

**Quantitative Synthesis of Rates for Projecting Deadwood  
in BC Forests**  
**Technical Report**

**David Huggard and Laurie Kremsater, Dec. 2007**

**Forest Sciences Project # SO84000**

David Huggard  
517 E. 10<sup>th</sup> St.  
North Vancouver, BC V7L 2E7  
huggard@interchange.ubc.ca

Laurie Kremsater  
Centre for Conservation Research  
University of BC  
lkrem@shaw.ca

## Quantitative Synthesis of Rates for Projecting Deadwood in BC Forests

David Huggard and Laurie Kremsater, Dec. 2007

### Executive Summary

We provide a quantitative synthesis of the published technical literature on parameters needed to project deadwood habitat in BC conifer forests, including rates of snag decay, breakage and fall, and coarse woody debris (CWD) decay. We also outline how these parameters are used in a detailed deadwood projection model that we have developed (Appendix 1). Additional information is provided by an extensive analysis of 5-year fates of tagged trees and snags in a large habitat monitoring program in variable retention cutblocks and uncut stands, conducted by Weyerhaeuser and Western Forest Products in coastal BC (Appendix 2).

The main points from the synthesis include:

#### Snag fall

- Snag fall rate decreases with DBH, following  $R_{DBH=X} = (40\text{cm}/X)^{0.60}$  (95% CI: 0.41-0.83), where  $R_{DBH=X}$  is the fall rate at DBH = X cm. For example, a snag with 20cm DBH would fall at 1.52 times the rate of a 40cm snag (95% CI: 1.33-1.78 times as fast).
- There was no obvious difference in this relationship of DBH and fall rate for different species or snags derived from different mortality sources (fire, beetle, other).
- We use this relationship to standardize results from studies that reported fall rates for various sized snags.

#### Snag fall

- Given the available data in the literature, species were best grouped to estimate fall rates as: 1) fast-decaying species (including *Abies* other than subalpine fir, spruces other than Engelmann-white spruce, and hemlock), 2) high-elevation species (subalpine fir and Engelmann-white spruce), 3) Douglas-fir, 4) all pine species and 5) deciduous species (which were not extensively analysed in these western studies). We also analysed lodgepole pine separately from other pines, because of particular interest in this species with the current mountain pine beetle outbreak in BC.
- There was a 6-fold range in the half-lives of snags (time since tree death until half the snags had fallen) of the different groups, from 11 years for southern and ponderosa pines and 14 years for the traditional fast-decaying species, to 30 years for Douglas-fir and 73 years for the high-elevation species. The groups also showed different patterns of fall rates through time, with a negative exponential type of survivorship curve for fast-falling species, compared to increasing rates of fall over time for longer-standing species.
- Data to compare the effects of different mortality sources on snag fall rates were only adequate for ponderosa pine, and showed no substantial differences between fall rates of snags from burns, beetle-kill or other mortality sources. Beetle-killed spruce may persist longer than spruce killed by other agents, while there was little difference for Douglas-fir, but data are very sparse for this comparison with these species.
- There is very limited direct data on snag fall by decay class, but it mainly shows increasing fall rates with increasing decay, typically 1.5-2 %/year for class 3 (Thomas 1979 classification), 2-3%/yr for class 4 and 2.5-4.5%/yr for class 5 and older. However, Weyerhaeuser/WFP data, mostly from small retention in cutblocks immediately after harvest, has much higher fall rates and no clear pattern with decay class.

#### Snag decay

- With limited published information, the best-supported model of snag decay supported grouping all conifers except for cedar.
- Cedar decayed from class 3→4 at 18 years, from 4→5 at 59 years and from 5→6 at 109 years, but confidence intervals are about -50% to +100% on those estimates.
- Other conifers made the decay transitions at about half these ages: 8 years for 3→4, 27 for 4→5 and 69 for 5→6.
- Within the non-cedar conifers, Douglas-fir had faster decay, and Abies and spruces slower decay, but confidence intervals are very wide on the specific values.

#### Snag breakage

- There are many factors potentially affecting breakage rates and little published information, even when information on changes in average snag height are converted to breakage rates.
- Individual studies show effects of burning, previous breakage and snag size on breakage rates, but considerable differences in the few cases where more than one study reported on a particular species.

#### CWD decomposition by diameter

- Five studies of density decomposition of logs of different diameters showed only a slight reduction in decomposition rate with log diameter.
- On the other hand, five studies of timber deterioration showed a strong, nearly-linear effect of log diameter in reducing deterioration rates. One long-term study of loss of log volume also showed a nearly-linear reduction in loss with increasing diameter.
- For structural decay of logs – as opposed to biomass decomposition – a power relationship with a coefficient of approximately 0.5 (intermediate between the values from density decomposition and timber deterioration and volume loss) is probably appropriate, and near values used in other CWD models.

#### Grouping species for CWD decay

- AIC analysis of studies of log decomposition suggest grouping CWD into fast-decaying species (Abies, eastern and Norway spruces, eastern hemlock), coastal species with moderate decay rates (western hemlock, Douglas-fir, Sitka spruce) and dry Interior or high-elevation species with lower decay rates (Engelmann spruce, lodgepole pine, ponderosa pine). Red-cedar could either be grouped with coastal species or treated separately. In part, these groupings reflect limited data to further distinguish among individual species.

#### Effect of ground position on CWD decay

- In most published cases, logs held off the ground by underlying logs decompose more slowly than logs on the ground, taking about 1.4-1.7 times as long to reach a particular density, and, presumably, a particular structural decay stage.

#### CWD time in decay classes

- The analysis of how long CWD spends in different structural decay classes – or, equivalently, the transition times between classes – combined the few direct measurements of this important parameter with more abundant indirect information from rates of density decomposition and density measurements in decay classes.
- CWD structural classes 1 and 2 were generally short-lived (roughly 12 years each for 40cm diameter logs of most species), while decay class 3 and 4 lasted longer (30-60 years each).
- The variation in transition times among individual logs, and uncertainty in the estimates, increase for the longer-lasting later decay stages.

Detailed values for all these parameters and their distributions are provided, along with data sources and a full description of the quantitative methods used to synthesize the available

data. A summary of the analysis of tagged trees and snags from the Weyerhaeuser/WFP plots is given at the beginning of Appendix 2.

---

## Quantitative Synthesis of Rates for Projecting Deadwood in BC Forests

### Table of Contents

1. Introduction .....	7
2. Snag Fall .....	8
2.1. Effect of snag diameter on snag fall rates .....	8
2.1.1. Methods – Snag fall by snag diameter .....	8
2.1.2. Results – Snag fall by snag diameter .....	9
2.2. Species differences in snag fall rates over time .....	11
2.2.1. Methods – Snag fall over time by species .....	11
2.2.2. Results – Snag fall over time by species .....	12
2.3. Effects of mortality source on snag fall rate .....	15
2.3.1. Methods – Mortality source and snag fall .....	15
2.3.2. Results – Mortality source and snag fall .....	15
2.4. Snag fall rates by decay class .....	17
2.4.1. Methods – Snag fall by decay class .....	17
2.4.2. Results – Snag fall by decay class .....	18
3. Snag decay .....	19
3.1. Snag decay – Time in decay classes .....	19
3.1.1. Methods – Snag time in decay classes .....	19
3.1.2. Results – Snag time in decay classes .....	21
4. Snag breakage .....	23
4.1. Snag breakage rates .....	23
4.1.1. Methods – Snag breakage .....	23
4.1.2. Results – Snag breakage .....	25
5. CWD Decay .....	29
5.1. CWD Decay – Effect of log diameter .....	29
5.1.1. Methods – Effect of log diameter on CWD decay .....	30
5.1.2. Results – Effect of log diameter on CWD decay .....	31
5.2. CWD Decay – Species groups .....	38
5.2.1. Methods – Species groups for CWD decay .....	38
5.2.2. Results – Species groups for CWD decay .....	39
5.3. CWD Decay – Effect of ground position .....	43
5.3.1. Methods – Effect of ground position on CWD decay .....	43
5.3.2. Results – Effect of ground position on CWD decay .....	43
5.4. CWD time in decay classes .....	48
5.4.1. Methods – CWD time in decay classes .....	48
5.4.2. Results – CWD time in decay classes .....	50
6. References .....	53
Appendix 1. Description of deadwood model .....	59
A1.1. Deadwood model overview .....	59
A1.2. Deadwood processes and parameters .....	61
A1.2.1 Snag fall .....	61
A1.2.2 Snag decay .....	62
A1.2.3 Snag fragmentation or breakage .....	62
A1.2.4 CWD decay .....	63
A1.2.5 Relationship with snag size or CWD diameter .....	63
A1.3. Initial deadwood conditions .....	63
A1.4. Management effects on deadwood .....	64
A1.5. Effects of parameter uncertainty .....	65

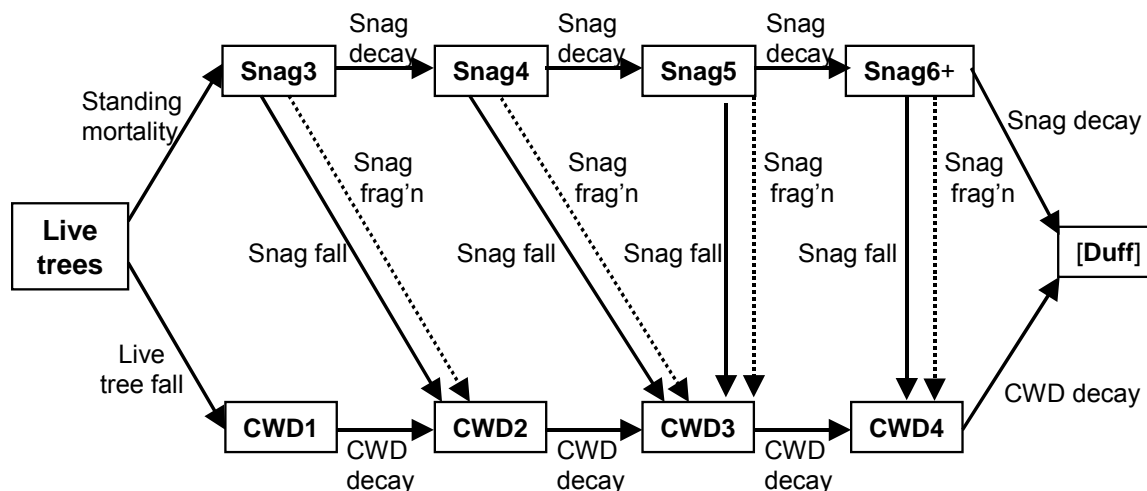
A1.6. Deadwood summaries .....	66
Appendix 2. Growth, mortality, fall and decay rates over 5 years for individually tagged trees and snags on the BC coast.....	67
A2.1 Overview .....	68
A2.2 Methods .....	69
A2.2.1 Field sampling .....	69
A2.2.2 Analyses.....	69
A2.2.3 Standardized DBH.....	70
A2.2.4 Edge effects .....	71
A2.2.5 Note on calculations of snag decay.....	71
A2.3. Results .....	71
A2.3.1 Diameter growth of live trees.....	71
A2.3.2 Mortality of live trees .....	74
A2.3.3 Mortality mode for live trees .....	78
A2.3.4 Fall rates of snags – class 3 .....	80
A2.3.5 Fall rates of snags – class 4 .....	83
A2.3.6 Fall rates of snags – class 5 .....	85
A2.3.7 Fall rates of snags – class 3-5 (hard snags) .....	87
A2.3.8 Fall rates of snags – class 6+ (soft snags).....	89
A2.3.9 Decay rates of snags – class 3→4 .....	91
A2.3.10 Decay rates of snags – class 4→5 .....	93
A2.3.11 Decay rates of snags – class 5→6+ .....	95
A2.3.12 Combined relationships of rates with DBH.....	96

