one open multi-layered spruce-fir stand, and one more single-layered pine-dominated stand. The averaged height of the 2 mature stands at upper Penticton Creek was also very similar to the height of the mature stand at Mayson Lake. Because there was considerable variation in tree height and ECA values for the 2 mature stands at Penticton Creek, they were also included in the analysis as separate points[6]. The ECA formula was also applied to Hardy and Hansen-Bristow (1990) and Buttle et al. (2005). Talbot and Plamondon (2002) present ECA values directly (using the same formula).

The main analysis related ECA to canopy height. Spline curves were fit through the data points for the 9 data sets (accumulation from 4 studies, ablation from 5 studies), using function "smooth spline" in the program R. Splines are locally-weighted regression models – the shape of the fitted curve at a given position is most heavily influenced by the nearest data points. This was considered appropriate in this analysis, because there is no particular theoretical reason to expect any particular parametric relationship between ECA and stand height across the range of height. However, the curve was constrained to a recovery value of 0% at 0m canopy height, and to a recovery value of 100% at the height of the mature forest in each study, since these values are fixed by the definition of "ECA".

The sampling distribution of the spline curves for all studies except Hardy and Hansen-Bristow (1990) was estimated using 1000 bootstrap resamples. Bootstrapping was not possible for Hardy and Hansen-Bristow (1990) because they only had 2 stands at intermediate heights. Confidence intervals for that study were therefore subjectively assigned as extending symmetrically 2/3 of the way to 0% ECA for fitted values <50% ECA, or 2/3 of the way to 100% ECA for fitted values >50% ECA. These intervals are wide, because the fitted curve is based on only 2 stands measured for a single year.

This analysis resulted in 9 curves relating recovery to tree height, along with the sampling distributions of those curves. The pairs of curves within a study were similar – that is, recovery as measured by maximum accumulation was similar to recovery measured by maximum ablation rate. However, the study areas did show different relationships. Hudson's results had a faster initial decrease in ECA value as the stands grew, then some tapering off (Figure 3.1a). Winkler's results showed more of a lag, with high ECA in the shortest stands, but then a faster decline in ECA for the taller regenerating stands (Figure 3.1b). Talbot and Plamondon (2002) had the most rapid recovery as trees grew, but this may partly reflect the lower height of their mature boreal stands. Buttle et al. (2002) showed fairly rapid recovery in accumulation, but slower recovery based on ablation. However, bootstrapped confidence intervals were extremely wide in this

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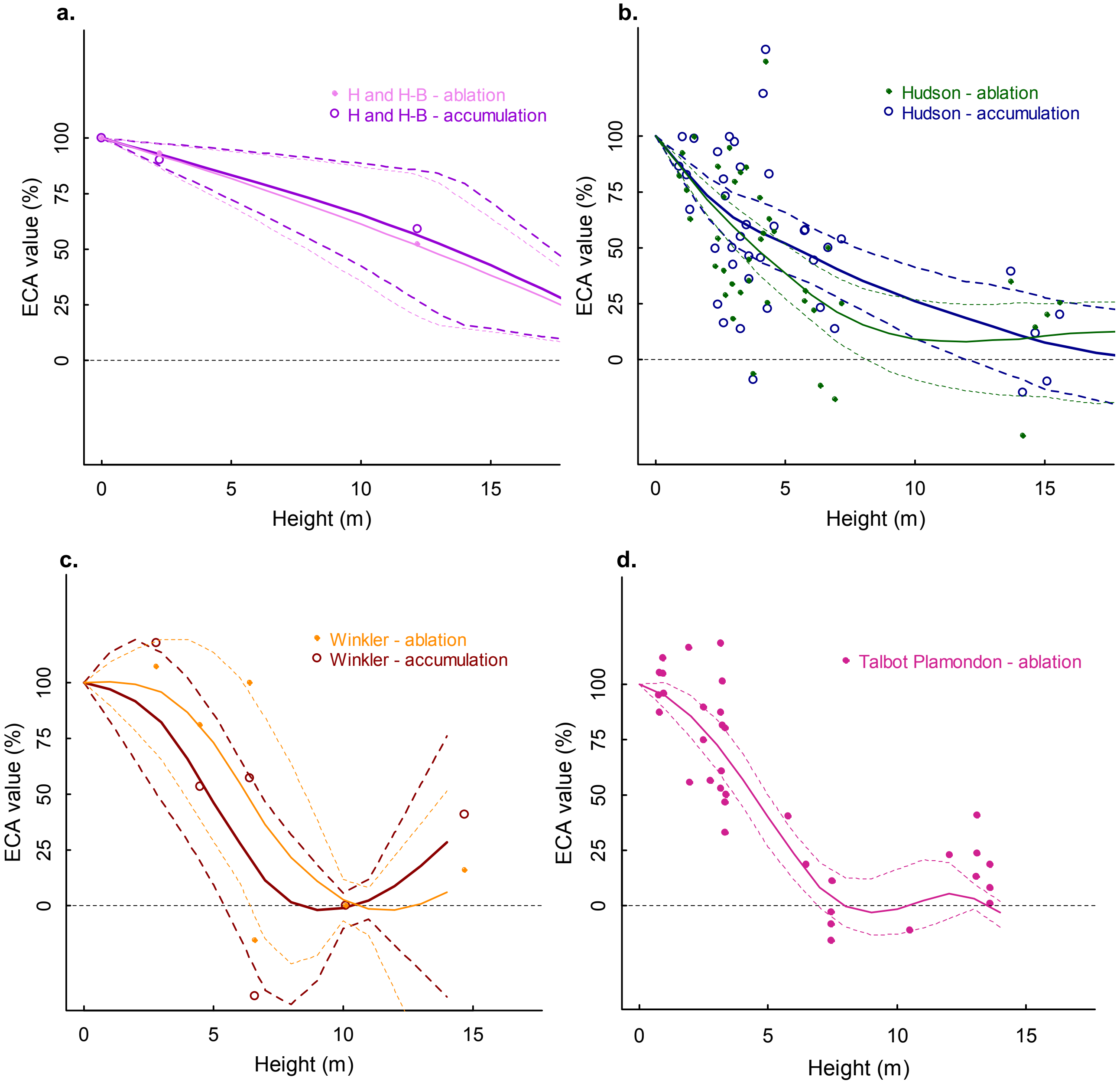
[4] Five recovery values were reported as "N/A" in Hudson (2000). Four of these were negative values. Such values are not impossible – they would reflect accumulation or melt rates in a regenerating stand that are greater than in the open. This is possible because of effects such as changes in wind scour or long-wave radiation, and also simply due to sampling error (chance). Excluding these negative values biases recovery rates upwards. These values were therefore included here. However, one calculated recovery value of <-300% was excluded as an outlier.

[5] ECA=100 – (value in clearcut – value in stand) / (value in clearcut – value in mature) x 100%

[6] This adds considerable uncertainty to the results from Winkler's study, since the shorter mature stand at upper Penticton Creek had lower ECA values than the tall stand.

study, reflecting the low intensity of measurements and single site at intermediate height. Hardy and Hansen-Bristow's results showed a considerably lower decline in ECA, because of the relatively high ECA value measured in the 12m tall stand (Figure 3.1c). Winkler's, Hudson's and Talbot and Plamondon's results, and Buttle et al.'s accumulation results showed ECA at or near 0 by 10-15m height, whereas the more linear ECA curves for Hardy and Hansen-Bristow and for ablation in Buttle et al. decreased more continuously with height. Some of this difference in shapes may be explained by differences in canopy density in the sampled stands, which increased more rapidly with height in Hudson's study compared to Winkler, Talbot and Plamondon and Buttle et al. and particularly Hardy and Hansen-Bristow (discussed below).



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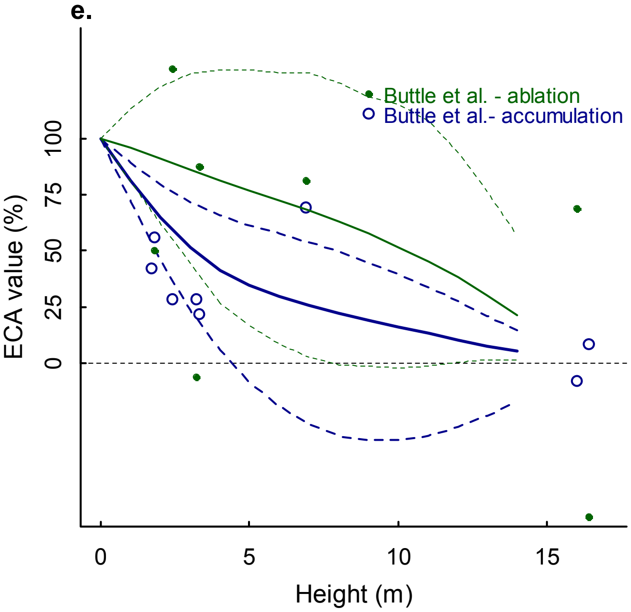

Figure 3.1. Data and smoothed curves (with 95% confidence intervals) for relationship between ECA and canopy height, based on a) Hardy and Hansen-Bristow (1990;"H and H-B"), b) Hudson (2000), c) Winkler (2001), d) Talbot and Plamondon (2002) and e) Buttle et al. (2005). Note that canopy density or closure also changes with canopy height in these studies. Points for Hudson (2000) come from each year's values for each stand; points for Winkler (2001) are a 3-year average for each stand (see text).

These individual curves were combined into a single best-estimate curve (and its error distribution) using Bayes rule[7], with 2 different weightings applied to the studies. The first combined curve uses the 9 curves with equal weighting. The resulting curve shows a fairly linear relationship between ECA and tree height, reaching a value of 11.6% ECA at 12m, followed by a slow decline towards an ECA of 0 in taller stands. The second combined curve weights Winkler's most heavily (as the most locally-relevant study). This combined curve has a slightly lower ECA, with a value of 9.7% at 12m and is close to the range recommended in the BC Watershed Assessment Procedure Guidebook[8]. This second curve, truncated to ECA=0 for heights >12m, was used subsequently. The advantage of truncating the curve at 12m was that tree heights did not have to be tracked beyond this height.

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[7] In practice, the posterior distribution was calculated by multiplying the probability of each recovery value (-50, -49…250%) for each of the 4 curves at each height (0, 1, 2 … 14m) and adjusting the products to sum to 1. This approximate numerical approach was used because it is more flexible to allow future additions, such as incorporating subjective priors that may not be expressed as normal distributions.

[8] Not surprisingly, since the WAP values were based substantially on Winkler's work, which is given highest weight in this combination.

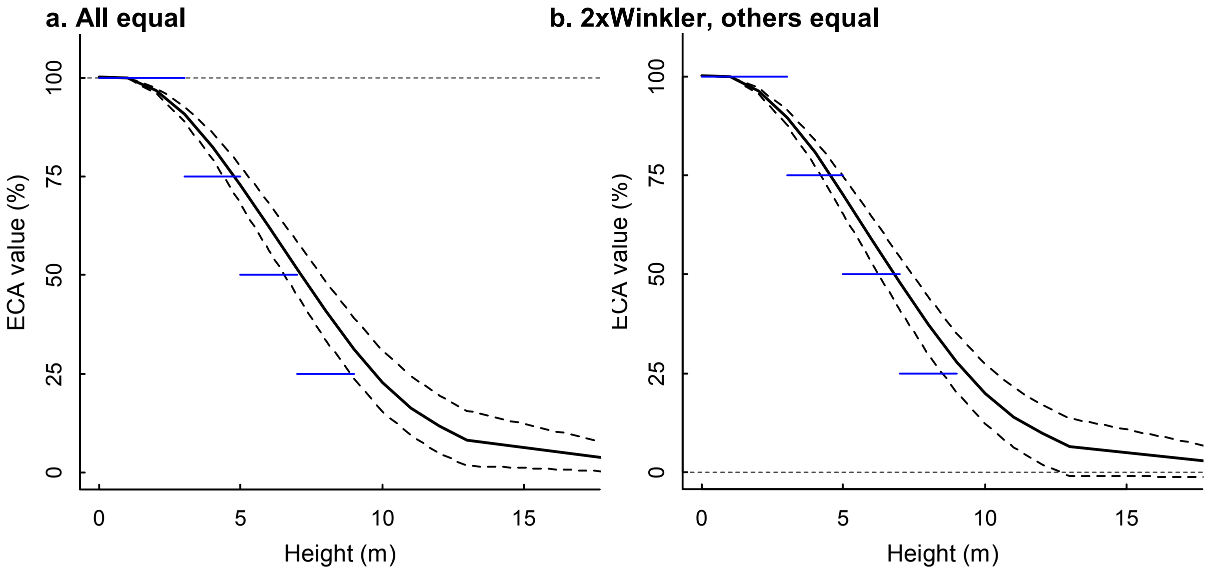

Figure 3.2. Best estimate of the relationship of ECA value to canopy height (with 95% confidence intervals), combining the data sets of Figure 3.1 in 2 ways: a) All studies weighted equally, b) All studies, but with relative weight of 2 for Winkler, and 1 for all others. Note that these results assume a relationship between canopy height and canopy density or closure (as shown in Figure 3.3). Horizontal blue lines are values used in the Watershed Assessment Procedures guidebook.

Adjusting the relationship for different canopy cover

In addition to height, ECA values are clearly affected by canopy density, cover or closure, as summarized in section 4. Most obviously, a single tree in a clearcut is not going to produce full hydrological recovery no matter how tall it grows. Ideally, there would be data from many regenerating stands, covering the full range of heights and canopy covers. If that were the case, then standard two-factor models could be used to examine the relationship of recovery with both variables and their interaction. However, the few data points and a high degree of confounding between the two variables prevent this 2-variable analysis. Instead, the recovery-versus-height curve presented in Figure 3.2 assumes that stands will show the same average relationship between canopy cover/closure/density and canopy height as those in the 5 studies used to generate the ECA curve. These relationships are shown in Figure 3.3[9]. The stands in Winkler (2000), Talbot and Plamondon (2002) and Buttle et al. (2005) showed a similar nearly-linear increase in canopy density or closure with tree height, with canopy similar to mature stands attained by 8-12m height. In Hudson's study, canopy density in the taller regenerating stands exceeded the density of the mature stand. In Hardy and Hansen-Bristow (1990), the 12m tall stand still had considerably less canopy cover than the mature stand. These measurements of canopy density may help explain some of the variation between studies – particularly the faster decrease in ECA value with height in Hudson's stands, which also showed faster increases in canopy density compared to other studies, and the slower decrease in ECA in Hardy and Hansen-Bristow's more open regenerating stands.