## Quantitative Synthesis of Rates for Projecting Deadwood in BC Forests

### 1. Introduction

Deadwood – snags and coarse woody debris (CWD) – have many well-recognized roles in forest ecosystems. As a result, forest legislation, policy, certification programs and companies' sustainability plans all contain goals and strategies for maintaining deadwood in managed stands. Several studies have compiled information from deadwood surveys of current stands, mainly uncut mature forest and recent harvest blocks (REFs). The inventories of unmanaged stands can help set objectives for maintaining deadwood elements, including showing differences in deadwood amounts among ecosystems and over time after natural disturbances. Monitoring recent harvest units shows how much of the various deadwood elements are being retained relative to uncut benchmarks, and can allow direct comparisons of the short-term differences among different management options. However, managers and policy-makers are also responsible for the long-term effects of their current decisions. Direct monitoring has a limited ability to address long-term trajectories of deadwood under different management options, because there simply are no old examples of many current harvesting practices. Models to project deadwood resources over one or more harvest rotations are therefore necessary to assessing current management decisions, and complement direct monitoring of recent cutblocks and mature forest.

In this project, we synthesize published information on rates of fall, breakage and decay of snags and CWD to parameterize a deadwood projection model. The projection model is described in detail in Appendix 1 and shown schematically in Figure 1.1. The model requires information on: 1) The fall and decay rates of different classes of snags (following the Thomas 1979 classification used also by the BC government), or, equivalently, how long snags stay in each decay class and fall by time-since-death. 2) Fragmentation of snags, in which a standing snag breaks, to produce a piece of CWD and a shorter snag. 3) Rate of decay of CWD, either the annual probability that a log will change decay classes, or the time logs stay in each class. We also summarize factors that are expected to affect these rates and are included in the deadwood projection model, including species and size of the snag or log, and other possible factors, such as cause of tree death, ecosystem type, or position relative to a



**Figure 1. Decay stages of snags and coarse woody debris (CWD) and processes in the deadwood model. Live tree growth and mortality are handled outside the deadwood model. "Frag'n" = fragmentation.**

harvested edge. The modeling of live trees, including mortality, is beyond the scope of this project; the deadwood model uses information on dying trees from external live-tree models as an input.

The project also includes analysis and summary of a large dataset from Weyerhaeuser (now Western Forest Products) on fates of individually tagged trees and snags remeasured after 5 years in uncut mature stands and stands recently harvested with variable retention (VR) in coastal BC (full summary in Appendix 2). This work supplements information on fall and decay rates of snags for VR stands, which are not reported on in the literature, including initial post-harvest edge effects. The analysis also provides further information on effects of stem size on fall and decay, and information on live-tree growth and mortality to support live-tree modeling of these stands.

## 2. Snag Fall

### 2.1. Effect of snag diameter on snag fall rates

*Question: How does the rate of snag fall change with snag diameter?*

Snags are often assumed to persist longer if they are larger. The specific relationship between snag diameter and snag fall is important for modeling snags, and directly affects recommendations about retention and regeneration of trees to produce a long-term snag supply. Estimating the relationship of snag fall and diameter at breast height (DBH) is a necessary first step for this synthesis, so that the effect of snag size can be factored out when combining different studies to compare fall rates of different species, snags with different mortality sources, etc.

#### 2.1.1. Methods – Snag fall by snag diameter

We compiled results from studies that reported some measure of snag persistence for 2 or more diameter classes of snags in the same study site. There were several types of studies:

- 1) Cohort studies followed a set of newly-dead trees until many of the snags had fallen.
- 2) Chronosequence studies used stands that had been disturbed at different times – typically by fire – and measured standing and fallen snags.
- 3) Fixed- duration studies marked a sample of snags at one time, and revisited them one or more times a number of years later.
- 4) Rate coefficients were reported directly by some studies, usually based on a negative exponential model, or negative exponential with lag time.

To compile the results from the 4 types of studies, we converted the results into the same measure, the expected half-life of a new snag (i.e., the time until half of the snags had fallen.) The half-life was estimated differently for the 3 data types:

Cohorts: A logit-transformed binomial regression (“logistic regression”) was fit to the proportion of standing snags versus time-since-death. The fitted curve was used to estimate the time-since-death at which 50% of snags have fallen.

Chronosequences: Chronosequences have the same type of data as cohorts – the proportion of snags still standing at different ages. Unlike cohorts, however, there can be a higher percentage at later times, simply because of variation among the different stands included in the chronosequence. Ideally, a model would be fitted that included both the binomial error distribution of snag fall, and an additional error distribution for the stand-to-stand variability. However, most of the chronosequence data available was not extensive enough to support estimating this more complicated (Bayesian) model, or the



individual data points (standing snags by individual stand) were not presented.

Therefore, a simple logit-transformed binomial model was also fit to the chronosequence data, as in the cohort data sets.

Fixed-duration: Studies with remeasurements of marked snags after a fixed time interval provided either 1 or 2 remeasurement values (for example, proportion of original snags still standing after 5 years, or after 5 and 10 years). When there was only 1 remeasurement, we fitted a negative exponential curve to the reported proportion standing. This single-parameter curve is the only biologically-sensible curve that can be estimated with a single remeasurement. When there were two remeasurement values reported, we fitted a negative exponential curve with an initial lag time in which no snags fell (after Harmon et al. 1986 and others). These curves may not be very realistic biologically, but they are all that can be fit reasonably with only one or two remeasurements. These curves were used to calculate the half-life.

Rate coefficients: Half-life values were calculated directly from the model and its coefficients.

Half-life values were calculated separately for each combination of study, site (a few studies reported results separately for different ecosystems), species, mortality source (some studies reported fall rates separately for different tree mortality sources, such as burned versus beetle-killed), and diameter class (classes as reported by the study). Each study\*site\*species\*mortality combination therefore provided a half-life value for 2 or more diameter classes. The actual half-life values varied widely, reflecting differences in fall rates among species, mortality sources and different ecosystems. In this initial analysis of the effects of snag DBH on fall rates, we are not interested in the absolute fall rates, but rather only how the rate changes with different diameters. Therefore, the half-lives for the different diameters of each study\*site\*species\*mortality combination were standardized to a value of 100 at 40cm DBH. This was done by fitting a log-log (power) regression through the 2 or more points (half-life versus DBH) within each combination, and using the fitted curve to estimate the half-life at 40cm DBH. The observed half-life at a given DBH was divided by this half-life expected for a 40cm DBH snag and multiplied by 100 to give the standardized value. A standardized value of 150 for a 80cm DBH snag, for example, means that snags in that diameter class had a half life 1.5 times as long as snags of 40cm DBH.

The goal of the analysis was to relate the standardized half-life of a snag of any DBH to a the half-life of a snag with a standard DBH, which was taken as 40cm. The relationship was assumed to be a log-log (power) relationship, in which  $T_{DBH=X} = (X/40)^A$ , where  $T_{DBH=X}$  is the half-life at DBH of X cm, and A is an exponent estimated from the data. The exponent A indicates how the persistence of snags changes as the diameter changes. An exponent A of 0.5, for example, means that the persistence of snags increases as the square root of their diameter – a 160cm snag would stand twice as long as a 40cm snag, while a 10cm snag would stand half as long ( $(160/40)^{0.5} = 2$ ;  $(10/40)^{0.5} = 0.5$ ). A log-log regression was fit through all the points (standardized half-life versus DBH) to estimate A. Confidence intervals on the log-log regression were estimated using bootstrapping, in which each study\*site\*species\*mortality combination was used as the resampling unit.

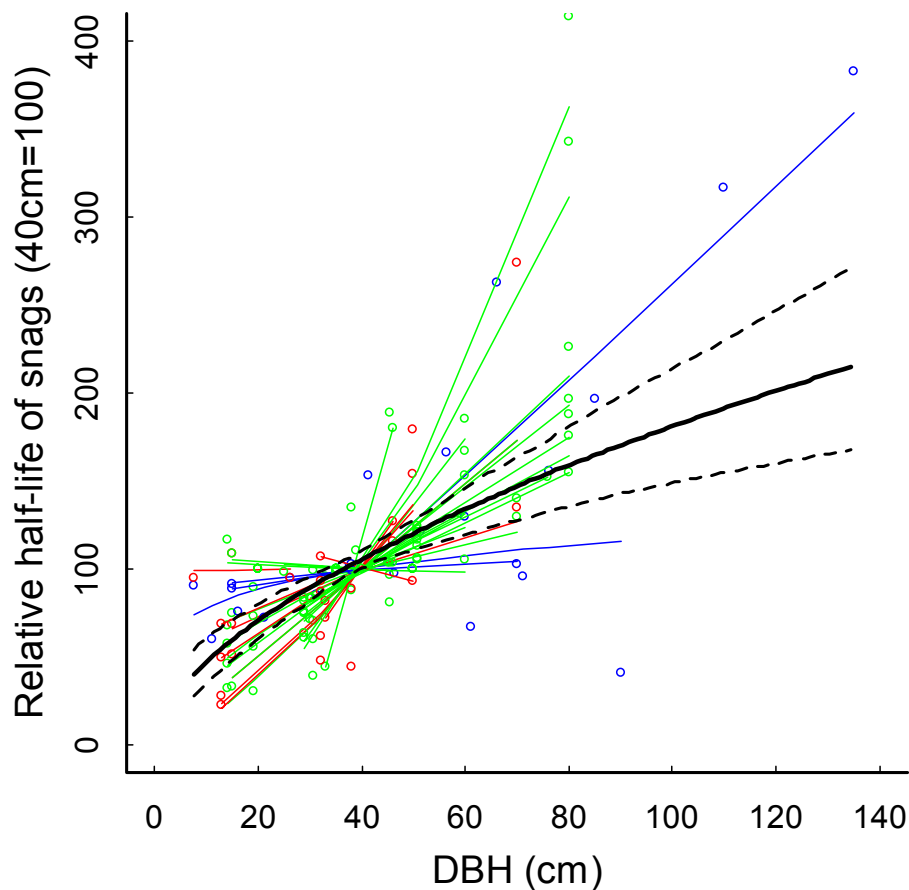
### 2.1.2. Results – Snag fall by snag diameter

Thirteen studies provided 33 study\*site\*species\*mortality combinations, each with 2 or more diameter classes. Only 1 of the combinations showed a (slight) decline in snag persistence with increasing DBH (based on only 2 diameter classes). Of the rest, 5 showed no change or slight increase in persistence with larger size, while the other 27 combinations showed more substantial increases (Figure 1). There was no obvious difference in the persistence-versus-DBH relationship between snags killed by fire, beetle outbreaks or “endemic” causes (different line colours in Figure 2.1). There were also no obvious differences

in the relationships for different species. (Note that this does not mean that the actual fall rates did not differ by species or mortality source, only that the change in fall rates with changing DBH was consistent among species and mortality sources.)

The bootstrapped log-log regression had a median slope coefficient of 0.60 (95% confidence intervals: 0.41-0.83). An 80cm DBH snag would therefore be predicted to have a persistence 1.52 times as long as a 40cm DBH snag (95% CI: 1.33-1.78); a 20cm DBH snag would persist 0.66 times as long (95%CI: 0.56-0.75).

The analysis of the Weyerhaeuser/WFP 5-year remeasurements of individually tagged snags showed a clear relationship between snag persistence and DBH, but no clear relationship between snag decay rate and DBH. The exponent for snag half-life was 1.05 (95% CI: 0.41-1.69), showing an essentially linear increase in half-life with increasing DBH, but with confidence intervals that overlap the estimate of 0.60 from the synthesized literature. The exponent for snag decay was 0.02 (95% CI: -0.46 - 0.50). Interestingly, combining the Weyerhaeuser/WFP data for both fall and decay versus DBH gave an exponent of 0.60 (95% CI: 0.16-1.05), identical to, but somewhat less certain than, the result from the literature synthesis.



**Figure 2.1. Relationship between half-life of snags, standardized to a value of 100 for a 40cm DBH stem, and snag DBH, for 33 combinations of study\*site\*species\*mortality source. Each line is fit through the 2 or more points at different DBH values for one combination. Colours distinguish different mortality types: red=burned, blue=beetle-killed, green=other. Thick black line is overall relationship, with bootstrapped 95% confidence intervals (dotted). Note that fall rate is the inverse of half-life – i.e., fall rate decreases with DBH.**

## 2.2. Species differences in snag fall rates over time

*Question: What are the fall rates of snags over time, and how do they differ by species?*

The persistence of snags over time after the tree dies is basic information for projecting snags. Fall rates of snags are thought to differ considerably among different species, with decay-resistant species like cedars or species in environments with slow decay, such as high-elevations, having lower fall rates. These differences can be important for decisions on which snags, and how many, to retain in managed blocks. Changes in fall rate with time-since-death are also important in projecting snags through time. We typically assume that snag fall rates will increase as the snags become older and more decayed, but it is also possible that snags may have a relatively constant fall rate (i.e., the same percentage falling every year, creating a negative exponential curve), or even decreasing fall rates over time as the less stable stems fall quickly. The analysis in this section combines studies that provide information on when snags fall as a function of time-since-death, which we call snag “survivorship”, and uses AIC-based model selection to decide how to combine individual species into species groups that have similar fall rates over time.

### 2.2.1. Methods – Snag fall over time by species

As with the preceding analysis of snag fall by diameter, studies present several types of results:

Cohorts, in which individual snags are tracked over time from tree death. This provides a direct measure of snag fall over time.

Chronosequences, in which snags in stands of different times since disturbance (often fires) are surveyed, with some field technique used to reconstruct how many snags were present shortly after disturbance. This provides similar information to the cohort approach, but with additional uncertainty in the data points due to variation among stands.

Parameters of a modeled distribution fit to field data. This is typically the exponent of a negative exponential decay model, sometimes with an initial lag time.

Because we are interested in (possible) changes in fall rates as the snags age, the studies had to follow the snags from the death of the tree, or include information on how long the snags had been dead. A fourth type of data, based on two or more observations of plots – with the first observation not immediately after the trees are killed, but when the snags are already some unknown age – could therefore not be used here, since information is not available on how long the snags have been dead. (Note: This fourth type of information could be used if we were fitting negative exponential models, which assume a constant proportion of snags falling each time period. However, a more flexible approach allowing changes in the fall rate over time is used here.)

The previous analysis of how snag fall rate is affected by snag DBH (section 2.1) showed decreasing fall rates with increasing DBH. The times since death from the various studies used here were therefore standardized to a DBH of 40cm, using the power exponent 0.60 as suggested in the analysis of snag size:  $\text{Time}_{\text{ADJ}} = \text{Time}_{\text{OBS}} \times (40/\text{DBH}_{\text{OBS}})^{0.60}$ , where  $\text{Time}_{\text{ADJ}}$  is the time since death adjusted to a 40cm DBH,  $\text{Time}_{\text{OBS}}$  is the reported time(s) for a study's observations and  $\text{DBH}_{\text{OBS}}$  is the DBH reported in the study. For example, if a study provided a data point for 20-cm DBH snags 10 years after tree death, this would be equivalent to 15.16 years after death for a 40-cm DBH snag ( $= 10 \times (40/20)^{0.6}$ ). The DBH was taken as the mean if that was reported, the mid-point if a range was reported, or a guess based on the study area description and other information in the paper if snag size was not reported.

A hybrid approach was used for the two tasks of deciding how to group species (and mortality sources within species in a later section), and fitting the actual survivorship curve for snags of each group. AIC-based model selection was used to decide on the species groupings, using a binomial logistic regression model. A parametric model like the logistic was needed to calculate the likelihoods required for AIC. Information on snag survivorship was available for 15 species: Douglas-fir, subalpine fir, balsam fir, red fir, white fir, hybrid (Engelmann x white) spruce, black spruce, Norway spruce, lodgepole pine, ponderosa pine, Jeffrey pine, 2 southern pines (combined), trembling aspen, cottonwood, and paper birch. Because of sparse data points, red and white fir were combined with balsam fir, and Norway spruce was combined with black spruce (partially based on initial inspection that showed similar fall rates in those two spruce species), producing 12 initial “species”. The AIC model selection for grouping species compared the following candidate models:

- M1 – Each species separate
- M2 – Each genus separate (but deciduous species combined)
- M3 – ‘Fast-decaying’ species, high-elevation species, Douglas-fir, lodgepole pines, southern pines, deciduous. (Fast-decaying species include *Abies* (except subalpine fir which is in the high-elevation group), hemlocks, Norway and black spruce. “Southern pines” are all non-lodgepole pines with available information, including ponderosa pine.)
- M4 – ‘Fast’ species, high-elevation species, Douglas-fir, all pines, deciduous
- M5 – ‘Fast’ species, high-elevation + Douglas-fir, all pines, deciduous
- M6 – ‘Fast’ species, other conifers, deciduous
- M7 – Conifers, deciduous
- M8 – All combined

This AIC analysis provided the best way of grouping species, given available data. To describe the actual survivorship of snags over time, smooth spline curves were used for each group identified in the AIC analysis. The spline curves have the benefit of being able to show some of the actual shape of the survivorship curves, rather than assuming a particular form (e.g., logistic, negative exponential, etc.). Confidence intervals were established on the spline curves by bootstrapping.

In the AIC analysis, and for bootstrapping the spline curves, each combination of study x species x mortality source x DBH class was taken as one sample unit, regardless of how many data points at different times-since-death were reported for that combination. This is because results for one cohort followed over many years are clearly not independent estimates of fall rates for that species. When a study only reported the parameters of a model, such as the exponent of a negative exponential decay model, data points were generated for years 1, 6, 11...121. This series of 25 points was given a total weight of 1 (i.e., the series counted as one sample), but higher weight was given to the younger times-since-death: 0.166 for the point at year 1, 0.114 at year 6, 0.087 at year 11... to 0.014 at year 121. [Weights proportional to  $1/(\text{time since death} + 10 \text{ years})$ ]. Skewing the weighting towards younger times since death was done since the model was usually fit to data from these younger times since death, and later points are less reliable extrapolations beyond the data.

The analyses were done both with and without data on snags that were created by fire. Because there was little difference between the results, the results based on all the data, including burned snags, are presented below. The analysis of the effects of mortality source (section 2.3) supports combining the results for snags from different mortality sources.

### 2.2.2. Results – Snag fall over time by species

The AIC analysis best supported model M4 (Table 2.1), grouping the individual species as: 1) fast-decaying (including *Abies* other than subalpine fir, spruces other than Engelmann-

white spruce, and hemlock), 2) high-elevation subalpine fir and Engelmann-white spruce, 3) Douglas-fir, 4) all pine species and 5) deciduous species. [Note that there was not enough information in these studies from western North America to compare different deciduous species well].