To use the ECA-versus-height curve of Figure 3.2, the stands should show a relationships between canopy density or closure and height that is similar to the average curve in Figure 3.3. If the canopy density or closure is different at a given height, then the relationship of Figure 3.2 should be adjusted proportionately. For example, at 6m height, Figure 3.2 predicts an

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[9] Note that Figure 3.3 standardizes the measurements to the value in the mature stand (or average of mature stands for Winkler's study), since the studies used different canopy measures.

ECA value of roughly 55% (95% CI = 47-63%). However, that would assume a canopy density of about 70% that of a mature forest (Figure 3.3). If the canopy density of the 6m stand was actually only 35% of the uncut stand, expected ECA would be 77.5% (95% CI = 73.5-81.5%). This procedure to correct for canopy cover will be important when applying this relationship to patchy regeneration in MPB-killed stands. This adjustment procedure also assumes a linear relationship between canopy cover or closure and ECA value at a given tree height. This simplifying assumption is supported by the empirical relationship summarized in Figure 4.6.

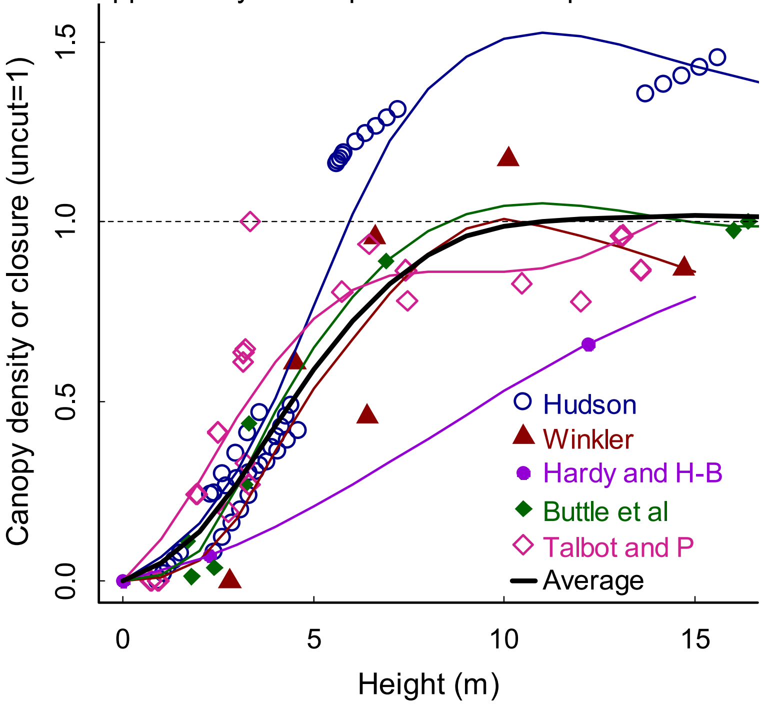

Figure 3.3. Relationship between canopy density or closure (relative to a level of 1 in mature forest) in the three studies, and the averaged relationship. The curve of ECA versus canopy height should be modified proportionally for stands in which canopy density or closure shows a different relationship with canopy height (See text). Points for Hudson (2000) come from each year's values for each stand.

4. Contribution of dead canopy pine (including ECA versus canopy closure)

This step looks at the (diminishing) contribution that canopy pine trees make to reducing ECA after they die. There are 3 parts to the analysis: 1) The fall rates of the beetle-killed pine, 2) The loss of canopy (needles, fine branches) within a standing dead pine, and 3) The relationship between canopy cover and ECA for beetle-killed stands. Parts 1) and 2) together give the expected canopy cover of a beetle-killed pure pine stand over time; part 3) converts this into the ECA of the stand over time. If a stand is only partly composed of pine that are killed by MPB, then these results apply to that beetle-killed part. The contribution of the rest of the stand (whether overstory, understory or both) is covered in separate sections (section 5 for immediate post-harvest; section 6 for long-term; section 7 for combining all the components).

Part 1. Fall rates of beetle-killed pine.

The best estimate of the fall rate of lodgepole pine snags was taken from an extensive quantitative synthesis of deadwood rates (Huggard and Kremsater 2007). That synthesis found significant differences in fall rates of lodgepole pine compared to southern pine species, so only studies of lodgepole were included here. Eight studies of lodgepole pine snag fall rates were available, some of which reported results for specific ages of snags (years since tree death) and others with regression equations. All results were converted into cumulative fall rates with time-since-death of the tree. The larger deadwood synthesis also found a relationship between fall rates and snag diameters. Results from empirical studies were therefore standardized to a diameter of 25cm, a typical average for MPB-killed stands.

The empirical data suggested a 2-year lag after tree death before any snag fall. A smoothing spline was therefore fit to the standardized results, starting at 0% fallen at year 2. Each of the 8 studies was weighted equally. Bootstrapping with the study as the unit of resampling was used to estimate confidence intervals on the splined relationship. The fitted curve reached an asymptote with about 6% of snags not fallen by age 60, but since this was beyond the age of the oldest snags included in the empirical studies, the curve and its confidence intervals were adjusted to remove this remaining 6% of snags (i.e., they were adjusted so that all snags had fallen by 60 years).

After the 2 year lag time, the annual fall rate gradually decreases from a initial high rate in the first 10 years to a low fall rate for any residual snags left standing after 30 years (Figure 4.1). The initial high rates represent unstable trees fall, with the fall rate lowering as only more stable snags – which have usually broken to a shorter height – are left. With this curve, snags have a half-life of about 13 years: half are left standing after 13 years, one-quarter after 26 years. By 26 years, however, lodgepole snags will almost certainly have no branches and the stems will have broken to relatively short heights (next section).

There was high variability among the different studies, with a 5-fold difference in annual rates during the period 5-15 years after tree death. Effects of snag size have been factored out of these results, but variability remains from site effects (warmer wetter sites tend to have faster fall rates) and random events like storm winds. This variability among studies produces wide confidence intervals in the bootstrapped results.

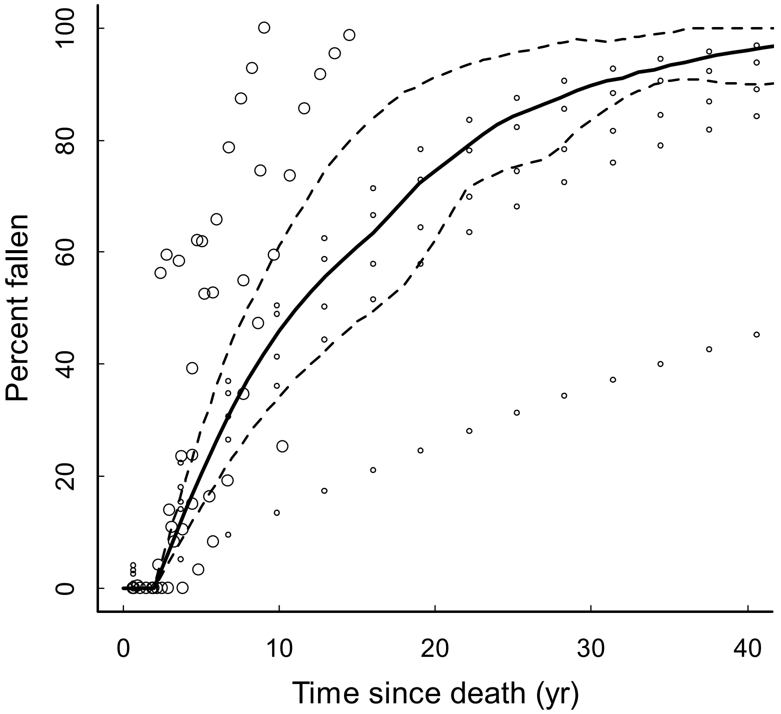

Figure 4.1. Cumulative proportion of lodgepole pine snag fallen over time (with dashed 95% confidence intervals), based on 8 empirical studies (individual data points shown, either larger symbols for estimates at specific times, or smaller points generated from published regression equations). All results have been standardized to a 25-cm dbh.

Part 2. Remaining canopy of each standing snag.

Snags that remain standing lose canopy coverage over time, as first needles are lost, then fine branches, and eventually all branches. I didn't find studies specifically reporting this value, but several studies did report that beetle-killed lodgepole pine lost all their needles by 3-5 years after death, and most of their branches by 10-15 years. Transition from class 3 to class 4 snags (Thomas et al. 1979 classification) occurred at 6.1 years (95% C.I.: 3.5-10.8 years) in a synthesis of 4 studies of 5 species of pine (Huggard and Kremsater, unpub.[10]). This transition represents the loss of fine branches, which I assumed provide about half of the tree's canopy cover. Transition from class 4 to class 5 occurred at 21.5 years (95% C.I.: 12.3-27.6 years), representing loss of all but short branch stubs. Based on light transmission reported by Coates and Hall (2006), lodgepole pine snags 8-17 years old had lost 47.4% of their (light-blocking) canopy compared to 0-7 year old snags. The Beaudry data were also used to estimate the change in canopy cover when a green stand first dies (i.e., becomes a red stand), and when a red stand loses its needles and becomes a grey stand. The green→red transition was simply estimated as occurring midway between the most open green stand and the densest red stand, with a canopy cover of 48%. Since the most open green stand had 58% cover, this implies a loss of about 10% cover when the trees first die. The transition from red→grey occurred at 33% cover, implying a reduction of about 15% from loss of needles and initial loss of small branches. (Low initial fall rates for snags mean that few will have fallen by 3-5 years when the red→grey transition occurs, so the canopy changes should mostly be due to changes within standing snags).

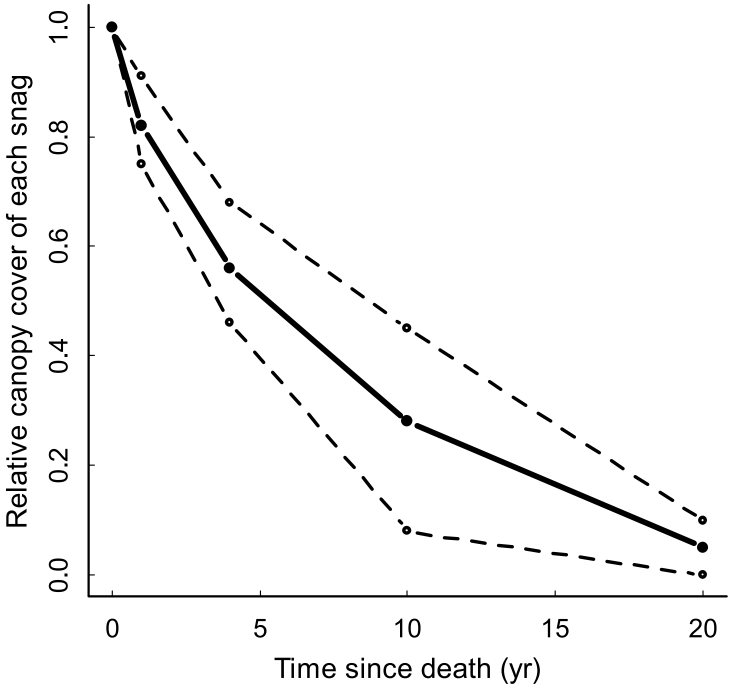

Figure 4.2. Best guesses at the loss of canopy cover for individual standing snags with increasing time since tree death. The cover is expressed relative to a value of 1 for the live tree. Dotted lines are subjective 95% confidence intervals.

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[10] Huggard, D.J. and L.L. Kremsater. Quantitative Synthesis of Rates for Projecting Deadwood in BC Forests – Technical Report. FSP project, in progress. Available from huggard@interchange.ubc.ca

I put this information together into a subjective best-guess, and subjective confidence intervals[11], of the loss of canopy coverage over time for a standing dead pine tree (Figure 4.2). The best-guess values at years 1 and 4 are based on Beaudry's canopy coverages for the most recently dead stands and the red-grey transition time. The curve in later years is based on the canopy loss reported between 8 and 17 years in Coates and Hall (2006) (using the 4-year value to represent their 0-7 year old snags), and the review of ages of transitions between snag classes. The exact numerical value is less important at the high time-since-death values, as most snags would have fallen by then anyway.

Part 3. Relationship between canopy cover of beetle-killed stands and ECA.

The third part of the analysis summarizes the data from Beaudry (2006 and 2007) by fitting smooth spline curves to his ECA results based on maximum SWE accumulation and ablation rates versus canopy coverage, with bootstrapping used to establish confidence intervals (Figure 4.3). A similar approach was taken to the results from Teti (2007) combined with Boon (2007) (Figure 4.4). These relationships were then compared with the relationship between ECA and canopy cover based on Winkler et al.'s (2004) synthesis of crown closure at many snow measurement sites in southern BC (Figure 4.5). Because Beaudry's results were nearly identical to those of Winkler et al., and the highly variable relationship from Teti (2007)+Boon (2007) also overlapped these other results, a curve combining all the results is used for the ECA versus canopy relationship (Figure 4.6). The similarity of the results from MPB and other stands implies that MPB does not have any special effect on snow accumulation and ablation, beyond that which would be expected due to its reduction of canopy cover.

The spline was forced through an ECA of 100% at 0% canopy, and 0% at the highest reported canopy cover. For Beaudry (2006 and 2007), one stand with -100% hydrological recovery for accumulation (i.e., substantially higher accumulations in the MPB affected stand than the opening) was omitted as an outlier. This assumes that the opening or green comparison stands were not representative of conditions at this outlying stand – i.e., that a less extreme result would have been obtained if more representative comparison stands had been available. The ECA calculations also omitted one mature stand with mixed spruce-fir and high canopy cover.

This analysis of Beaudry's 2006 data showed a relationship with canopy cover that was close to linear for the ECA based on accumulation rates, from 0% ECA at 63% canopy to the fixed ECA of 100% at 0% cover (Figure 4.3a). Red and grey stands were both generally along this same line. The relationship for ECA based on 2006 ablation rates was slightly different, with ECA values somewhat below the linear relationship for stands in the middle of the range of beetle-killed stands (Figure 4.3a). In particular, some of the grey stands with relatively high canopy cover had ablation rates more similar to the live forest than would be expected from a linear relationship with canopy cover. Hydrologically, these more open uniform grey stands could still provide considerable shade from the low-angle sun (keeping ablation rates low), but with no needles and fewer branches to catch snow (thus allowing greater accumulation). Beaudry's 2007 results (accumulation only), however, suggested a quicker decline in ECA with canopy cover, reaching 0 for stands with >40% cover.