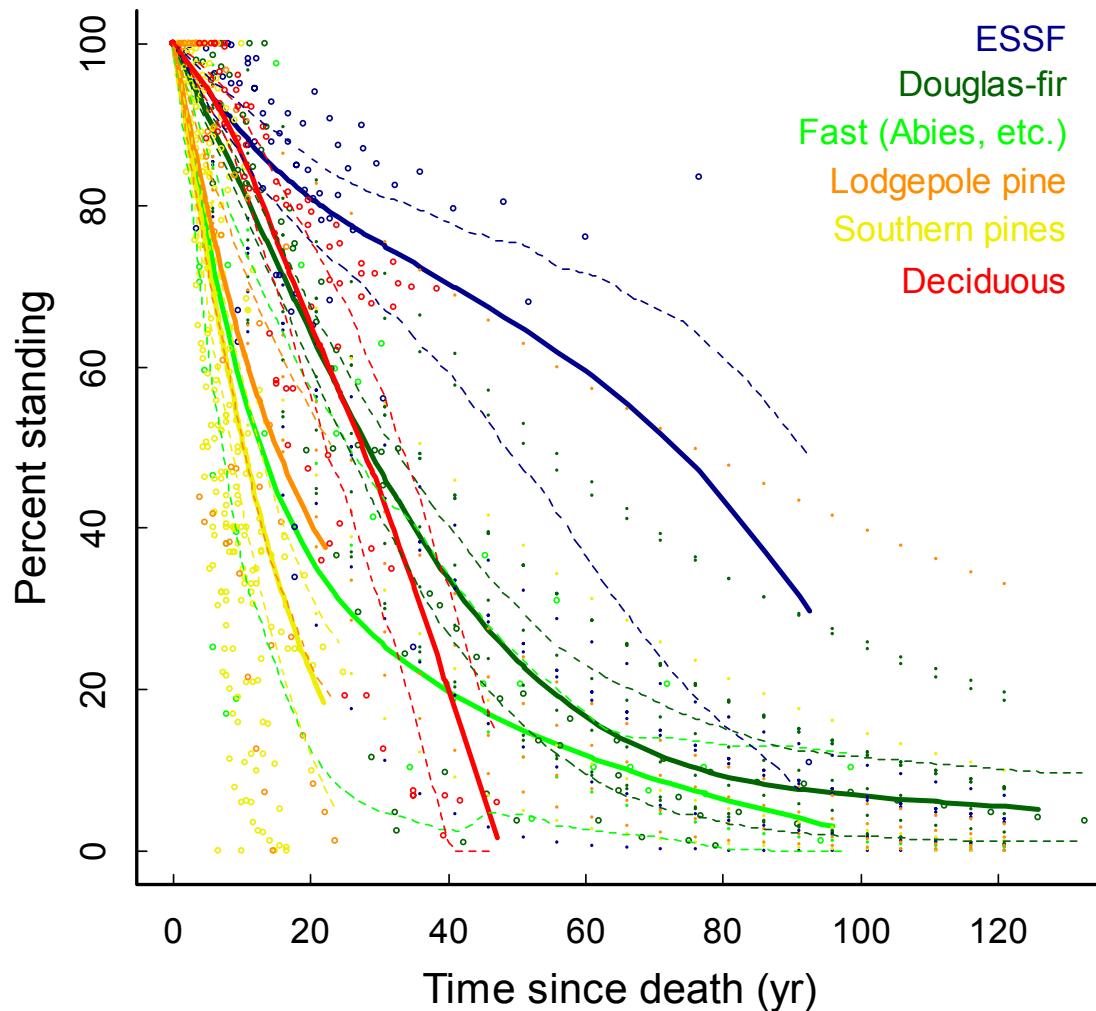
Although model M4 had the strongest AIC support, we grouped the species for the spline curve-fitting based on model M3. This was the second-best supported model, and differs from M4 only in having lodgepole pine separated from other pines (primarily ponderosa pine). We chose to fit a snag survival curve for lodgepole pine separate from the other pines because there is particular interest in lodgepole pine snag longevity with the current mountain pine beetle outbreak in British Columbia.

**Table 2.1. AIC results comparing models of grouping species for snag survivorship curves.**

Model	AICc	Weight
1 Species	521.7	0.000
2 Genus	492.0	0.009
3 Fast, high-elevation, Fd, <u>PI, southern pines</u> , deciduous	487.4	0.093
4 Fast, high-elevation, Fd, <u>all pines</u> , deciduous	482.9	0.897
5 Fast, high-elevation+Fd, all pines, deciduous	500.9	0.000
6 Fast, other conifers, deciduous	648.4	0.000
7 Conifers, deciduous	641.3	0.000
8 All	658.9	0.000

The smooth spline survivorship curves for these species groupings (Figure 2.2) showed considerable differences in fall rates, and in the pattern of fall rates over time, with only the fastest-falling species approximating a negative exponential curve:

- The two high-elevation (ESSF) species had the slowest rates of snag fall, though with considerable spread between 3 studies with low fall rates and several with moderate rates (Figure 2.2, blue).
- Southern pines, dominated by results for ponderosa pine, had the fastest fall rates (Figure 2.2, yellow).
- Lodgepole pine fell somewhat more slowly than other pines (Figure 2.2, orange), at a rate similar to the “fast” group. For both lodgepole pine and other pines, the available data did not extend much beyond 20 years since tree death, so it is unclear if some proportion of the pines might last for several decades. The confidence intervals on the curve for lodgepole pine are wider than for the other pines, reflecting fewer studies and variation between some studies that reported very fast fall rates and others that reported moderate rates for this species.
- The traditional fast-decaying conifer group had a slightly slower initial fall rate, with some indication that a small proportion of these snags remained standing for several decades (Figure 2.2, green). Confidence intervals were particularly wide on this group, suggesting considerable variation among its member species or different study areas. Unfortunately, there are too few available studies to examine different ways of further dividing this group.
- Douglas-fir, which included both coastal and US inland studies, had survivorship curves mid-way between the faster-falling conifers and the high-elevation species (Figure 2.2, dark green).
- Deciduous species showed a somewhat surprising moderate fall rate initially, although they did not appear to have the extended tail of some long-standing individual that most conifers showed (Figure 2.2, red). However, because we focused on western studies, deciduous results come mainly from boreal or sub-boreal systems, where fall rates may be slower than for deciduous species in warmer and more humid environments.



**Figure 2.2. Percent of snags standing versus time-since-death. Data points include direct measurements (circles) and points generated from fitted equations provided by some papers (mostly negative exponential rates and lag times) (dots). Dashed lines are bootstrapped 95% quantiles.**

One summary of the species comparison is provided by the half-lives of snags – the time since death when 50% of snags are expected to have fallen (Table 2.2). We calculated this value and its confidence intervals from the curves shown in Figure 2.2. Half-lives varied about 6-fold from the three faster-falling groups through the two intermediate groups to the slow-falling high-elevation species. The wide confidence intervals are apparent for the fast and high-elevation groups, and for lodgepole pine.

**Table 2.2. Years-since-death until half of snags are fallen ( $T_{50}$ ) and 95% confidence intervals.**

Species group	$T_{50}$	95% CI
Fast	14	(8-24)
High-elevation	72	(48-93)
Douglas-fir	30	(26-34)
Southern pines (incl. ponderosa)	11	(9-14)
Lodgepole pine	16	(11-26)
Deciduous	28	(22-34)

### 2.3. Effects of mortality source on snag fall rate

*Question: How does the cause of tree death affect fall rates of snags?*

Trees killed by different mortality sources may produce snags with different fall rates. Root rots or fires that damage roots may lead to snags with short persistence times, while trees killed by beetles, competitive effects, wind-snap, etc., may stand longer. On the other hand, some of these mortality agents may promote decay organisms that hasten snag fall. If there are large differences in snag persistence with different mortality sources, then this is important to incorporate in snag projection models, especially where these are being used to compare managed versus natural stands.

#### 2.3.1. Methods – Mortality source and snag fall

Available data allowed survivorship curves for snags created by different mortality sources to be compared within 3 species: burned versus endemic mortality<sup>1</sup> for Douglas-fir; beetle-killed versus burned versus endemic mortality for ponderosa pine; and beetle-killed versus endemic mortality for Engelmann-white spruce. As with the species comparisons, AIC model selection used a logistic regression of survivorship versus time-since-death to compare different groupings of the mortality sources (Table 2.3). Survivorship curves were also plotted for each mortality source, using smooth splines, with confidence intervals established by bootstrapping with study x species x DBH class as the resampling unit (as for the species groups, section 2.2).

#### 2.3.2. Results – Mortality source and snag fall

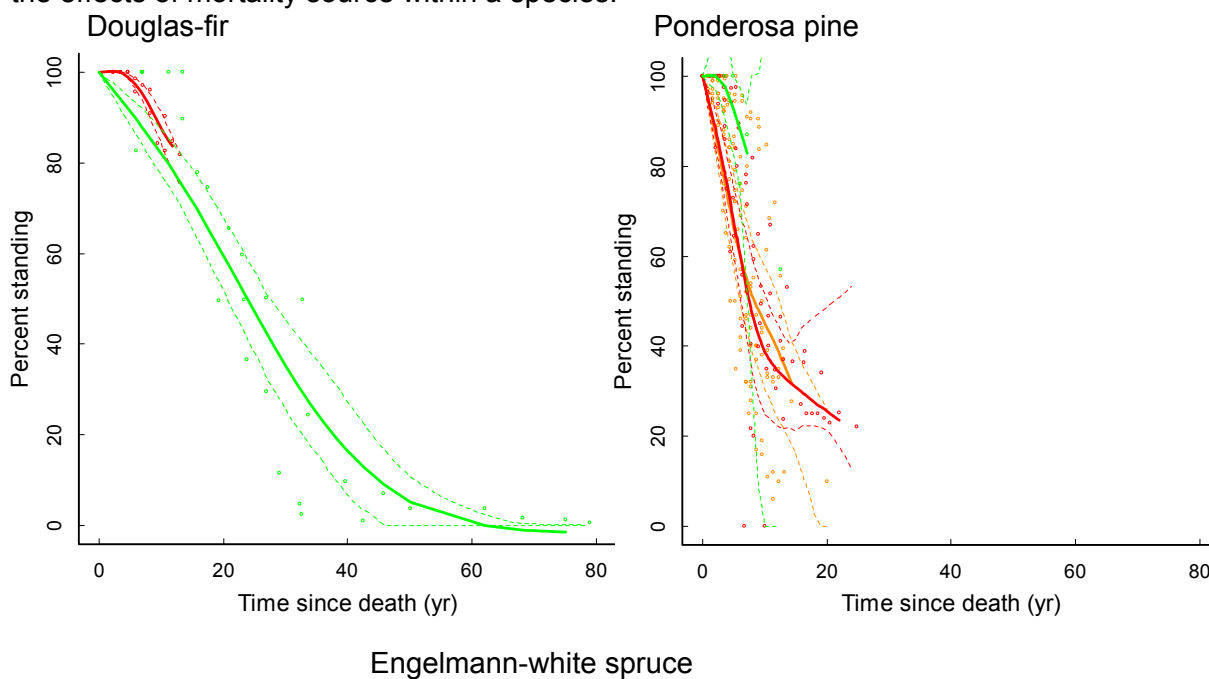
AIC supported combining mortality sources within all 3 species (i.e., no effect of mortality source on snag survivorship; Table 2.3). However, the comparisons within Douglas-fir and spruce were made weak by very limited data (few studies, short duration) for one of the two mortality sources. Within spruce, there was some support (AIC weight 30.3%) for separate survivorship curves for beetle-killed versus endemic mortality.

**Table 2.3. AIC results comparing effects of mortality sources on snag fall rates of 3 species.**

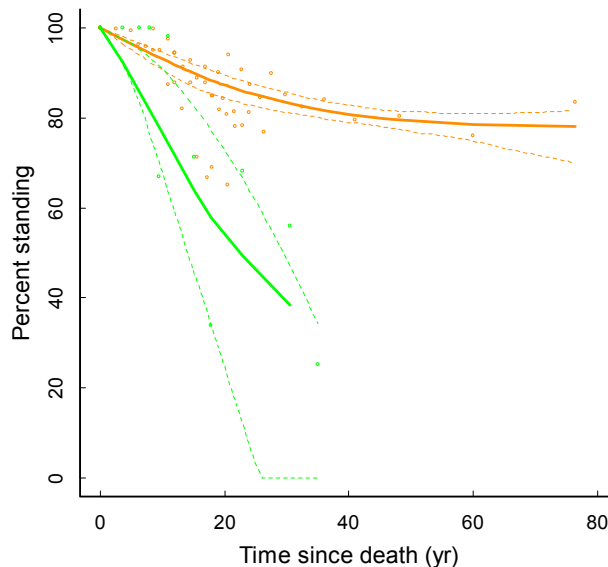
<sup>1</sup> “Endemic” mortality here is any non-catastrophic source within a forest, including pathogens, endemic (non-outbreak) insects, competition, wind-snap, etc.

Species	Model	AIC	Wt
Douglas-fir	Burned, endemic	30.4	0.032
	<b>Burned=endemic</b>	<b>23.6</b>	<b>0.968</b>
Ponderosa pine	Beetle, burned, endemic	193.2	0.015
	Beetle=burned, endemic	189.1	0.119
	Beetle=endemic, burned	190.2	0.069
	<b>Beetle=burned=endemic</b>	<b>185.3</b>	<b>0.797</b>
Spruce	Beetle, endemic	34.5	0.303
	<b>Beetle=endemic</b>	<b>32.9</b>	<b>0.697</b>

Separate curves for the different mortality sources show the similar survivorships within the two types of mortality for Douglas-fir (and the limited data for burned fir) and within the three types of mortality for ponderosa pine (Figure 2.3, top left and right). The survivorship curve for beetle-killed spruce is quite different from the curve for endemic mortality. However, the fall rates of beetle-killed spruce seem excessively low, and the few data points for each type of mortality within spruce support for the AIC result to combine the two curves. A main conclusion of this analysis is that substantially more data would be needed to allow strong comparisons of the effects of mortality source within a species.







**Figure 2.3. Snag survivorship curves for different snags created by different mortality sources within a species: green = endemic mortality, red = fire, orange = beetles. Dotted lines are 95% bootstrapped confidence intervals.**

## 2.4. Snag fall rates by decay class

*Question: What are the fall rates of snags in different decay classes?*

Most modeling of snags in different decay classes relies on fall rates based on time-since-death (or, in some simple models, fixed fall rates), combined with estimates of how long snags remain in the different decay classes. This produces projections of different decay classes of snags, without requiring direct estimates of the fall rates of each decay class. However, in field surveys, it is far easier to classify snags into decay classes than to use dendrochronology techniques to determine when the snag died. It would therefore be useful for practical reasons to have estimates of snag fall rates by decay class, particularly for making management recommendations about which snags to retain and for quickly assessing the longer-term consequences of retaining a particular set of snags.

### 2.4.1. Methods – Snag fall by decay class

Unfortunately, we only found 3 published studies, covering 5 species, that provided fall rates by decay class. Two of these studies used classification systems different from the Thomas (1979) classification that underlies our deadwood projection model. Decay classes in these studies were converted to Thomas (1979) classes based on descriptions of the classes provided in the publications. Some of the classes in these other systems overlapped two classes in Thomas, and were partially assigned to each of the two classes. For example, snag class “X” in a publication might be 50% Thomas class 4 and 50% class 5. A data point for class X would then count as 50% of a data point for Thomas class 4 and 50% for class 5. Fall rates were adjusted to a standard DBH of 40cm, based on the analysis in section 2.1:  $\text{Fall Rate}_{40\text{cm}} = \text{Fall Rate}_{\text{ORIG}} \times (\text{DBH}_{\text{ORIG}}/40)^{0.6}$ , where  $\text{Fall Rate}_{\text{ORIG}}$  and  $\text{DBH}_{\text{ORIG}}$  are the original fall rate and DBH from the paper. A yearly fall rate of 0.02 (2% fall/yr) for a 20cm DBH snag would

equal a 0.013 fall rate for a 40cm DBH snag. Fall rates for Huggard (1999) class 3A+B and class 3C were averaged to a single value for class 3. The fall rates for the 3 size classes in Mellen and Ager (2002) were averaged within a decay class, after standardizing to 40cm DBH.

There was only one study for each species, so fall rates are simply summarized directly (after standardizing to 40cm DBH, and weighting data points that were allocated to two Thomas decay classes). Confidence intervals on the estimates were not provided in all 3 studies, and are not included here. Based on the much more extensive analysis in section 2.2, 95% confidence intervals of about  $\pm 30$ -50% of these mean estimates might be appropriate.

The analysis of tagged snags from the Weyerhaeuser/WFP monitoring plots provides additional information on snag fall rates by decay class. Most of the information comes from trees in 0.25-1-ha retention patches within recent cutblocks; the fall rates are affected by initial windthrow along edges and possibly by some direct snag-falling for worker safety or firewood-cutting. The 5-year remeasurements also included relatively few fallen stems, so the results have wide confidence intervals. For these reasons, the Weyerhaeuser/WFP results are summarized separately from the 3 published studies.

#### 2.4.2. Results – Snag fall by decay class

Fall rates increase, as expected, with increasing decay class, with the exception of class 6+ snags in the two pine species. The lower fall rates in these older pines may be due to low sample sizes for these rare old pine snags.

**Table 2.4. Annual fall rates (%/yr) for 40cm DBH snags in decay classes described by Thomas (1979).**

Species	Thomas et al. (1979) class			
	3	4	5	6+
Subalpine fir	0.34	2.88	4.66	
Douglas-fir	1.48	2.02	2.43	2.93
Western hemlock	2.10	2.67	3.08	3.62
White pine		0.94	2.74	1.25
Red pine	2.25	3.05	4.85	3.29

Weyerhaeuser/WFP results were averaged across ecosystem types and harvest types (most plots in retention patches in cutblocks, but some in uncut forest), and confidence intervals are omitted in summary Table 2.5. See Appendix 2 for complete results. These results do not show the consistent pattern of increasing fall rates with increasing decay class seen in the published studies. This may partially reflect anomalously high fall rates for recent (class 3 and possibly 4) snags, due to enhanced windthrow of these snags on edges of retention patches.

**Table 2.5. Annual fall rates (%/yr) by decay class from Weyerhaeuser/WFP monitoring in coastal BC, for snags standardized to 40cm DBH.**

Species	Thomas 1979 class			
	3	4	5	6+
True fir	10.16	7.23	3.39	
Douglas-fir	4.49	0.55	3.82	
Hemlock	2.55	3.18	3.20	
Red-cedar	7.99	1.35	3.95	
Red alder	11.27	0.18	2.10	
All				5.96

### 3. Snag decay

#### 3.1. Snag decay – Time in decay classes

*Question: At what ages (times since tree death) do standing snags change from one age class to the next?*

Knowing how long after tree death snags acquire the characteristics of a particular decay class allows us to project classes of snags over time under different management options. Harvest activities often remove all snags, or leave only the most recent snags, which tend to be safer. However, species require snags in various older decay stages. These can only be provided in managed stands by retaining enough live trees or safe recent snags that are allowed to decay into older classes. Planning activities to allow this recruitment of older decay classes is an important part of long-term deadwood management, particularly in short-rotation or multiple-entry silvicultural systems.

##### 3.1.1. Methods – Snag time in decay classes

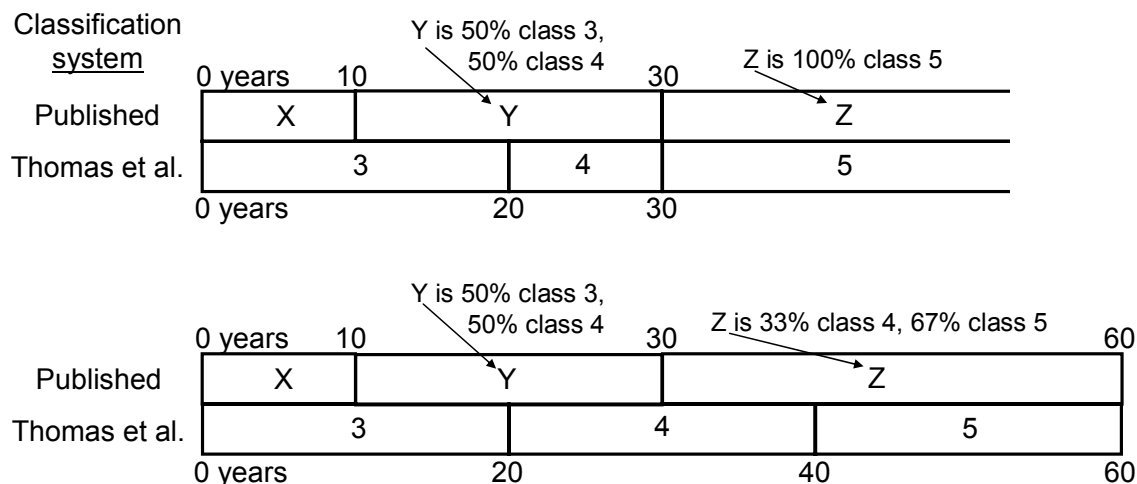
There are many systems for defining the decay class of snags. We use the system of Thomas (1979), also used for operational snag management in BC. Much of the work on snag-using animals – a main reason for managing and modeling snags – has used this system to describe habitat relationships. In this system, classes 1 and 2 are live healthy trees, and live declining trees, respectively. These are not addressed here. (The transition from class 2 to class 3 is tree death; mortality is not included in this deadwood synthesis project). Class 3 snags are recently dead, with intact bark and fine branches present (with or without dead needles). Class 4 snags have cracked bark with patches missing, and have lost their fine branches. Class 5 snags have lost most or all of their bark and most of their branches, but still have mainly hard wood. Class 6 snags have softening wood, and as a result the trunk is almost always broken. There are later stages of decay in the system, but we combine these with class 6 as “class 6+”, because it becomes increasingly difficult and unreliable to age snags after class 5.