Combining the 3 Beaudry curves using Bayes rule produced a smooth relationship that dropped slightly below linear (Figure 4.3b). The confidence intervals are narrow, but do not account for any dependence in the data (e.g., the same stands measured in both years, or correlations between accumulations and ablation rates).

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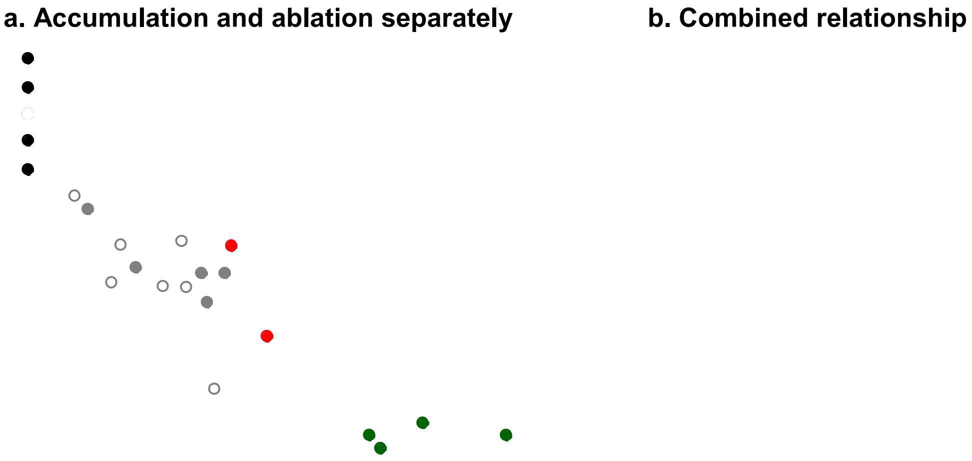
[11] "Confidence interval" is used here in the intuitive Bayesian sense – the range in which I believe there is a 95% chance of the true value occurring.



a. Accumulation and ablation separately

b. Combined relationship

relationships in Figure 4.4a are roughly linear, but this is mainly because they are fixed at the 0% and 100% extremes, with the variable data allowing almost any curve between these fixed points.) The combined curve (Figure 4.4b) also has a similar slightly curved shape to the curve based on Beaudry's results, but with very wide confidence intervals.

The data on snow accumulation and ablation versus crown closure compiled by Winkler et al. (2004) produced similar curves when scaled the same as Beaudry's data (i.e., to ECA values, and with mature stands (ECA=0) assumed to begin at 63% crown closure) and also to the more variable relationship of Teti (2007). In particular, the crown closure relationship for ECA based on accumulation was nearly linear, while the relationship for ECA based on ablation was below linear (Figure 4.5a). The confidence intervals based on the Winkler et al. (2004) data were considerably wider than those based on Beaudry (2006 and 2007), as expected from the site-to-site variation included in Winkler et al. (2004). The combined curve is, of course, between the accumulation and ablation curves, and has moderately wide confidence intervals (Figure 4.5b).

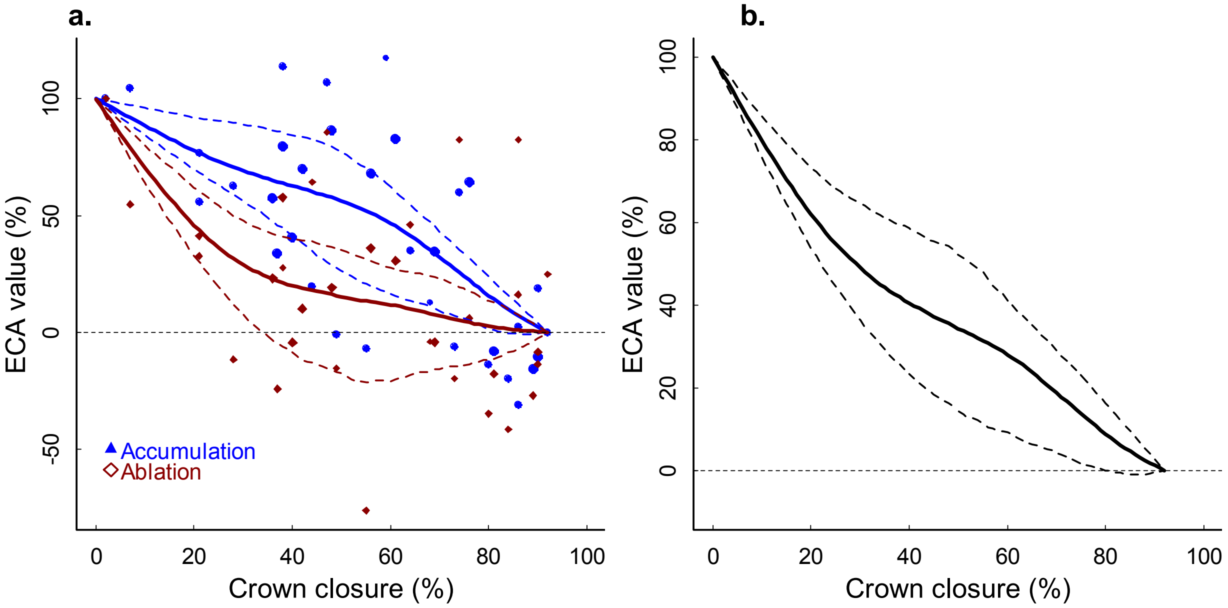


Figure 4.5. Spline curves and 95% confidence intervals fitted to the data from southern BC snow courses compiled by Winkler et al. (2004), with ECA values based on a) accumulation (blue) and ablation rates (red), and b) both measures combined.

The generally similar curves based on Beaudry (2006 and 2007), Teti (2007)+Boon(2007) and Winkler et al. (2004) were combined, after scaling the x-axis of each to the same canopy of 63% for the mature ECA=0 stands (based on Beaudry's data, assumed to represent mature pine canopy). The curves were weighted based on the number of stands in each study. The combined curve, with the moderately wide confidence intervals due to site variability, is shown in Figure 4.6. This curve and its confidence intervals were used for projecting the ECA value of the dead pine component (next subsection).

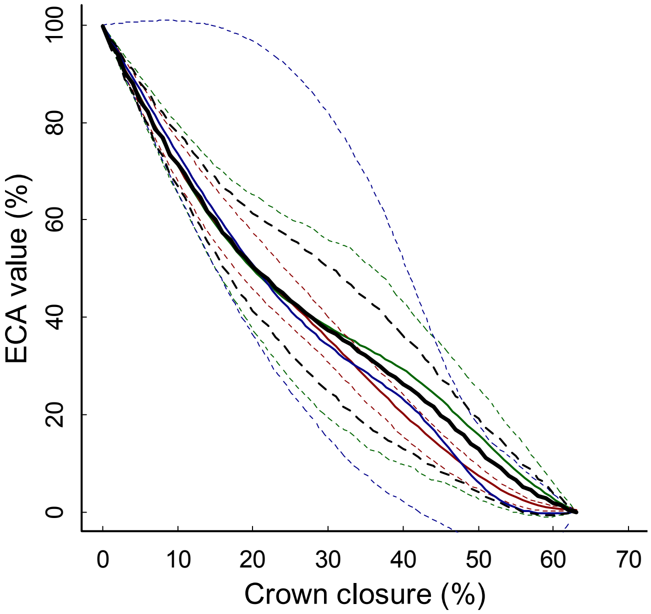


Figure 4.6. The combined relationships between ECA and crown closure from Beaudry (red), Winkler et al. (green) and Teti+Boon (blue), and the overall combined relationship (thick black). Dotted lines are 95% confidence intervals on the individual and combined curves.

Combining the 3 parts → ECA over time for the beetle-killed component of stands

The proportion of standing snags (1 minus the cumulative values in Figure 4.1b) multiplied by the remaining relative canopy cover of each snag (Figure 4.2) gives the expected canopy cover of the beetle-killed part of a stand over time (relative to the uncut stand). Assuming that the stand started with 63% cover, the relationship in Figure 4.5 is then used to convert the expected canopy cover over time into the expected ECA over time. The distribution around each of the 3 values is used to generate the distribution around the resulting curve of ECA over time (Figure 4.7). The combined curve shows that the dead pine part of the stand is expected to have an ECA of 50% after 5 (2-8) years, and an ECA of 80% after 10 (8-13) years.

Again, these results only apply to the part of the stand killed by beetles. If 50% of the canopy of a mature stand is killed, the overall stand ECA would go from 0 to 50% over the ~10-15 years of Figure 4.7 (all else being equal – i.e., if the remaining live trees remain the same). How the ECA value of the dead pine component is combined with the other components of unsalvaged stands is outlined in detail in section 7.

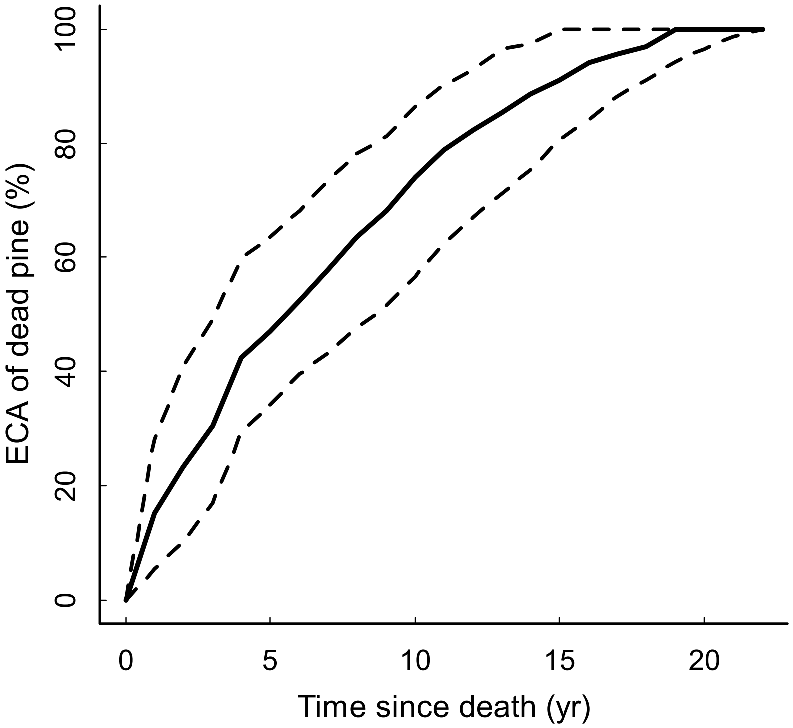


Figure 4.7. Expected ECA of the beetle-killed pine components of stands over time, based on combining the curves (and their uncertainty) from Figures 4.1, 4.2 and 4.6. Dotted lines are 95% confidence intervals. Note that the uncertainty in all figures in this report refers to "statistical uncertainty" – there should be considerable additional uncertainty about how well the simplifying assumptions of the analysis represent the complex real world! This also represents an "average" curve – there will also be more variability for individual stands or years.

5. Immediate contribution of understory and non-pine canopy

This step estimates the contribution made by understory trees (including pine that is too small to be attacked by MPB) and non-pine overstory trees to reducing a stand's ECA value. It only deals with the live part of unsalvaged stands just after harvest. A subsequent step (section 6) assesses the growth of the understory trees and how that contributes to ECA reduction over time. A previous step (section 4) looked at the contribution of the dead pine over time.

Two data sources on understory and non-pine canopy trees in pine-leading stands were used:

1. Coates et al. (2006) compiled data on density of seedlings (10cm to 1.3m height) and saplings (1.3m height to 7.5cm dbh), and basal area of non-pine canopy and sub-canopy trees from mensuration plots in the SBS zone in the Nadina, Vanderhoof and Prince George districts. Five subzone variants were represented by 43-399 plots.
2. Vyse et al. (2007) surveyed density of seedlings, saplings, and poles (7.5cm to 15cm dbh) and % basal area of non-pine canopy trees in 11 subzone variants in the Kamloops area, including in the Chase Creek watershed. The IDFdk1, 2 and 3 variant had similar distributions of density of understory components, and were combined for the understory analysis. However, although there were only 6 plots in the IDFdk2, these showed much more non-pine basal area than the many more plots in IDFdk1 and IDFdk3, so the IDFdk variants were kept separate for summaries of basal area of non-pine canopy.

Data were taken from the report of Coates et al. (2006) and from Vyse et al. (2007). Data on saplings (and pole trees; Vyse et al. only) were available as proportions of surveyed plots in classes of 200 stems/ha (i.e., 0-200, 200-400, 400-600, etc. stems/ha)[12]. Basal area of non-pine subcanopy and canopy trees in Coates et al. were presented in classes of 0-1, 1-2, 2-5, 5-10, 10-15, 15-20, 20-25 and 25+ m^2/ha. Vyse et al. presented basal areas of pine as percentages of the total basal area of the plot; non-pine basal area is 100 minus this percentage.

The analysis treats the stand as 2 components: 1. The contribution from the basal area of non-pine canopy. This is directly proportional to the proportion of total basal area made up of non-pine species. For example, the canopy component of a stand with 40% non-pine basal area in the canopy would reduce the ECA value for the stand by 40%. 2. The contribution of the saplings (and pole trees; Vyse et al. only). The contribution of these small trees is based on both their density and height, as explained below. This contribution is only considered to apply in the part of the stand that was pine canopy. For example, with 40% non-pine, the sapling (and pole) contribution would only apply in the 60% of the stand that was pine. If that sapling contribution was, for example, 10%, the total contribution to reducing ECA of the example stand would be 40% (from non-pine canopy) + 10%*60% (from understory) = 46% of a fully live mature stand (i.e., the ECA would be 54% if there was nothing else in the stand).

All the analyses were done separately for the reported BEC units, with the exception of combining Vyse et al.'s three IDFdk variants for the sapling and pole analyses. Results are presented here separately for each BEC unit, but there may be better ways to combine some units – especially where sample sizes were small and/or BEC units had similar results. Results are reported for all sampled units, not just those in Chase Ck.

Contribution of non-pine canopy

The contribution of the basal area percentage of non-pine canopy was simply given by the reported data on percentage non-pine for Vyse et al. – 40% non-pine would equal a contribution to reducing ECA of 40%. For Coates et al., where actual basal area was reported (rather than percentage of the plot's total basal area), the total basal area was assumed to come from a normal distribution with mean of 45 m^2/ha and SD 7.5m^2/ha (producing 95% CI of ~30-60 m^2/ha). For example, a non-pine basal area of 10m^2/ha in Coates et al. would constitute 22.2% of the stand on average with 95% CI 16.7%-33.3% (10/45=22.2%; 10/60=16.7%; 10/30=33.3%).