Studies could be used if they provided information on the age (time-since-death) at which snags changed from one decay class to the next, information on average or median age of snags in two or more decay classes, or ages of individual snags and their decay classes. When average age in a decay class or individual ages were provided, the transition time was calculated by assuming that it occurred midway between the average ages for subsequent classes. For example, if the average age in class 3 was 10 years, and in class 4 was 30 years, the transition from class 3→4 was assumed to occur at 20 years. Often ages were not provided for class 6+ snags, because these are difficult or impossible to age. The transition from class 5→6+ was therefore estimated by assuming that the average age in class 5 was midway between the class 4→5 transition and the class 5→6 transition. For example, if the class 4→5 transition was at 50 years and the average age in class 5 was 75 years, the class 5→6 transition was calculated as 100 years ( $=75+(75-50)$ ).

When studies used other classification systems, we converted these to the Thomas classes based on the published characteristics of the different classes, sometimes partially allocating a class to more than one Thomas class. For example, class “X” in a paper might be identical to Thomas class 3, while class “Y” was half like class 4 and half like class 5. A data point on class “Y” would therefore count as 0.5 of a data point for Thomas class 4, and 0.5 of a point for class 5.

The possibility of decay classes that were partially allocated to a Thomas class made the calculation of the transition ages out of the Thomas classes more complicated. When a

published snag class was partially allocated to an earlier Thomas class and partially to the later one, the time for the proportion in the earlier class was added to the previous class. For example, if class X was entirely Thomas class 3 and had a transition age of 10 years, while class Y was 50% Thomas class 3 and 50% Thomas class 4 and had a transition age of 30 years, the transition age out of class 3 was calculated as  $10 + 50\% \times (30 - 10) = 20$ . If the next published class, class Z, was entirely class 5, then the transition time out of class 4 was the transition out of class Y, namely 30 years. If class Z was partially allocated to class 4 and partially to class 5, then the transition time out of class 4 added the proportion of class Z that was in class 4. (This calculation is difficult to explain verbally, but makes intuitive sense when seen graphically (Figure 3.1)).



**Figure 3.1. Graphical illustration of translating transition times from a non-Thomas published classification system to transition times for Thomas classes. The transition times for the non-Thomas classes are determined from the published data. The proportion of the published classes that are in each Thomas class are determined from the described characteristics of the classes. The transition times for the Thomas classes are calculated from this information, as described in the text.**

All ages were standardized to a DBH of 40cm, based on the relationship estimated in section 2.1:  $\text{Age}_{40\text{cm}} = \text{Age}_{X\text{cm}} \times (40/X)^{0.6}$ , where X is the published DBH. For example, a transition age of 10 years reported for a 20cm DBH snag would be standardized to 15.2 years for a 40cm DBH. This equation is based on analysis of snag fall rates, rather than decay rates, but is used here because of a lack of information on how decay rates change with DBH. The Weyerhaeuser/WFP analysis suggests that snag decay rate may change little with DBH. If that result was widely applicable, decay rates for species that can be much larger than 40cm (e.g., cedar, Douglas-fir) may be underestimated here.

Relatively few studies have provided both decay classes and times-since-death for standing snags. There were at most 3 studies of a single species (Douglas-fir and subalpine fir), and often just 1 study for a species. The analysis therefore included an examination of how to combine information from different species. AIC was used to select among 7 candidate models for grouping the 13 species with available information. The candidate models were generated based on expectations of decay rates and modes of the different species:

M1: Each of the species separate: southern Abies, subalpine fir, red-cedar, yellow cedar, Douglas-fir, western hemlock, red pine, white pine, Scots pine, southern pines, ponderosa pine, Norway spruce, Engelmann-white spruce

M2: Eight groups: All Abies, all cedars, Douglas-fir, hemlock, all pines except ponderosa pine, ponderosa pine, Norway spruce, Engelmann-white spruce.

M3: Six groups: All Abies, all cedars, Douglas-fir, hemlock, all pines, all spruces.

M4: Four groups: All Abies, cedars, Douglas-fir+hemlock+spruces, pines

M5: Three groups: Abies+Douglas-fir+hemlock+spruces, cedars, pines

M6: Cedars, all other species

M7: All species combined

The AIC analysis assumed log-normally distributed error around each of the 3 transition ages (class 3→4, class 4→5, class 5→6<sup>2</sup>).

### 3.1.2. Results – Snag time in decay classes

Transition ages between decay classes were surprisingly consistent among the different species and studies. The AIC analysis supported combining all species except the cedars (Table 3.1). In part this reflects the fact that there are not a lot of studies providing this information; if there had been more information, the data would support further differentiation between faster and slower decaying species.

**Table 3.1. AIC weights for candidate models for combining species for snag decay class transitions.**

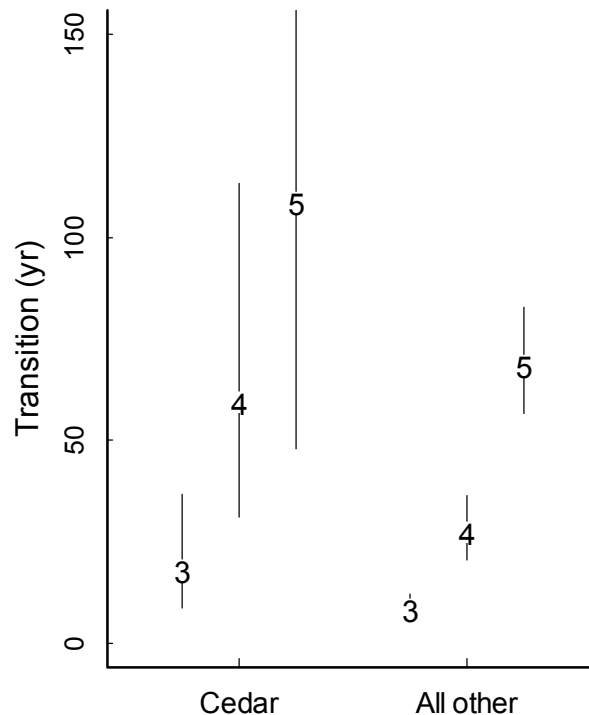
Model	AIC weight
M1 All species separate	0.000
M2 Eight groups	0.000
M3 Six groups	0.000
M4 Four groups	0.002
M5 Three groups	0.036
M6 Two groups	<b>0.686</b>
M7 All combined	0.275

Cedars changed between the decay classes at about twice the time-since-death as the other species (Table 3.2, Figure 3.2). Note that confidence intervals are wide for the cedars, with considerable variation among the 3 available studies. For other species, the relatively long time for the transition from class 5→6+ means that there will be relatively few well-decayed snags for species with higher fall rates (see previous section).

**Table 3.2. Best estimates of transition ages (years) (95% confidence intervals) for cedars and for all other species combined.**

Species group	Class 3→4	Class 4→5	Class 5→6
Cedars	18.1 (8.9-36.8)	59.3 (31.0-113.3)	108.6 (48.0-245.8)
All others	8.4 (5.9-12.0)	27.4 (20.6-36.4)	68.6 (56.8-82.8)

<sup>2</sup> Note that there is no transition out of class 6+, because there is no older snag class. Class 6+ snags either fall, or collapse into duff (which, of course, cannot be aged with normal dendrochronology techniques).



**Figure 3.2. Transition ages for cedars versus all other species. 3=transition from class 3→4, 4=transition 4→5, 5= transition 5→6+. Error bars are 95% confidence intervals (upper bar truncated for 5→6+ cedar).**

Model M5, which separated *Abies* from the other non-cedars (and had only weak AIC support), showed *Abies* with a similar transition age from class 5→6+, but transitions from 3→4 and 4→5 that were about 40% later than for the other non-cedars. That is, *Abies* appears to retain its fine branches and intact bark relatively longer than other non-cedars, but the wood becomes soft at about the same age.

Separate estimates for each of 6 species groups are shown in Table 3.3. Note the wide and overlapping confidence intervals of these more specific estimates.

**Table 3.3. Estimates of transition ages (years) (95% confidence intervals) for 6 species groupings.**

Species group	Class 3-->4	Class 4-->5	Class 5-->6
Abies	12.9 (6.2-27.0)	45.0 (26.8-75.6)	83.1 (61.5-112.2)
Cedars	18.1 (8.9-36.8)	59.3 (31.0-113.3)	108.6 (48.0-245.8)
Douglas-fir	6.6 (3.2-13.8)	18.1 (12.4-26.4)	50.2 (42.0-59.9)
Hemlock		32.2	57.0
Pines	6.1 (3.5-10.8)	21.5 (12.3-37.6)	68.0 (44.4-104.1)
Spruces	10.5 (4.7-23.5)	35.5 (21.7-57.9)	83.5 (54.9-127.0)

## 4. Snag breakage

### 4.1. Snag breakage rates

*Question: At what rate do standing snags?*

This process of snag breakage<sup>3</sup> is included in detailed deadwood models, because it allows some CWD to be created before the entire snag falls. Snags with broken tops are also important as a particular habitat element themselves, with different characteristics from unbroken snags. The broken tops allow the centers of the snags to rot more quickly, creating nest sites for weaker cavity-nesters, such as nuthatches, and, for large broken snags, roosts for swifts, bats and other species. At the same time, snag fragmentation reduces the abundance of tall snags preferred by other species. Broken snags may also be less prone to falling, but there is not enough direct data to assess whether that is true.