For both studies, there is uncertainty in the distribution of plots by BA class (i.e., what proportion is in each of the BA classes). Bootstrap resampling was used to estimate this uncertainty. The total number of plots for a BEC unit was randomly reassigned to the classes, with the chance of assignment to a class being given by the observed proportion of plots in that class. 1000 bootstrap iterations were used to establish the sampling distribution. These bootstrap resamples (along with the distribution of the total basal area for Coates' study) were used to establish the expected distribution of the percent of non-pine BA – and hence the contribution of the non-pine canopy component to reducing the ECA value of the stand.

Contribution of understory

A similar bootstrapping procedure with 1000 iterations was used to establish the distribution of saplings (and poles; Vyse et al. only) in the different density classes. Both studies reported actual densities of the understory components. These were converted to percentages of the densities assumed to produce a completely stocked stand by using a total understory density for a stocked stand that was normally distributed with a mean of 1200 stems/ha, SD of 100 stems/ha (and therefore 95% CI of ~1000-1400 stems/ha).

Calculating the contribution of the understory also needs to account for the height of these trees. For saplings, defined in both studies as being >1.3m height and <7.5cm dbh, the

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[12] Proportions in each category were derived from the cumulative proportions presented by the authors.

average sapling height was considered to come from a normal distribution with mean 3.2m and SD 0.66m [13]. For the poles in Vyse's study, average height was considered to come from a normal distribution with mean 8.0m and SD 0.97m [14]. This height value was converted into an ECA reduction value using the ECA versus height relationship generated in section 3. The uncertainty of that ECA-height relationship was also incorporated into the uncertainty of the ECA reduction of the saplings.

Four uncertainty components were thus incorporated in calculating the ECA contribution of the saplings (and poles): 1. The sampling distribution of the density classes for the stems themselves, 2. Some uncertainty in the density required for a fully stocked stand, 3. Uncertainty in the average height of the saplings (or poles), and 4. Uncertainty in the relationship converting height to ECA reduction.

Combining the components

This analysis results in a distribution for each BEC unit for: 1) Non-pine canopy contributions, 2) Sapling contributions, and 3) Pole contributions (Vyse et al. only). The overall contribution is calculated simply by combining 1) and 2) (and, optionally, 3) for the units sampled by Vyse et al.). Because there is a sampling distribution of the non-pine canopy contribution, and the understory contribution (which itself is a distribution) only applies to the remainder of the stand, 1000 Monte Carlo iterations were used to calculate the total contribution and its sampling distribution. For the Vyse units, this was done as two options, with and without a contribution from poles. (No pole contribution would occur if all pole sized trees were assumed to be pine susceptible to MPB). This summing of the components assumed that their distributions were independent (i.e., that there were not more or less understory trees with more or less non-pine basal area). Plots provided by Alan Vyse suggested no relationships between understory density and non-pine BA.

Summary of results

Non-pine canopy contributions to reducing ECA were in the range of 10-20% in 5 of the 12 BEC units across the two studies. Non-pine levels were lower in SBSdk and SBSmc3, which are dominated by pine. Higher levels of non-pine species in stands designated as pine-leading occurred in MSdm3, SBPSmk, SBSdw1, and ESSFdc3. IDFdk2 plots were dominated by Douglas-fir, despite being labeled as pine-leading, but there were only 6 plots in this variant. True firs and spruce were the common non-pine species in the other variants.

Although saplings were common in many stands, their short height reduced their contribution to reducing ECA, with the majority of resulting values between 2.5 and 6%. These trees, however, are generally expected to release after the overstory pine dies, and make a greater long-term contribution to reducing ECA (examined in section 6). Pole-sized understory trees were also fairly common in all BEC units in Vyse et al.'s study, and with their greater height, were predicted to have a greater contribution to reducing ECA. This ranged from 7-14% across the variants.

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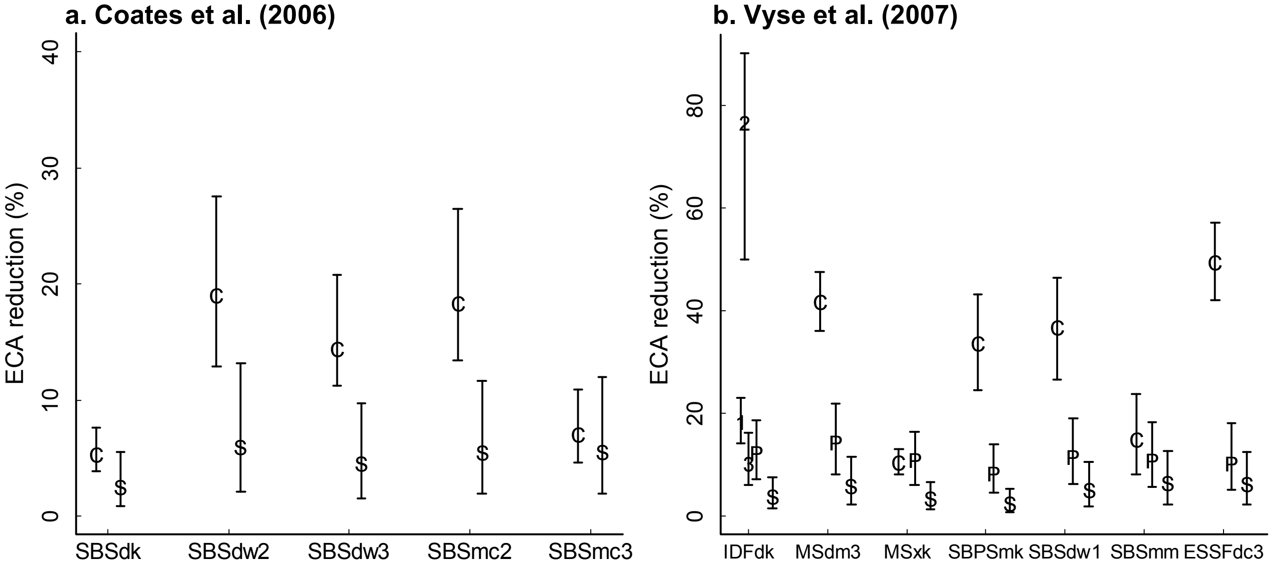
[13] This mean and SD were derived by assuming sampling from a distribution of individual saplings that ranged from 1.3m to 6m in height, with twice as many at the lower end than the upper end of the height scale.

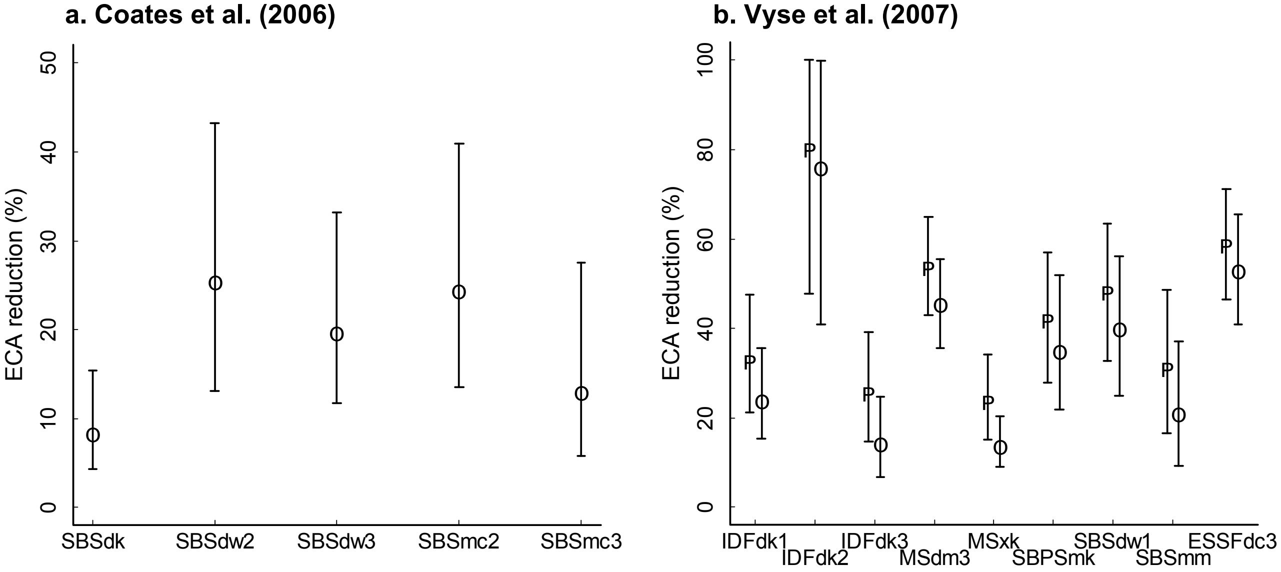
[14] These values came from a similar derivation, assuming poles ranged from 5 to 12m tall, with twice as many at the lower end of the height scale.


a. Coates et al. (2006)

b. Vyse et al. (2007)

Figure 5.1. Expected reduction in ECA of pine-leading stands shortly after MPB attacks, from contributions of non-pine canopy ("C"), saplings ("S") and poles ("P"; Vyse et al. only). Separate values for canopy contributions from IDFdk1, 2, and 3 are shown for Vyse. Error bars are 95 confidence intervals. Note the different y-axis scales.

Summing the components produced total expected contributions from understory and non-pine canopy mainly in the range of 15-40% (with wide confidence intervals – typically at least ±10%). SBSdk had the lowest expected contribution at 8.3% (95% CI: 4.4-15.9%), with higher total contributions in the fir-dominated IDFdk2, and in the MSdm3 and ESSFdc3. Most of this immediate post-disturbance contribution was due to non-pine canopy. Poles made a substantial additional contribution in most of Vyse's BEC units. Beliefs about whether these poles are likely to be susceptible to MPB will have a noticeable influence on the expected hydrological value of unsalvaged MPB stands shortly after attack.


a. Coates et al. (2006)

b. Vyse et al. (2007)

Figure 5.2. Total expected ECA reduction of pine-leading stands shortly after MPB attacks, due to contributions of understory and non-pine overstory, without poles ("O") versus with poles ("P"; Vyse et al. only). Error bars are 95 confidence intervals. Note the different y-axis scales.

6. Projected changes in the contribution of understory over time

This step looks at changes over time in the contribution of understory saplings and seedlings in unsalvaged MPB-killed stands, and of planted pine seedlings in clearcut-salvaged stands. It uses a simple modeling approach to track the changes in the components. Because this step is more complicated than previous ones and there is less directly relevant information, it relies more heavily on assumptions about different parameters. All these parameters are specified with associated uncertainty. As comments are received from reviewers, we are incorporating other people's different assumptions about the parameters, or conducting additional runs to see the effects of their different assumptions. Some of these extra runs are presented in section 7, where the understory, dead pine and non-pine canopy contributions are totaled, to compare salvaged, 'partially salvaged' and unsalvaged stands over time.

The contributions[15] of 5 components of unsalvaged pine stands are tracked until ECA is predicted to be return to 0:

1. MPB-killed overstory pine. This contribution was examined in section 4. It is expected to decline from near 100% at the time of tree death to 0% in 10 to 20 years.
2. Non-pine overstory trees. The contribution and associated uncertainty for this component was specified in section 5, based on field surveys by Coates et al. (2006) and Vyse (in progress). The contribution of this stand component is assumed to remain the same over time. Although some of these trees will undoubtedly die, the remainder will grow. In the absence of any direct information on these rates of change, a simplifying assumption was made that these two processes would more-or-less cancel out in terms of ECA effects.
3. Understory saplings (optionally including the poles in Vyse's study). To model these, the distribution of initial (time 0) densities and heights are as reported in section 5 summarizing Coates et al (2006) and Vyse (in progress). These initial values depend on the BEC variant. The saplings grow over time, following the curve of height versus time predicted by VDYP. The VDYP height-versus-time curve depends on site index (SI), and the mix of 4 main species (spruce, true fir, Douglas-fir and lodgepole pine). Saplings at time 0 are assigned an effective age, based on what age trees on the VDYP curve would be when they reached the height of the existing saplings. For instance, if the saplings are 3m tall, and the VDYP curve shows that trees reach 3m at 12 years for that SI and mix of species, the saplings are considered to be 12 years old at the time of disturbance. The saplings only start to grow in height after a "release delay", specified (with its uncertainty) by the user. In the examples presented below, a release delay averaging 5 years was used, with fairly broad uncertainty (Figure 6.1a).

   Density of saplings decreases over time due to mortality. The mortality rate and its distribution is specified by the user, as the proportion of existing saplings that will survive to age 30. In the examples, the 30-year survival rate was 50%, with 95% CI's of about 30-70% (Figure 6.1b). One additional run was conducted in which there was an initial 50% mortality of saplings, followed by the same 50% survival over 30 years of the remaining 50% of the saplings[16].

   Once growing saplings have reached the height producing an ECA of 0 at full stocking (12m), they continue to grow following the VDYP curve, with increasing basal areas leading to increasing effective density. For example, if saplings were initially at 50% the density required for full stocking, this density might have declined to 25% by the time they reached

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[15] Note that the contributions of the different components do not simply sum together to give the total contribution ECA reduction of the stand – because the components overlap. See subsection "Summing the component contributions…" later in this section, and section 7.

[16] Results for "additional" runs are only presented in section 7, where the understory results developed here are combined with the dead pine and non-pine canopy contributions to compare the 3 management options.

12m height, due to mortality. Having reached the height representing ECA=0, they would then be making a 25% contribution to reducing ECA. After that point, however, their basal area would continue to increase, causing the effect

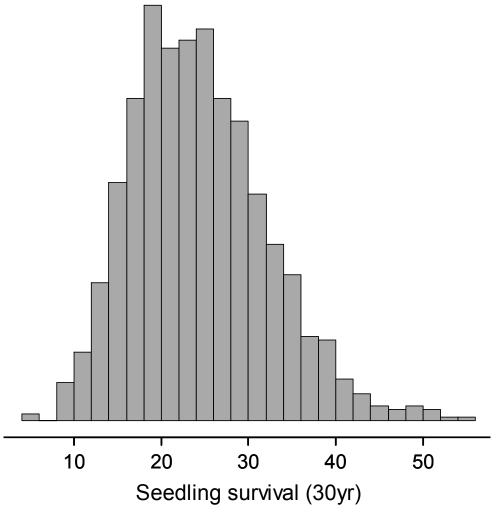

Figure 6.2. The distribution used in the examples for seedling survival – the percentage of existing seedlings that will survive for 30 years. The average value is 25%.

5. New seedlings. Seedlings establish over time after the MPB disturbance, eventually producing full stocking levels in the stand. Users specify how many years (with uncertainty) are expected until the stand is fully stocked by natural regeneration. In the examples, an average delay before full stocking of 20 years was used, with skewed 95% confidence intervals of 5-45 years (Figure 6.3). An additional run was conducted with full natural stocking occurring in an average of 10 years (with a similar shaped distribution as Figure 6.3). The same density of seedlings are added every year to reach this stocking level.

Species composition of these seedlings are assumed to be the same as the existing seedlings and saplings, except that pine is omitted on the basis that nearby seed sources would be dead, and pine is less likely to regenerate without fire. However, cones from dead pines will still be viable and can probably open when they dry out on hot ground (Vyse pers. comm.) Pine could therefore be included in the new regeneration. The main effect this would have is a somewhat faster recovery time, because pine is assumed to grow faster than other species in VDYP. One additional run was conducted with new pine regeneration to see the effect of the assumed exclusion of new pine regeneration.

New seedlings also grow following the VDYP height growth curves for the SI and species mix. Each year's cohort of new seedlings is tracked separately, since they are all different heights as they grow through time. These seedlings also make contributions to reducing ECA based on their height and relative density. This means that although full stocking might be attained after, for example, 20 years, many of the seedlings are still small at that point, so that full reduction of ECA from these seedlings would not occur until considerably later, when they had all grown to 12m. For simplicity, the new seedlings do not have mortality – just enough are started each year to produce the full stocking level after the specified number of years[18].

Note: There is no uncertainty associated with the VDYP and TIPSY curves, because it was beyond the scope of this project to go back to the original data these curves are based on (or to test plots) to establish this uncertainty. Since tree growth is quite variable, this lack probably substantially – and falsely – reduces the uncertainty of the results.

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[18] This is somewhat conservative for ECA – if there were extra new seedlings originally and only some survived to produce full stocking levels, there would be more seedlings growing overall, and hence greater reduction in ECA. However, because most of that mortality would take place when the seedlings were small, the ECA effect would also be small. Given that little difference is expected, the simplified approach used here is easier to implement and understand.

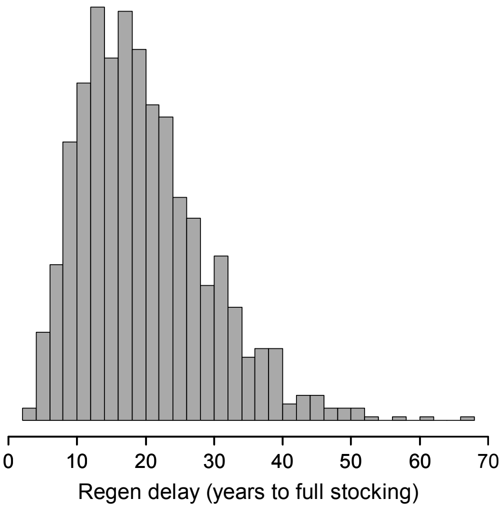


Figure 6.3. The distribution used in the examples for regeneration delay – years after disturbance until new seedlings would reach full stocking levels. (Note: Since these new seedlings are assumed to initiate in equal numbers every year, some would still be very small once the regeneration delay had passed. They would grow over time, finally leading to 0% ECA once the youngest new seedlings had reached 12m).

Summing the component contributions for unsalvaged stands

A "top-down" approach is used to sum how these components contribute each year to reducing ECA. First, the non-pine overstory trees are assumed to occupy their proportion of the stand's space. The contribution of the MPB-killed overstory pine then applies to the remainder of the space. This contribution declines over time as these snags lose needles and branches, and fall. The contribution of the understory saplings each year applies to the space vacated by the declining snags. Existing seedlings contribute in the space left by the saplings, and new seedlings contribute in the remaining space. As a simple example, if each of the components happened to be making a 20% contribution to reducing ECA at some time, the total contribution would be:

Component	Contribution	Remaining "space"
Non-pine overstory	20%	80%
Dead overstory pine	80% x 20% = 16%	80% - 16% = 64%
Saplings	64% x 20% = 12.8%	64% - 12.8% = 51.2%
Existing seedlings	51.2% x 20% = 10.2%	51.2% - 10.2% = 41%
New seedlings	41% x 20% = 8.2%	
Total ECA reduction	67.2%	

In other words, the ECA value for that stand would be 100 - 67.2 = 32.8%. The underlying assumption is that the different components are randomly located independently of each other. If there is 20% non-pine overstory, there is a 20% chance that a particular sapling will be under an overstory tree, and therefore not making any additional contribution to reducing ECA. Because each of the contributions (the 20% values in the example) has an associated uncertainty, Monte Carlo simulations are used to establish the uncertainty of the resulting total.

Regeneration in clearcut-salvaged and planted stands

For the salvaged stands, it is assumed that lodgepole pine are planted at full stocking density, and that they grow successfully following the TIPSY curve for the BEC variant and SI. Tree height is converted to ECA value with the same ECA-versus-height curve used above.

Other possible complications to consider

Full spatial stand modeling would be needed to deal with all the complexities of a regenerating unsalvaged stand with residual structure and advanced regeneration:

- Overstory affecting understory. This would include the possibility that understory densities differ depending on the amount of non-pine basal area in the overstory. Species composition of the understory could also reflect the overstory on a stand-by-stand basis (rather than across the whole BEC unit). Probably most importantly, remaining non-pine overstory would affect both the rate of natural regeneration and the rate of growth of the understory. This would tend to reduce the extremes of the distribution of total contribution (because there would be less understory contribution with more overstory contribution, and vice versa).
- Spatial non-independence of the overstory and understory. If saplings tends to be located away from non-pine canopy trees, they would be making a somewhat greater additional contribution than is accounted for above. If they tend to be clumped under canopy trees, they would be making less of a contribution.
- Growth rates of advanced regeneration faster for smaller saplings. Alan Vyse suggests that taller advanced regeneration releases and grows more slowly than smaller trees. Taller advanced regeneration may also have shallower crowns than smaller released trees would have when they get to that height. These effects could not be captured well in the simple approach used here, because we track only the average height of each layer (with variation around that average in the different model iterations). Again, detailed modeling of different cohorts in a stand, including their crowns, is needed to capture all the complexities of regenerating MPB stands.
- The simple approach does not account for the possible effects of young regenerating stands that have understory densities well above full stocking levels. Both pine and cedar-hemlock regeneration can occur at very high densities in some stands. These dense stands may produce ECA values below those expected for their height. This type of regenerating stand was not included here (except to the extent that somewhat “overstocked” stands were included in the studies used to establish the ECA-versus-height relationship), and there seems to be little data on the effects of these dense young stands on snow accumulation and ablation.
- Extreme clumping of the understory or non-pine overstory would reduce its hydrological effectiveness, although part of this is incorporated in the mortality of these components. (The mortality can be thought of as including both the actual death of the trees and the loss of hydrological function – as, for example, closely spaced seedlings grow together, producing less hydrological effects than they would if they were further spaced.)
- Others?...

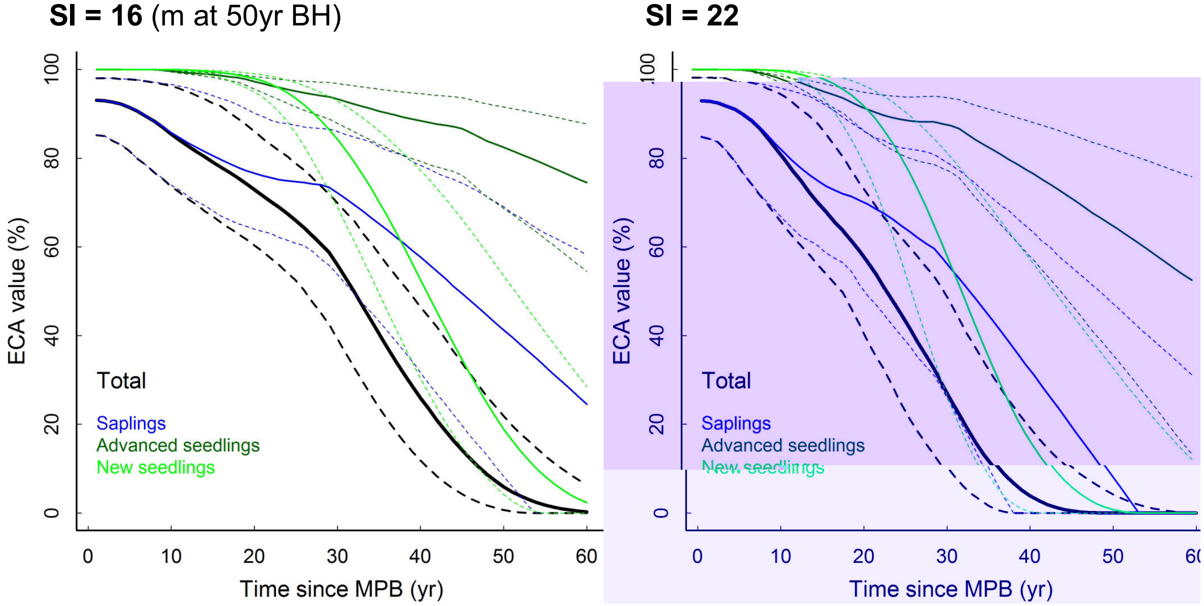
Example results

Results are presented for just 3 stand types (combinations of BEC variant and SI – MSdm3 at SI=16, MSdm3 at SI=22 and IDFdk3 at SI=22), to illustrate the approach and check that the results seem sensible. To look at a whole watershed, this is done for a larger set of stands that bracketed the range of stand type found on the landscape.

An important point is that these results – and in particular the associated confidence intervals – apply to “**the average stand**”. The uncertainty indicated by the confidence intervals is due to the uncertainty in all the input parameters. The results therefore indicate the expected average response of a large population of stands (e.g., a bunch of stands in a typical watershed). *Individual* stands will show much more variability. Similarly, results for an *individual year* will also be much more variable.

In the MSdm3 example, with 50% spruce and 50% subalpine fir in the understory, the understory ECA value decreases from the high initial amount to ECA of 0 in about 55 years in SI 16, and in about 40 years in the SI 22 example. This SI effect is as expected from the faster growth rates in higher SI. An increase in the rate of ECA decline is seen at about 5 years, when the saplings start to release. Another moderate increase in rate of decline occurs in about the middle of the recovery, when the saplings have reached the 12m height and basal area growth increases their effective density. This is also the point where new seedlings start to make a noticeable contribution. Poles make a substantial initial contribution (top versus bottom figures of Figure 6.4), but this contribution increases less than the other components because the poles are at lower densities (and also have the same release delay and mortality as saplings).

MSdm3 Understory: 50% spruce, 50% subalpine fir – Not including poles



MSdm3 Understory: 50% spruce, 50% subalpine fir – Including poles

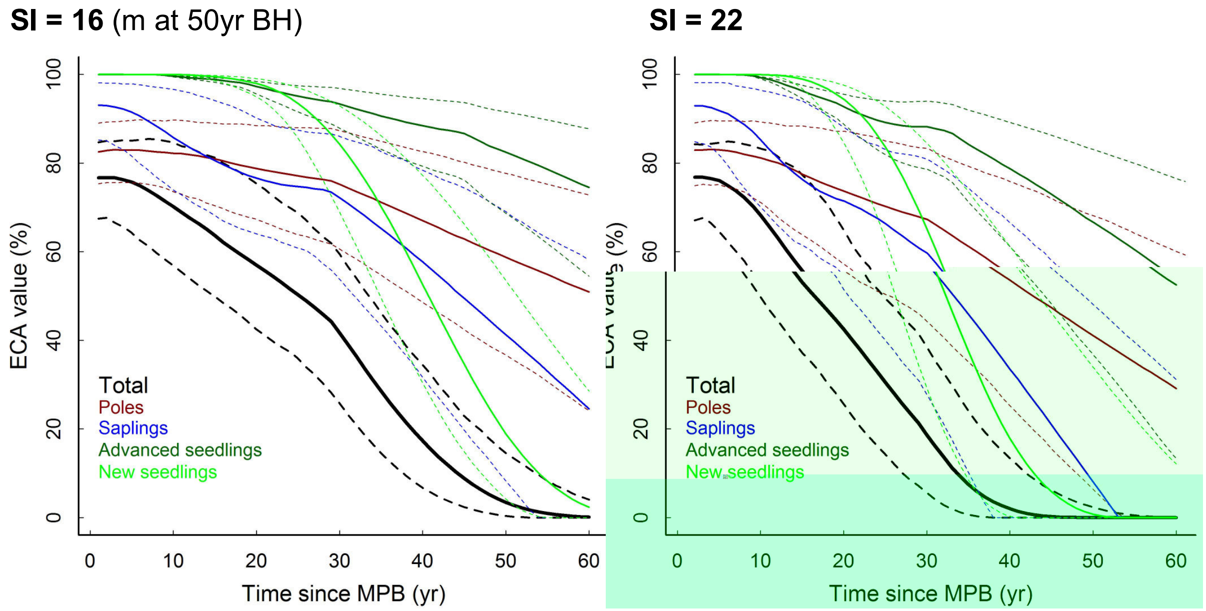


Figure 6.4. Example results for the understory **contribution of a MPB-killed pine-leading stand with non-pine components <u>50% spruce and 50% subalpine fir</u> in MSdm3. Results are presented as the ECA value of each component separately, and their combined ECA value (which recognizes overlap of components). Top 2 figures do not include a contribution from poles; bottom 2 do. Left figures use a site index of 16; right figures a SI of 22. Thicker black line is the total understory contribution (with 95% CI's); thin lines are individual components (with 95% CI's). [See section 7 for additional contribution of overstory non-pines and dead pines, and comparison to projections for salvaged stands.] Note that the slope of the curves for each component reflects both its growth rate** and the amount of the stand it occupies **(e.g., advanced seedlings grow as fast as new seedlings, but reduce ECA much less because they occupy much less of the stand's space.)**

The example with Douglas-fir and pine understory started with slightly lower initial understory contributions in the sparser IDFdk3, but showed slightly faster declines in ECA with these better-growing species (Figure 6.5).