#### 4.1.1. Methods – Snag breakage

Relatively few studies have reported on snag breakage. The information is mostly in the indirect form of average height of snags over time or average loss of height over a fixed period. To convert reported changes in height over time into the *proportion of snags breaking* annually, we first assumed that snags break with equal probability at any height, from >0 - <100% of their total height. This assumption generally matches the observation that snags break at a variety of heights, because there are different processes that produce breaks higher or lower along the trunk<sup>4</sup>. On average, snags would break at 50% of their height (half-way up the trunk). For low percentages of average height loss, that would mean that the percentage of snags breaking would be twice the percentage average height loss of all snags. For example, if average snag height declined 5%, that would mean that 10% of snags lost half their height.

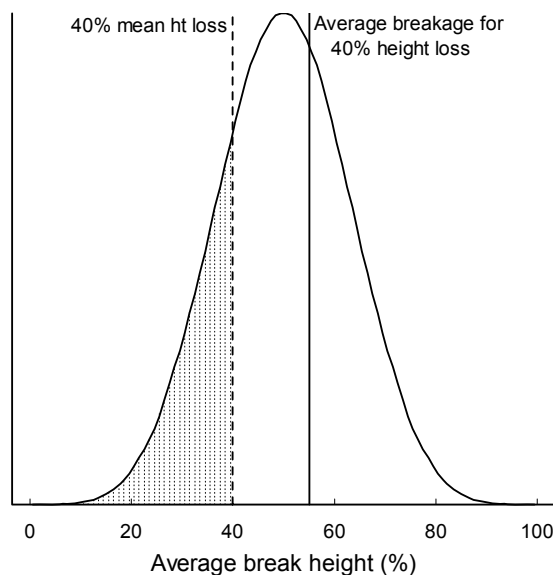
The conversion of average height loss to percentage of snags breaking is trickier, however, when the height loss is high. For example, if average height decreases 60%, it is clearly not possible that 120% of snags lost half their height; the percentage of snags breaking is necessarily less than 100%, and the average height loss of breaking snags consequently >50%. Therefore, we converted average height loss to percentage of snags breaking in a slightly more complex way. First, we assumed that the reported average height loss is created by 5 snags independently breaking at >0 - <100% of their height (or, equivalently, more than 5 snags, but with some dependency in the heights at which they break). This gives a roughly normal curve for the average proportion of height lost for snags that break, centred on 50% (Figure 4.1). For a given average height loss, the proportion of heights lost by snags that did break must be at least as high as the average height loss (otherwise, >100% of snags would have to break). Therefore, we used only the part of the distribution in Figure 4.1 that was greater than the observed average height loss. For example, if the observed average height loss was 40%, we only used the part of the distribution >40%. We then assumed that the height loss of the snags that broke was the average of this truncated distribution (e.g., 55% height loss for snags that broke in the example with 40% average height loss). We then used this value to calculate the proportion of snags that broke. In the example, with 55% height loss of breaking snags, 72.7% of snags would have to break to produce an average height loss of 40% across

<sup>3</sup> We separate the process of snags breaking somewhere above their base from snags that break at the base (which are part of snag fall rates). Sometimes both processes are included as “snag fragmentation” (e.g. Harmon et al. 1986), but the result of the two processes are different from a habitat point-of-view.

<sup>4</sup> Also, a conical trunk is roughly equally prone to breaking at any height from simple physics – the cross-sectional area that resists breaking increases at lower heights, but the leverage and mass to break the trunk also increase at lower heights.

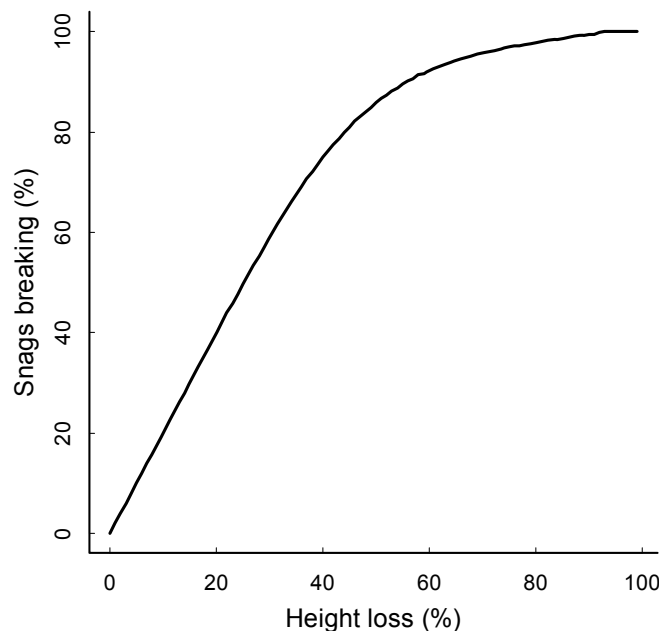
all snags (including the 27.3% that didn't break). Thus, 40% average height loss of snags equals 72.7% of snags breaking.

The relationship between reported average height loss of all snags and the percentage of snags that break is shown in Figure 4.2. For lower values of average height loss, the proportion of snags breaking is very close to twice the height loss (because a breaking snag loses 50% of its height); for higher values of average height loss, the percentage of snags breaking levels out towards 100% (and the height lost on snags that broke increases above 50%). This curve was applied to all reported values of average height loss to convert them to proportion of snags breaking. These rates were then converted to annual rates, as  $P_{\text{ANNUAL}} = P_{\text{REPORTED}}^{1/T_{\text{REPORTED}}}$ , where  $P_{\text{REPORTED}}$  is the proportion breaking over the reported time interval  $T_{\text{REPORTED}}$ .



**Figure 4.1. Distribution of average break height for 5 snags breaking independently at >0 - <100% of their height. Example shows how the distribution was used to calculate the average height loss of snags that break when the average height loss (including the 0% loss of snags that didn't break) was 40%. The average of the distribution for values >40% is 55%. Hence, 40% average height loss of snags is equal to 55% height loss for the 72.7% of snags that break (72.7% x 55% = 40%).**





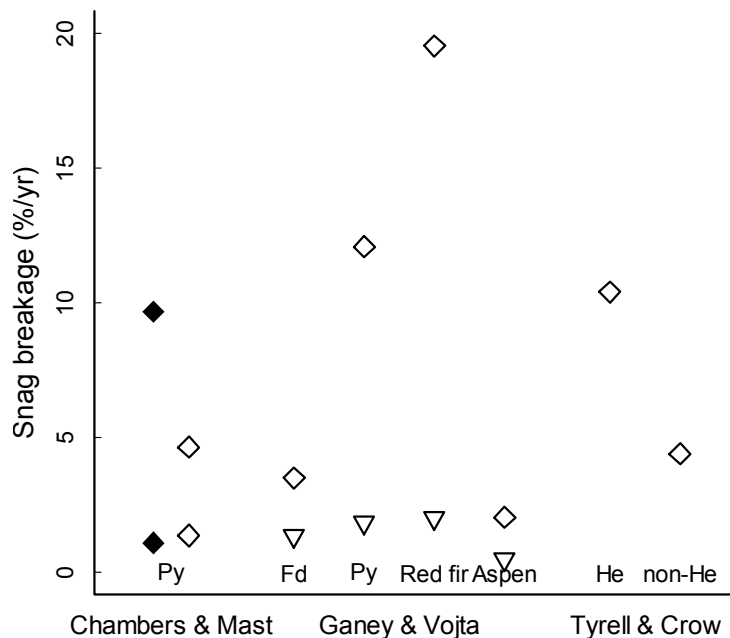
**Figure 4.2. Percentage of snags breaking as a function of the total height loss percentage of all snags (including those that don't break).**

Among the 6 studies that reported height loss or breakage of snags, there was very little overlap in species or in the other variables that the studies examined (e.g., changes in breakage over time in 2 studies of different species, burned versus not burned in one study, size and decay class in another, intact versus previously broken snags in another.) Therefore, we did not try to combine results in any way, and simply present the breakage rates reported by the studies, or the values calculated from height loss, each converted to an annual rate.

#### *4.1.2. Results – Snag breakage*

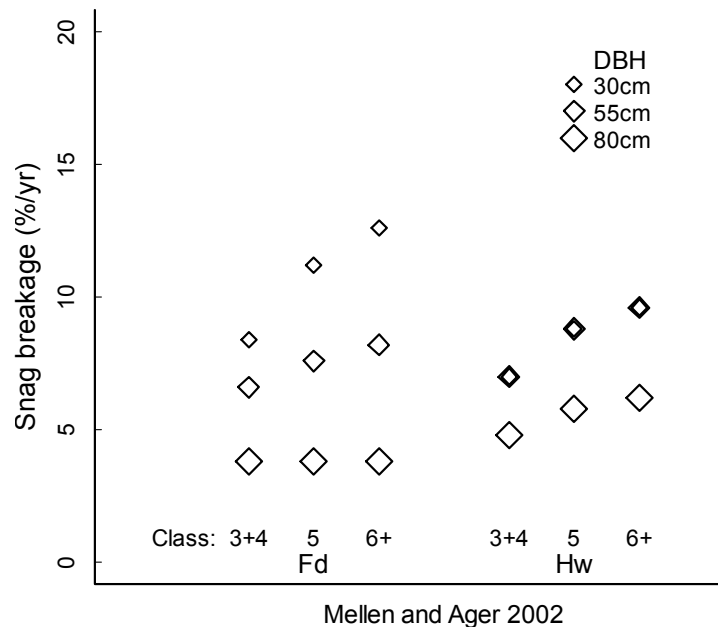
Burned ponderosa pine snags showed higher breakage rates in one study area, but not in the other in Chambers and Mast (2005), with rates ranging from 1-10%/yr (Figure 4.3, left).

Intact snags had higher breakage rates than previously broken snags in the study of Ganey and Vojta (2005) (Figure 4.3, middle). This makes sense, as broken snags have less leverage in their tops to break the trunk. In the deadwood model, we reduce the annual snag breakage rate in proportion to the loss of height of each snag. For example, a snag that had lost 50% of its height would have half the breakage rate of an intact snag.