IDFdk3 Understory: 50% Douglas-fir, 50% pine, SI=22

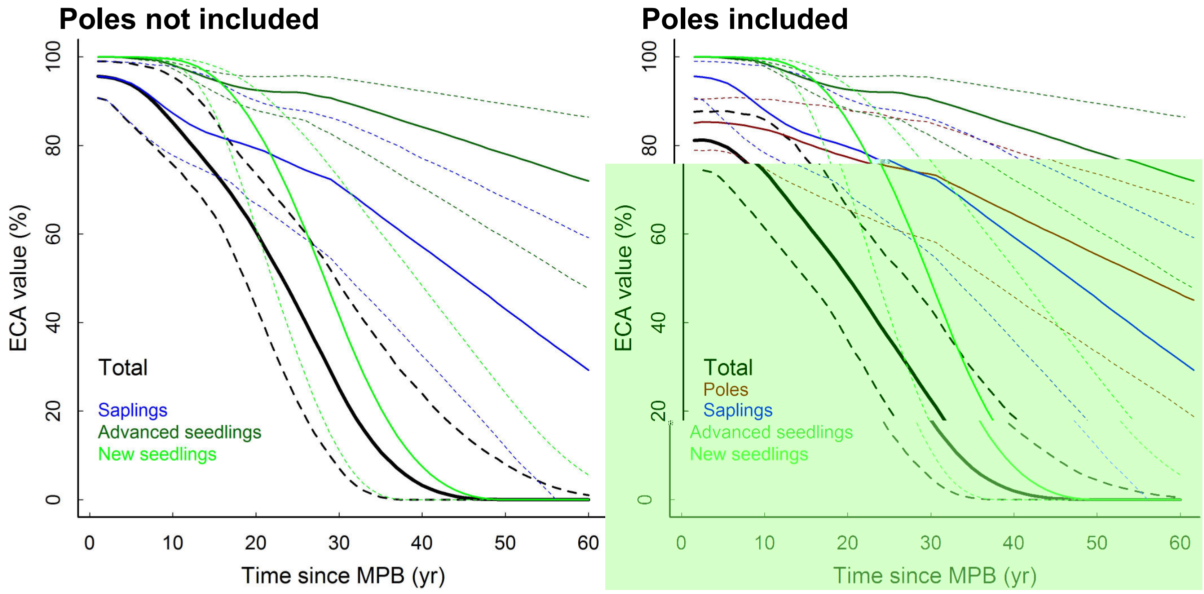


Figure 6.5. Example results for the understory **contribution of a MPB-killed pine-leading stand with understory components 50% Douglas-fir and 50% lodgepole pine (Douglas-fir only for new seedlings) in IDFdk3, SI = 22. Results are presented as the ECA value of each component separately, and their combined ECA value (which recognizes overlap of components). Left figure does not include a contribution from poles. Thicker black line is the total understory contribution (with 95% CI's); thin lines are individual components (with 95% CI's). [See section 7 for additional contribution of overstory non-pines and dead pines, and comparison to projections for salvaged stands.]**

7. Combining dead pine, non-pine overstory, and growing understory contributions to compare unsalvaged, salvaged and 'partially salvaged' stands

As a final step for comparing ECA projected over time for different salvage options, the above results for understory contributions over time were added to the previous results on the non-pine overstory contributions and the contributions of dead pine. The "top-down" approach explained in section 6 was used to sum the contributions of the overlapping components, with Monte Carlo simulations used to incorporate the effects of all sources of uncertainty. For salvaged stands, the only contributing component is the planted pine. This was grown following the TIPSY curves, with height converted to ECA value using the same ECA-versus-height relationship. Results are given for the MSdm3 examples with an understory of 50% spruce and 50% subalpine fir, at SI=16 and SI=22 (understory results presented above, Figure 6.4). Because Vyse's results showed that MSdm3 had one of the highest levels of non-pine overstory in pine-leading stands, results for SI=16 were also generated using the much lower levels of non-pine overstory found in SBSmm, and for a stand that has 100% pine in the overstory (i.e., no non-pine contribution). The third example is for stands with 50% Douglas-fir and 50% lodgepole pine understory, SI=22, in IDFdk3 (understory results in Figure 6.5). [IDFdk2 was not used, because the “pine-leading” stands in this variant surveyed by Vyse were mainly dominated by Douglas-fir]. These comparisons assume no contribution from pole-sized trees.

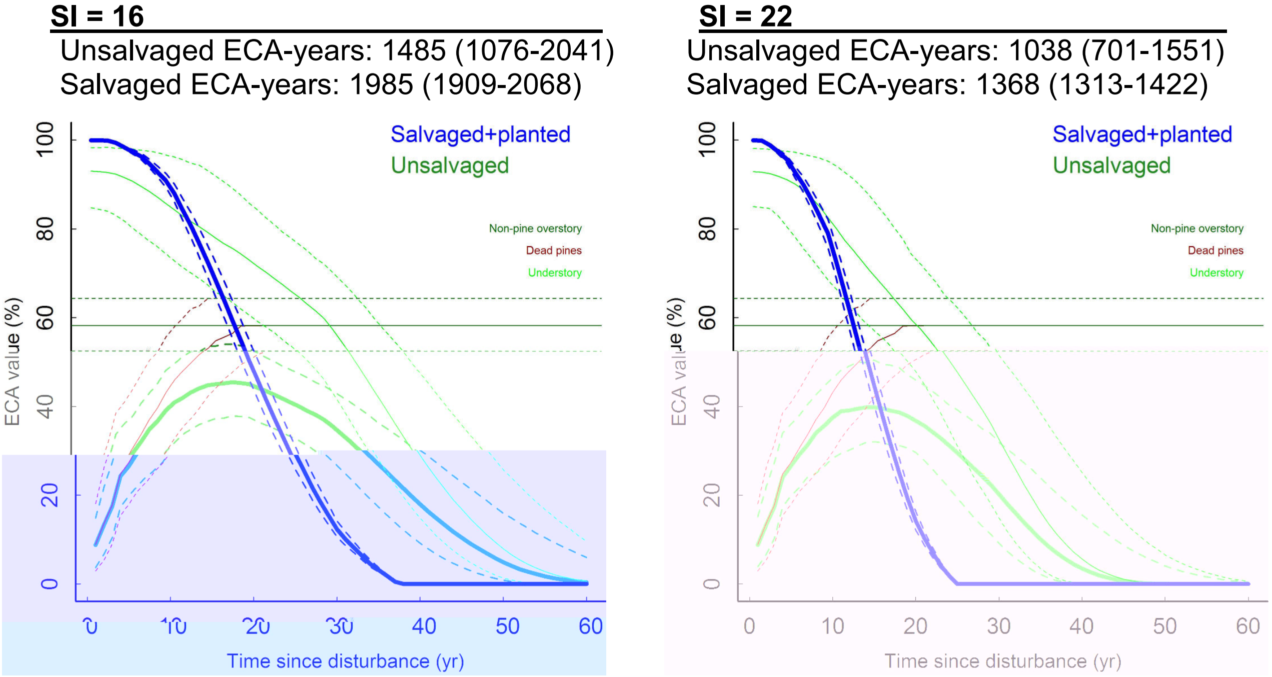
Another option examined here is ‘partial salvage’. In this scenario, all MPB-killed canopy pine are removed, along with half the non-pine canopy. Half of the sapling and seedling cover is also removed. The remaining advanced regeneration grows and undergoes mortality as in the unsalvaged stands. The stand is planted after harvest to ensure full stocking. Two options are examined for the growth of the planted stock: option 1 assumes pine is planted and grows following the TIPSY curves for managed stands; option 2 assumes that a mix of species the same as the existing seedlings are planted and grows following the VDYP curves for unmanaged stands. These options probably bracket what would really happen in ‘partial salvage’ (assuming the stands are in fact re-planted).

A quantitative index of ECA over time for the three management options is given by summing the ECA value over each of the years. The result is a value in “ECA-years”, which combines the magnitude and duration of the ECA effects. [In the figures below, this is the area below the thick green (unsalvaged or partial salvage) or blue (salvaged) curves.] With this index, 10 years at 100% ECA would be equivalent to 20 years at 50%, or 40 years at 25%, etc.

As above, the confidence intervals represent the uncertainty in results for “the average stand”, or for a watershed of many stands. Individual stands and years will show much more variability.

Note: Table 7.1 at the end of this section summarizes the ECA-years for all the options presented graphically in this section.

Salvaged versus□□□□□□□□□□□□□P□□□□□□□□.□□□□□□□□□□□e□□□□C□□□□□□□C□□e□□□□□□□

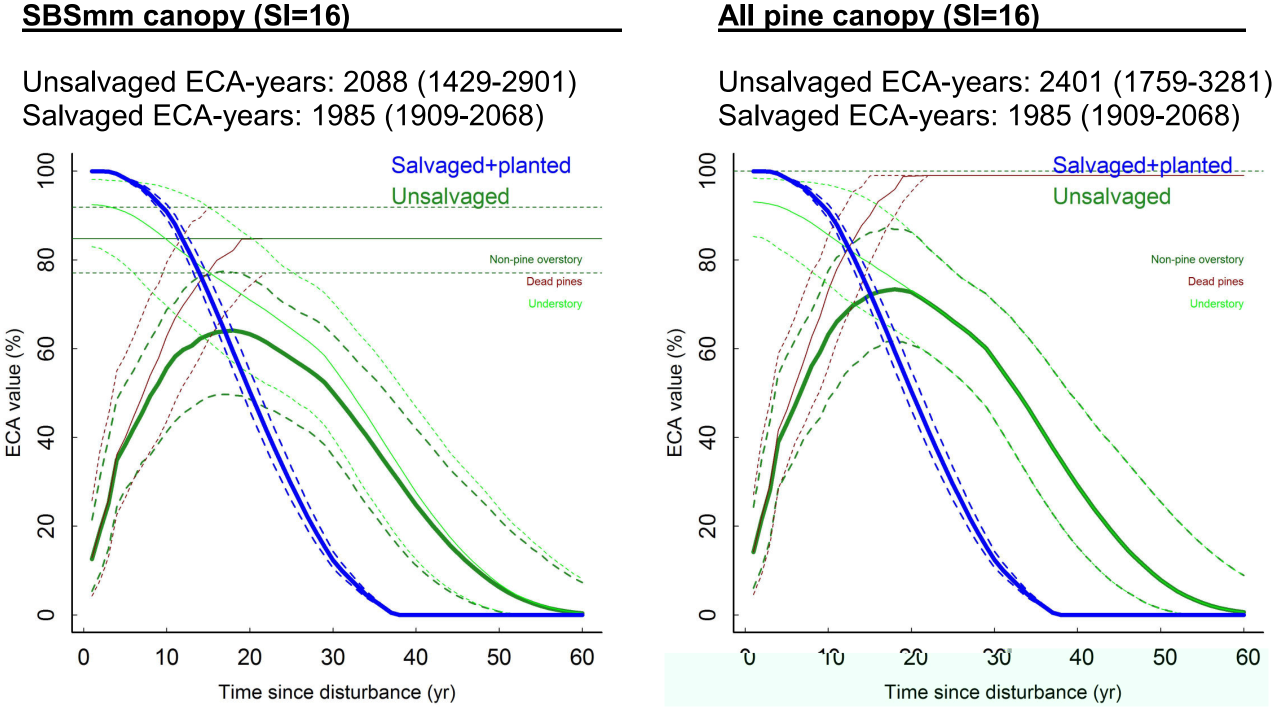

SI = 16

Unsalvaged ECA-years: 1485 (1076-2041)
Salvaged ECA-years: 1985 (1909-2068)

SI = 22

Unsalvaged ECA-years: 1038 (701-1551)
Salvaged ECA-years: 1368 (1313-1422)

Figure 7.1. ECA expected over time in unsalvaged and salvaged+planted stands with <u>50% spruce and 50% subalpine fir</u> understory, using initial conditions from <u>MSdm3</u>. Left: SI=16 (m at 50 yr BH), right: SI=22. Thin lines show components of the unsalvaged stands.


SBSmm canopy (SI=16)

Unsalvaged ECA-years: 2088 (1429-2901)
Salvaged ECA-years: 1985 (1909-2068)

All pine canopy (SI=16)

Unsalvaged ECA-years: 2401 (1759-3281)
Salvaged ECA-years: 1985 (1909-2068)

Figure 7.2. ECA expected over time in unsalvaged and salvaged+planted stands with 50% spruce and 50% subalpine fir understory, using initial conditions from <u>SBSmm</u> (left), and a stand with all pine in the canopy (right). SI=16 (m at 50 yr BH). Thin lines show components of the unsalvaged stands.

In contrast, in the example that used the initial unsalvaged conditions based on Vyse's surveys of the SBSmm (with no other changes), the unsalvaged ECA curve rose higher (Figure 7.2 left). As a result, the total ECA effect of the unsalvaged option was slightly greater than for the salvage and plant option. With all pine in the canopy, and hence no contribution from non-pine canopy, the total projected ECA of the unsalvaged option would be 21% higher than the salvaged option (Figure 7.2 right). The amount of non-pine overstory clearly makes an important difference in the results.

For the IDFdk3 Douglas-fir and pine example, recovery is faster in both scenarios (Figure 7.3), which limits the height and duration of the high point on the ECA curve for the unsalvaged option (despite relatively low non-pine canopy in this variant). Overall, the unsalvaged option is projected to have about 7% greater ECA effect. With all pine canopy (no non-pine contribution), the unsalvaged option has 17% greater ECA effect (1592 ECA-years; not shown).

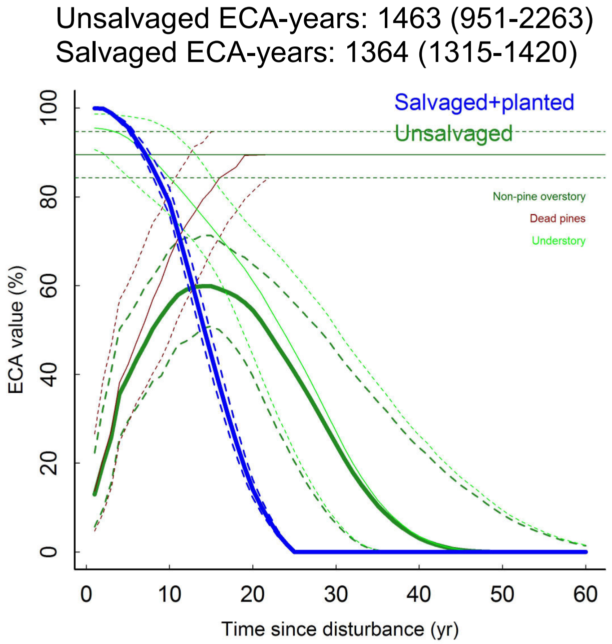

Unsalvaged ECA-years: 1463 (951-2263)
Salvaged ECA-years: 1364 (1315-1420)

Figure 7.3. ECA expected over time in unsalvaged and salvaged+planted stands with <u>50% Douglas-fir and 50% lodgepole pine</u> understory, using initial conditions from IDFdk3. SI=22 (m at 50 yr BH). Thin lines show components of the unsalvaged stands.

These examples did not include pole trees (7.5-12.5cm dbh). Additional contributions from poles, if these were not affected by MPB, would have reduced the total ECA effect for the unsalvaged option.

These results, of course, directly depend on the assumptions made about the various parameter values and their distributions. Different people's assumptions would produce different results. The results also depend on various aspects of the simplified version of a stand model, such as the independence of the understory and overstory, etc. The effect of some of the assumed parameters are examined in the section following the comparison of partial salvage.

Partial salvage

The partial salvage option includes contributions from the remaining half of the non-pine canopy trees, the remaining half of the understory, and the planted seedlings. The latter was the main driver of changes in ECA over time, with substantial differences due to the faster growth in the TIPSY-pine option compared to the VDYP-species mix option.

With the TIPSY option, 'partial salvage' had less total ECA effect than 'clearcut salvaging' in the 3 example stands (Figure 7.4 left figures). This is necessarily the case, because the planted stock is growing back at the same rate as in the clearcut (TIPSY pine growth curves), but the ‘partial salvage’ stand starts out with ECA already somewhat reduced by the non-pine canopy and advanced regeneration. The partial salvage had 32% and 31% less total ECA effect than clearcut salvaging in the MSdm3 examples, and 17% less in the IDFdk3 example. The total ECA-years of the partial salvage under this first option were close to the total ECA-years of the unsalvaged option at both SI values in MSdm3. However, the distribution of the ECA effect through time is very different. In the IDFdk3, the partial salvage option with TIPSY growth had 22% less ECA effect than not salvaging. (Remembering that confidence intervals are quite wide on most of these values).

With the VDYP species mix option, partial salvage had 2-10% more total ECA effect than clearcut salvage (Figure 7.4 right figures). The partial retention of existing non-pine canopy and understory does not compensate for the slower growth in the partial salvage assumed in this option. Partial salvage also had higher ECA effect than not salvaging, with this growth option. Although new seedlings were planted in the partial salvage option (as opposed to filling in naturally over time), the loss of the dead pine contribution and some of the contributions from the non-pine canopy and understory is a larger effect if the planted trees are not growing any faster than in unsalvaged stands.

The differences in the results based on the 2 growth options clearly illustrate that growth assumptions are crucial to the long-term projections of ECA effects. In the partial salvage scenario, the first option, with TIPSY growth, is probably most likely, since the assumptions for this scenario are not very different from clearcuts – most overstory and half the understory removed, and probably similar site conditions created by harvesting or site prep. This is particularly the case for the stands with the least non-pine canopy and understory. Additionally, the spacing of planting should reduce some of the competition effects that are inherent in the natural VDYP curves, leading to more “TIPSY-like” growth.

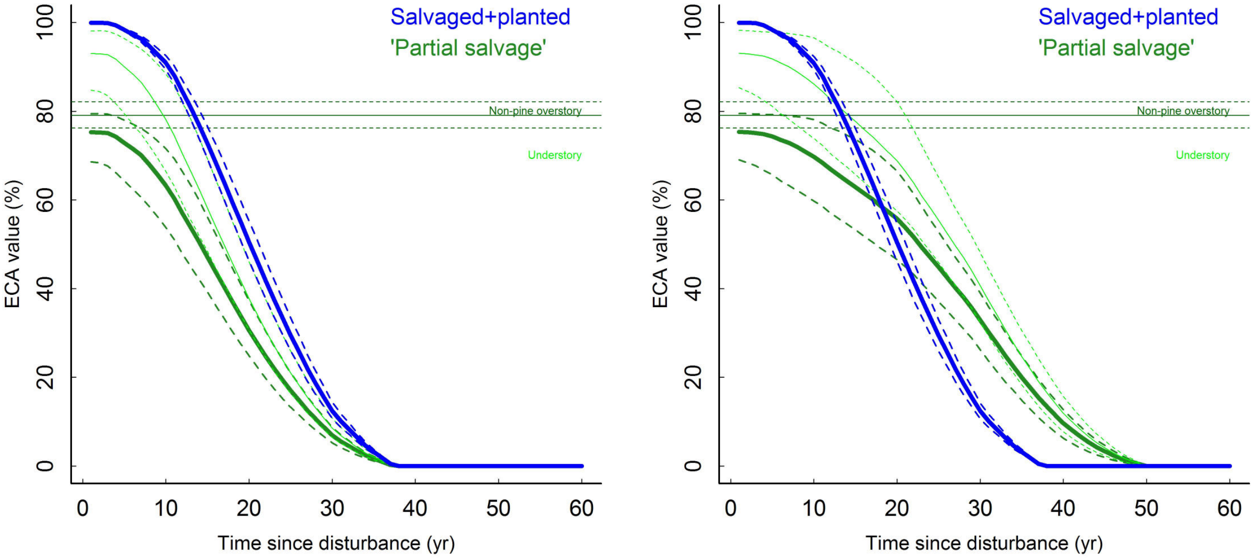
MSdm3, SI=16

Option 1 – TIPSY growth of planted pine

Partial salvaged ECA-years: 1348 (1146-1533)
Salvaged ECA-years: 1985 (1909-2068)

Option 2 – VDYP growth of planted mix

Partial salvaged ECA-years: 2017 (1695-2314)
Salvaged ECA-years: 1985 (1909-2068)



[Figure 7.4 – Continued next page]

Some variations

This section examines the effect of changing 3 variables, as suggested by reviewers of the initial draft: 1. Using an average of 10 years for natural ingress to reach full stocking levels in unsalvaged stands (versus 20 years in the models above), 2. Including pine in the new natural seedlings, 3. Including a 50% initial mortality of advanced regeneration for understory trees that die due to the disturbance or fail to release. (The understory also continues to sustain mortality over time, as in the original runs). Alternatives 1 and 3 are examined for the 3 stand types; alternative 2 is only examined for IDFdk2.

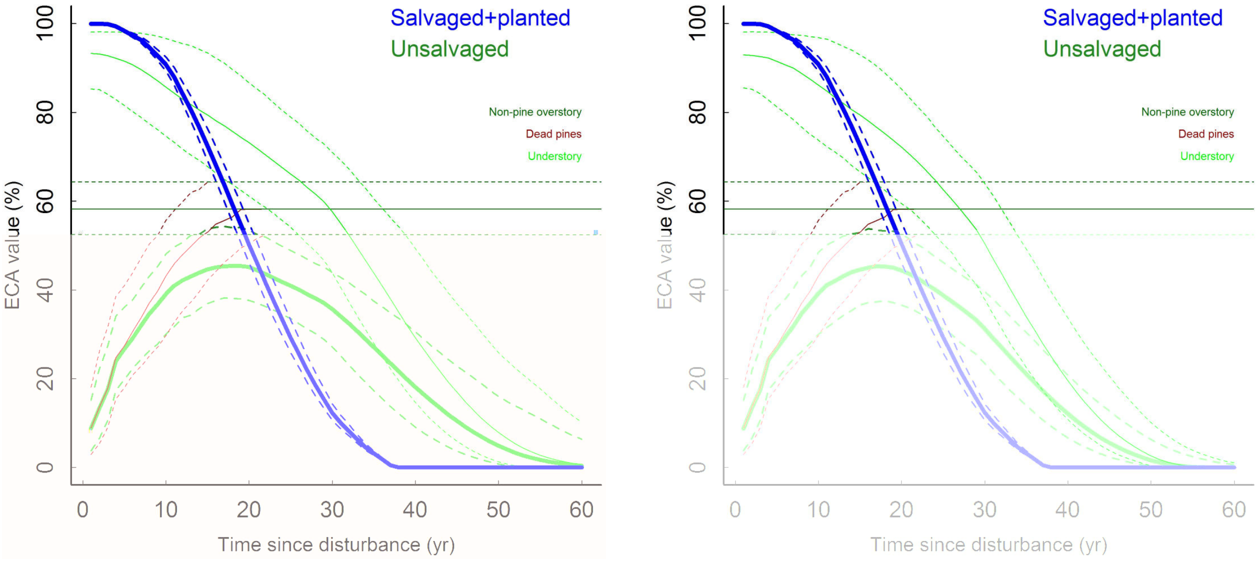
Changes in the rates of natural ingress and initial survival or release of advanced regeneration have substantial impacts on the projected results. These sensitive parameters would be a good place to focus effort on collating existing information and collecting new field measurements. Inclusion of pine in the new seedlings had only a small effect, given the simplified projection model used here.

1) 10 year natural ingress period

This option looks at the effect if full stocking is obtained by natural ingress in an average of 10 years, instead of 20 in the original runs. A distribution was also used around the 10-year average, similar in shape to the distribution around the 20-year average ingress period.

The faster natural ingress rate reduces the total ECA-years of the unsalvaged option by 10% and 12% in the MSdm3 with SI=16 and 22, respectively, and by 19% in the IDFdk3 where less non-pine canopy means that the regeneration plays a relatively larger role (Figure 7.5). The faster natural ingress rate reduces the total ECA effect of the unsalvaged option below that of salvaging and planting in the IDFdk3.

MSdm3, SI=16



20-year average for natural stocking
Unsalvaged ECA-years: 1485 (1076-2041)
Salvaged ECA-years: 1985 (1909-2068)

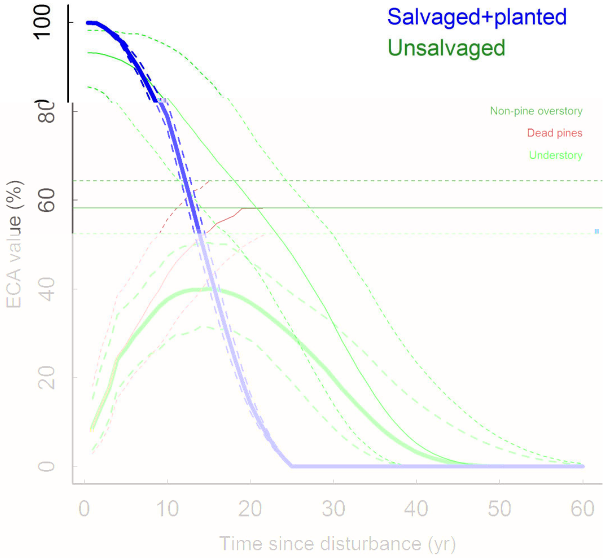
10-year average for natural stocking
Unsalvaged ECA-years: 1341 (1005-1770)
Salvaged ECA-years: 1985 (1909-2068)

[Figure 7.5 – Continued next page]

MSdm3, SI=22

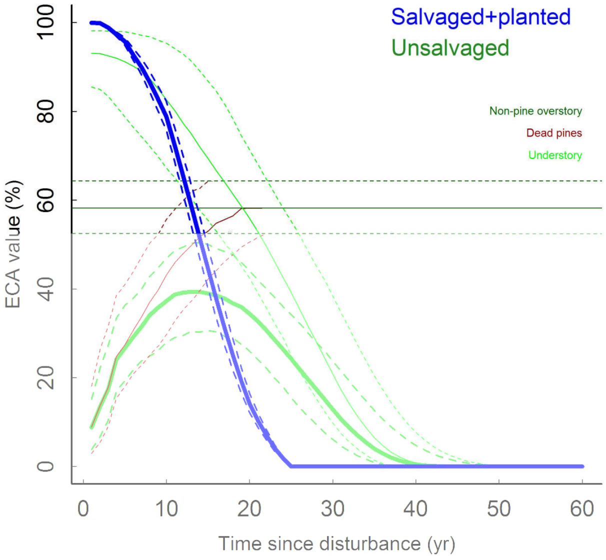
20-year average for natural stocking

Unsalvaged ECA-years: 1038 (701-1551)
Salvaged ECA-years: 1368 (1313-1422)



10-year average for natural stocking

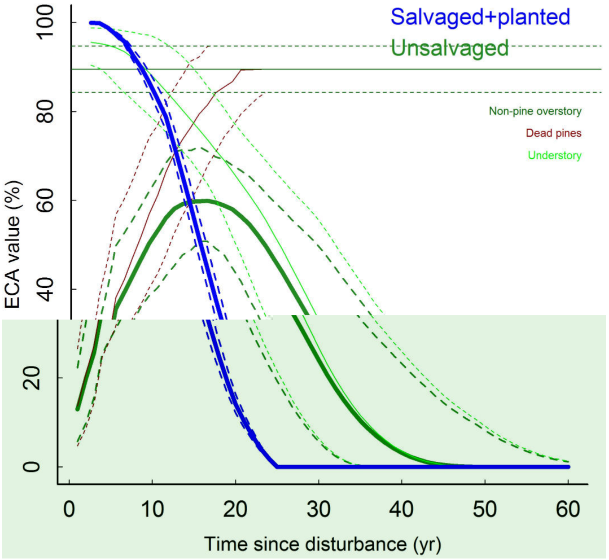
Unsalvaged ECA-years: 910 (634-1297)
Salvaged ECA-years: 1368 (1313-1422)



IDFdk3, SI=22

20-year average for natural stocking

Unsalvaged ECA-years: 1463 (951-2263)
Salvaged ECA-years: 1364 (1315-1420)



10-year average for natural stocking

Unsalvaged ECA-years: 1179 (844-1728)
Salvaged ECA-years: 1364 (1315-1420)

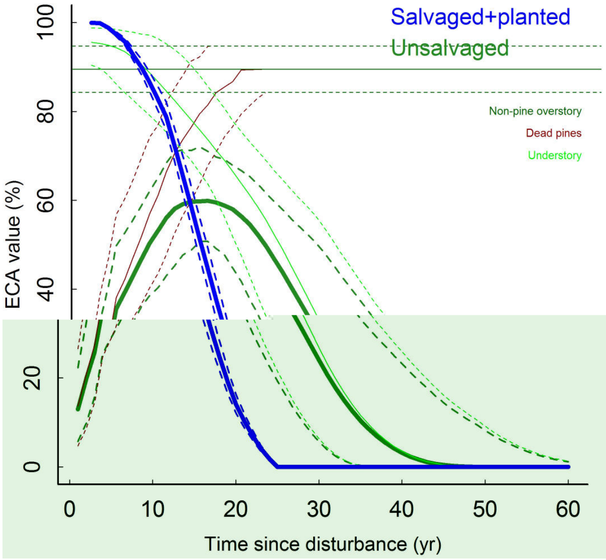


Figure 7.5. Comparison of ECA effects in unsalvaged stands assuming an average of 20 years for natural ingress to reach full stocking (left) versus 10 years (right). The clearcut-salvage option is unaffected by this assumption, and is presented for comparison with the salvaged results. Dotted lines are 95% confidence intervals.

2) Including pine in natural seedlings

Pine grows faster than other species, but the difference makes only a minor effect on total ECA when pine is included in the new seedlings in unsalvaged IDFdk3, reducing total ECA by 5% (Figure 7.6). In practice, differences in the establishment and survival of seedlings of different species is likely to have more important effects on total ECA than the different growth rates of the species.

IDFdk3, SI=22

No pine in new seedlings

Unsalvaged ECA-years: 1463 (951-2263)
Salvaged ECA-years: 1364 (1315-1420)

Pine in new seedlings

Unsalvaged ECA-years: 1387 (886-2212)
Salvaged ECA-years: 1364 (1315-1420)

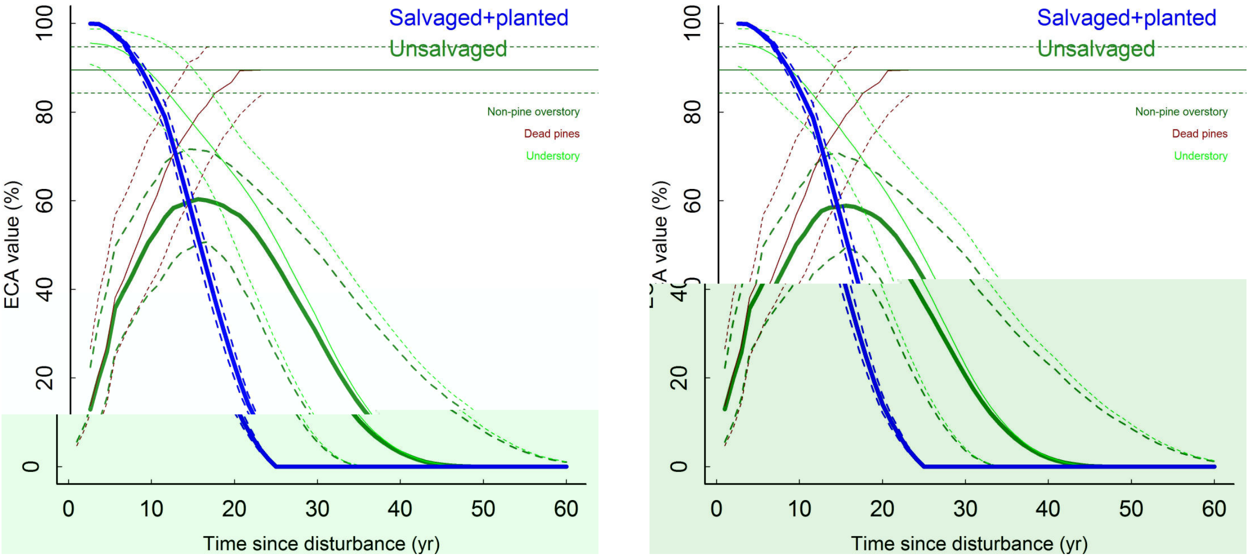


Figure 7.6.Comparison of ECA effects in unsalvaged IDFdk3 stands assuming new seedlings contain no pine (left) versus 50% pine (right). The planted clearcut-salvage option is unaffected by this assumption, and is presented for comparison with the salvaged results. Dotted lines are 95% confidence intervals.

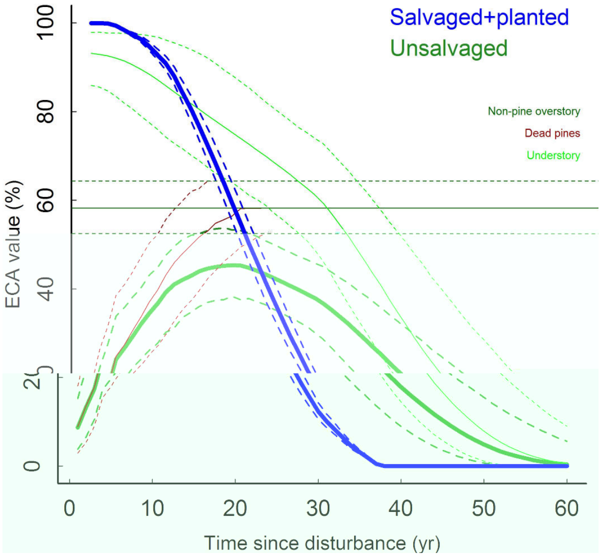
3) 50% initial mortality of natural understory

Because growth of the understory makes a substantial contribution to reducing ECA over time, a 50% initial mortality (or failure to release) in the understory increases total ECA in unsalvaged stands by 21% and 26% in the MSdm3 with SI=16 and 22, respectively, and by 16% in the IDFdk3 (Figure 7.7). The increase is due to a slightly higher and longer-lasting peak in the ECA curve after the dead pine contribution has declined. In the MSdm3 examples, this increase makes the total ECA effect of salvaging versus not salvaging more similar.

MSdm3, SI=16

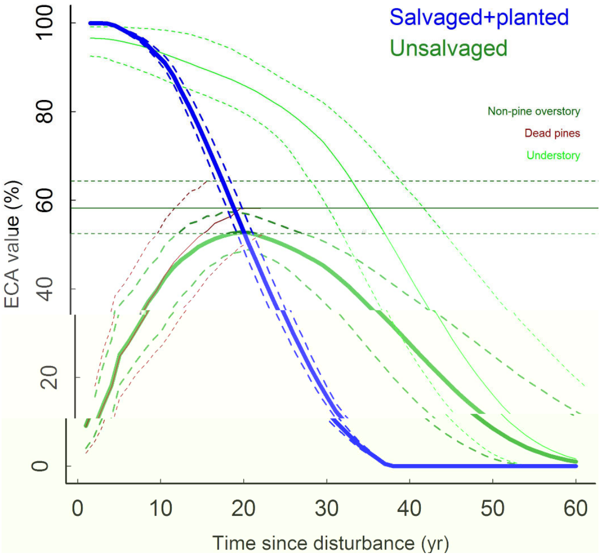
No extra initial mortality

Unsalvaged ECA-years: 1485 (1076-2041)
Salvaged ECA-years: 1985 (1909-2068)



50% extra initial mortality

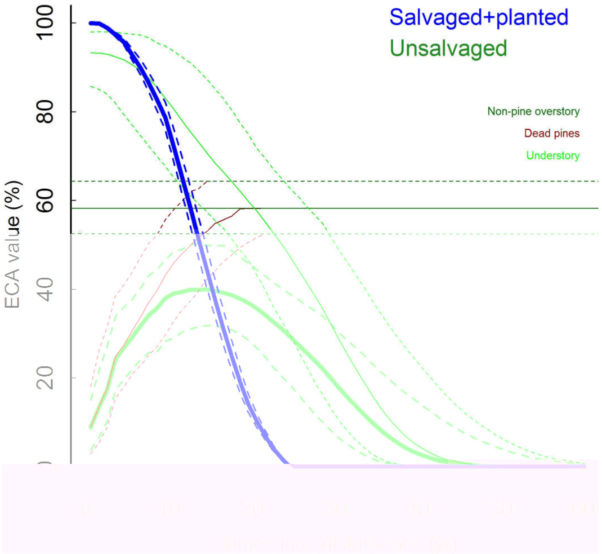
Unsalvaged ECA-years: 1796 (1368-2347)
Salvaged ECA-years: 1985 (1909-2068)



MSdm3, SI=22

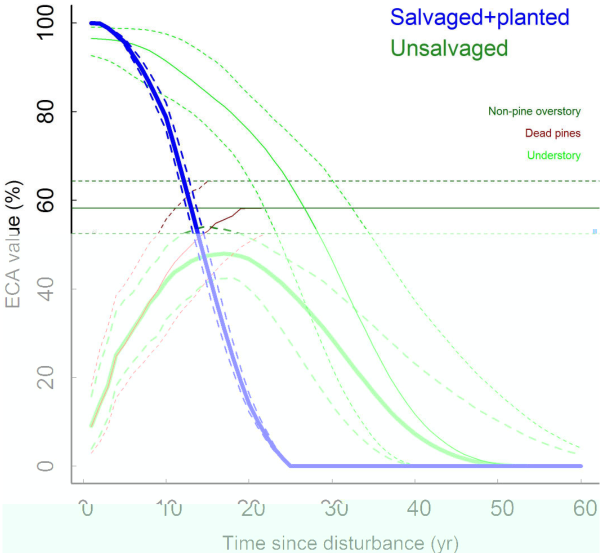
No extra initial mortality

Unsalvaged ECA-years: 1038 (701-1551)
Salvaged ECA-years: 1368 (1313-1422)



50% extra initial mortality

Unsalvaged ECA-years: 1306 (906-1863)
Salvaged ECA-years: 1368 (1313-1422)



[Figure 7.7 – Continued next page]

IDFdk3, SI=22

No extra initial mortality

Unsalvaged ECA-years: 1463 (951-2263)
Salvaged ECA-years: 1364 (1315-1420)

50% extra initial mortality

Unsalvaged ECA-years: 1692 (1071-2656)
Salvaged ECA-years: 1364 (1315-1420)

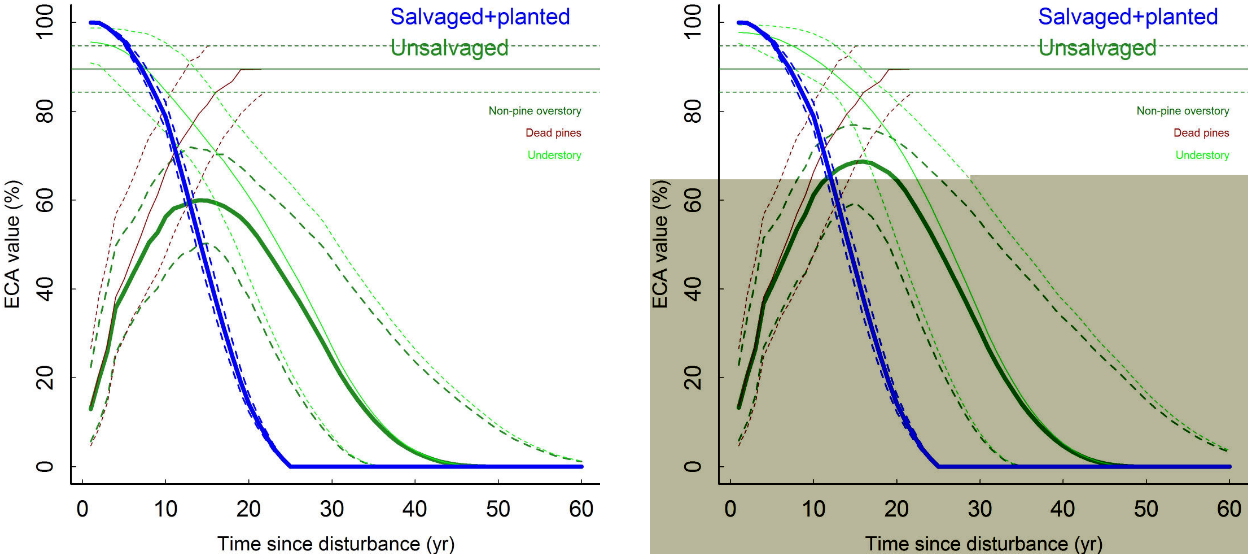


Figure 7.7. Comparison of ECA effects in unsalvaged stands assuming no initial mortality (left) versus 50% initial mortality (or failure to release) (right) of understory. Understory components also experience mortality through time in both cases, as described in the text. The clearcut-salvage option is unaffected by this assumption, and is presented for comparison with the salvaged results. Dotted lines are 95% confidence intervals.

Table 7.1 summarizes the total ECA-years for the options discussed in this section. Although these values are informative, the different distributions of the ECA values through time should also likely play a role in deciding on which options to use. In particular, the different timing of the effects will have implications for the amount of hydrological risk at any one time.

Table 7.1. Summary of total ECA effects (ECA-years) of the various options discussed in this section.

BEC	SI	Treatment	Variation	ECA-years	95% CI
MSdm2	16	Unsalvaged		1485	(1076-2041)
MSdm2	16	Partial	TIPSY pine regen	1348	(1146-1533)
MSdm2	16	Partial	VDYP mixed regen	2017	(1695-2314)
MSdm2	16	Salvage		1985	(1909-2068)
MSdm2	16	Unsalvaged	SBSmm canopy (more pine)	2088	(1429-2901)
MSdm2	16	Unsalvaged	All pine canopy	2401	(1759-3281)
MSdm2	16	Unsalvaged	10-year average for natural ingress	1341	(1005-1770)
MSdm2	16	Unsalvaged	50% extra initial understory mortality	1796	(1368-2347)
MSdm2	22	Unsalvaged		1038	(701-1551)
MSdm2	22	Partial	TIPSY pine regen	940	(791-1060)
MSdm2	22	Partial	VDYP mixed regen	1444	(1185-1692)
MSdm2	22	Salvage		1368	(1313-1422)
MSdm2	22	Unsalvaged	10-year average for natural ingress	910	(634-1297)
MSdm2	22	Unsalvaged	50% extra initial understory mortality	1306	(906-1863)
IDFdk3	22	Unsalvaged		1463	(951-2263)
IDFdk3	22	Partial	TIPSY pine regen	1137	(1011-1251)
IDFdk3	22	Partial	VDYP mixed regen	1518	(1337-1692)
IDFdk3	22	Salvage		1364	(1315-1420)
IDFdk3	22	Unsalvaged	10-year average for natural ingress	1179	(844-1728)
IDFdk3	22	Unsalvaged	Pine in new regen	1387	(886-2212)
IDFdk3	22	Unsalvaged	50% extra initial understory mortality	1692	(1071-2656)

8. Watershed roll-up

A separate report examines the projected ECA when these stand-level options, and other options for landscape level partial salvage, are applied to the Chase-Charcoal Creek watershed (including the effects of past harvesting).

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