**Figure 4.3. Annual breakage rates of snags reported by 3 studies. Chambers and Mast (2005) compared burned (◆) and unburned (◇) ponderosa pine (Py) snags. Ganey and Vojta (2005) compared intact (◇) and previously broken snags (▽) of Douglas-fir (Fd), ponderosa pine (Py), red fir and aspen. Tyrell and Crow (1994) reported averages for eastern hemlock (He) and all other species (non-He) in their Michigan study area.**

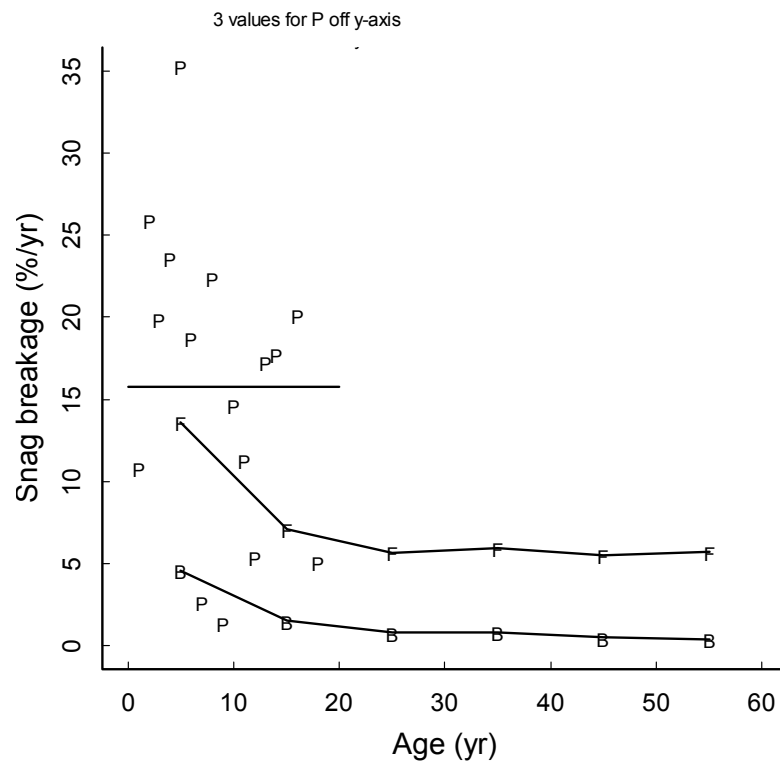
Mellen and Ager (2002) reported higher breakage rates for smaller diameter snags, with 30cm DBH Douglas-fir snags having up to triple the breakage of 80cm DBH snags (Figure 4.4). It is not entirely clear why there should be this difference, since the top parts of larger snags are morphologically similar to smaller snags (and potentially more exposed to severe wind). The effect of size was less pronounced in hemlock snags. Breakage rates also increased for more decayed classes of snags, though this effect was less pronounced than the diameter effect. The breakage rates for Douglas-fir in Mellen and Ager (2002) were considerably higher than for Douglas-fir in Ganey and Vojta (2005).



**Figure 4.4. Annual breakage rates of snags used in the model of Mellen and Ager (2002). They presented separate values for 3 size classes of snags (averaging 30, 55 and 80cm DBH) and 3 decay classes (hard, medium and soft, converted to the Thomas (1979) classes 3+4, 5 and 6+, respectively), for Douglas-fir (Fd) and western hemlock (Hw).**

Breakage rates were higher 0-10 years after tree death than in older snags in Everett et al. (1999) (Figure 4.5) (but the specific form of the curve is determined by a logarithmic model that the authors fit to snag height over time). The greater breakage rate of intact snags (c.f. Ganey and Vojta 2005) appears to be more important than any increase in breakage due to softening of snags as they age (c.f. Mellen and Ager 2002). Douglas-fir showed a higher breakage rate in this study, in contrast to Ganey and Vojta (2005) where Douglas-fir has the lowest breakage rate among conifers. The raw data on heights in Conner and Saenz (2005) did not show any clear evidence of a trend in breakage rates with time since death of the snag. These southern pines and the red fir in Ganey and Vojta (2005), both with soft wood, had the highest breakage rates of any species. However, subalpine fir, also a species with soft wood and prone to heart rot, had the lowest rates (Everett et al. 1999).

Overall, this summary of published information on snag breakage shows that current information is inadequate to establish patterns among the various factors that determine snag breakage for a particular species and study area.



**Figure 4.5. Annual breakage rates of snags as a function of snag age (time since death) based on the fitted curves of height loss of Everett et al. (1999) for Douglas-fir (F) and subalpine fir (B), and based on the raw data on height loss of Conner and Saenz (2005) for southern pines (P). The flat line is the average for the Conner and Saenz (2005) data, which do not show any substantial trends with time since death. Note that 3 values from Conner and Saenz are not shown – 62-69% breakage rates at years 15, 17 and 19.**

## 5. CWD Decay

Our interest here is in parameters to model CWD as structure, not as a biomass component. There has been much work on biochemical decomposition of logs, mainly as part of carbon budgets or nutrient balance studies, but considerably less on decay of logs as physical structures. Logs can lose substantial amounts of carbon and other nutrients, and still function as cover for animals, substrates for plants, lichens and fungi, and areas with altered microclimates. On the other hand, old logs disappear as coherent, above-ground structures before all their carbon is respired and nutrients released.

Although our interest in CWD as physical habitat structure, we do access the larger literature on biochemical decomposition for two purposes. The first is to complement the limited number of studies that look at how CWD decay is affected by log diameter. Here, we assume that biochemical decomposition rates will show the same general relationship with log diameter that decay as physical structure does (even if the rates themselves are potentially very different). We also use the decomposition literature to supplement information on how long logs stay in the different physical decay classes. There is limited direct information on this important modeling variable, but several studies have assessed the density (dry weight or carbon) of logs in different physical decay classes. This can be combined with estimates of how density changes over time as the log decomposes to give estimates of how long logs spend in each decay class. In the end, though, we are trying to estimate how fast logs decay through different structural classes, and how these decay rates are affected by various factors.

### 5.1. CWD Decay – Effect of log diameter

*Question: How does the decay or decomposition rate of CWD change with log diameter?*

As with the relationship between snag fall and DBH, this relationship is a basic part of modeling deadwood with different size pieces. It is also a necessary first step for summarizing studies of CWD decay, because if there is a strong relationship between decay and log diameter, results need to be standardized to a common diameter before being combined. The relationship also has direct implications for managing CWD: larger logs provide some ecological benefits compared to an equivalent volume of smaller logs, but a main point favouring retention of larger CWD is the belief that downed wood persists longer in larger logs.

Many studies report biochemical decomposition<sup>5</sup> rates of logs and give a single mean diameter for logs. We did not use these studies, because, while the suite of studies cover a range of mean log diameters, the variation in size across studies is potentially confounded with many other variables. A main concern would be that bigger average log size is correlated with higher productivity ecosystem and older forest stands, which may have higher decay rates. Instead, we only synthesized results of studies that directly compared decomposition or deterioration of logs of different sizes in the same ecosystems. This included 4 studies on decay of log density (Foster and Lang 1982, Graham and Cromack 1982, Edmonds and Eglitis 1989, Tarasov and Birdsey 2001), which looked at a total of 5 species, and 2 studies of loss of acceptable timber (Buchanan and Englerth 1940, Childs and Clark 1952 – both summarized in REF), also covering a total of 5 species. Two modeling papers also presented parameters used for modeling CWD decay (Mellen and Ager 2002, Vanderwel et al. 2006), and one review study analysed decay rates by size (Yin 1999). We didn't find any papers that directly measured structural decay of CWD as a function of log size.

---

<sup>5</sup> We try to use “decomposition” to refer to biochemical decomposition (loss of biomass, carbon or other nutrients) and “decay” to refer to structural decay (specifically here, transitions among Thomas' (1979) decay classes for CWD). Some forestry studies refer to “deterioration”, loss of timber value.

### 5.1.1. Methods – Effect of log diameter on CWD decay

There were 4 overall steps in the analysis. Steps 3 and 4 follow the similar analysis of snag fall versus DBH:

- 1) For studies that reported actual densities, we converted the reported density values into percent of density at tree death, where the density at death of the different species were either reported directly in the studies, or were estimated as the average of the (1 or more) data points of the youngest logs. (The timber deterioration studies directly reported percent of suitable timber remaining, relative to 100% at tree death).
- 2) For both density and timber studies, we converted the measurements to the common scale of time until 50% decay or deterioration (=“half-life”). Information on decay of logs as a function of time and diameter came in 2 forms in the 6 empirical studies, which required different approaches to calculating the half-life:
  - i) The two timber studies and the study of Edmonds and Eglitis (1989) on density decomposition presented data points for logs of different diameters measured at 1-3 fixed times after death. The half-life for each data point could be calculated directly based on  $T_{50} = x_i \cdot \log_e(0.5) / \log_e(T_i)$ , where  $T_{50}$  is the half-life in years,  $x_i$  is the reported measurement expressed as proportion of the undecayed state (i.e., 0.8 for a density 80% of the density at death), and  $T_i$  is the reported time since death for the measurement.
  - ii) The other 3 studies of density decomposition presented the time since death for individual logs, grouped into diameter classes. For each diameter class, a logistic curve was fit, with intercept fixed at 100% at year 0 and long-term asymptote at 0%. The half-life was calculated from this curve. The error distribution of the fitted logistic curve was used to generate a distribution of the half-life for each species x study combination.
- 3) Half-life values differed considerably among the two measurement types (density and timber deterioration), and among the species and studies. This analysis was focused only on how the decay rates changed as a function of diameter. Therefore, the half-life values from each species x study combination were standardized to a value of 100 for a 40-cm diameter log. For the studies that presented the data by the diameter of the individual logs, a power regression was fit to the data (next step) and scaled directly to a value of 100 at 40cm. For the studies that reported age of individual logs by diameter classes, a linear regression was fit through the medians of the distributions of the half-life values (previous step) for the 2 or 3 diameter classes for each species x study combination, and this regression was used to scale the half-life distributions to the value of 100 at 40cm.
- 4) A power (log-log) regression was then fit to the standardized half-lives versus log diameter. The slope coefficient of this regression is the value of interest, because it shows how decay rates should be scaled as a function of diameter. For example, a coefficient of 0.5 means that half-life scales as the square-root of diameter (or, equivalently, rate of decay scales as the inverse of the square root of diameter). If a 40-cm diameter log in some ecosystem had a half-life of 50 years, a 20-cm log would have a half-life of 35 years ( $=50 \times (20/40)^{0.5}$ ). The 20-cm log would be decaying 1.41 times as fast as the 40-cm log ( $=(40/20)^{0.5}$ ). A coefficient of 0 means that there is no difference in half-life or decay rate with different diameters. The 3 studies (4 species x study combinations) that presented times since death for individual logs in 2-3 diameter classes did not have enough different diameter values to fit a regression with diameter for each individual species x study. Instead, the results for the 4 species x study combinations were pooled and the regression fitted across the resulting 10 diameter values (2-3 diameter classes per species x study).

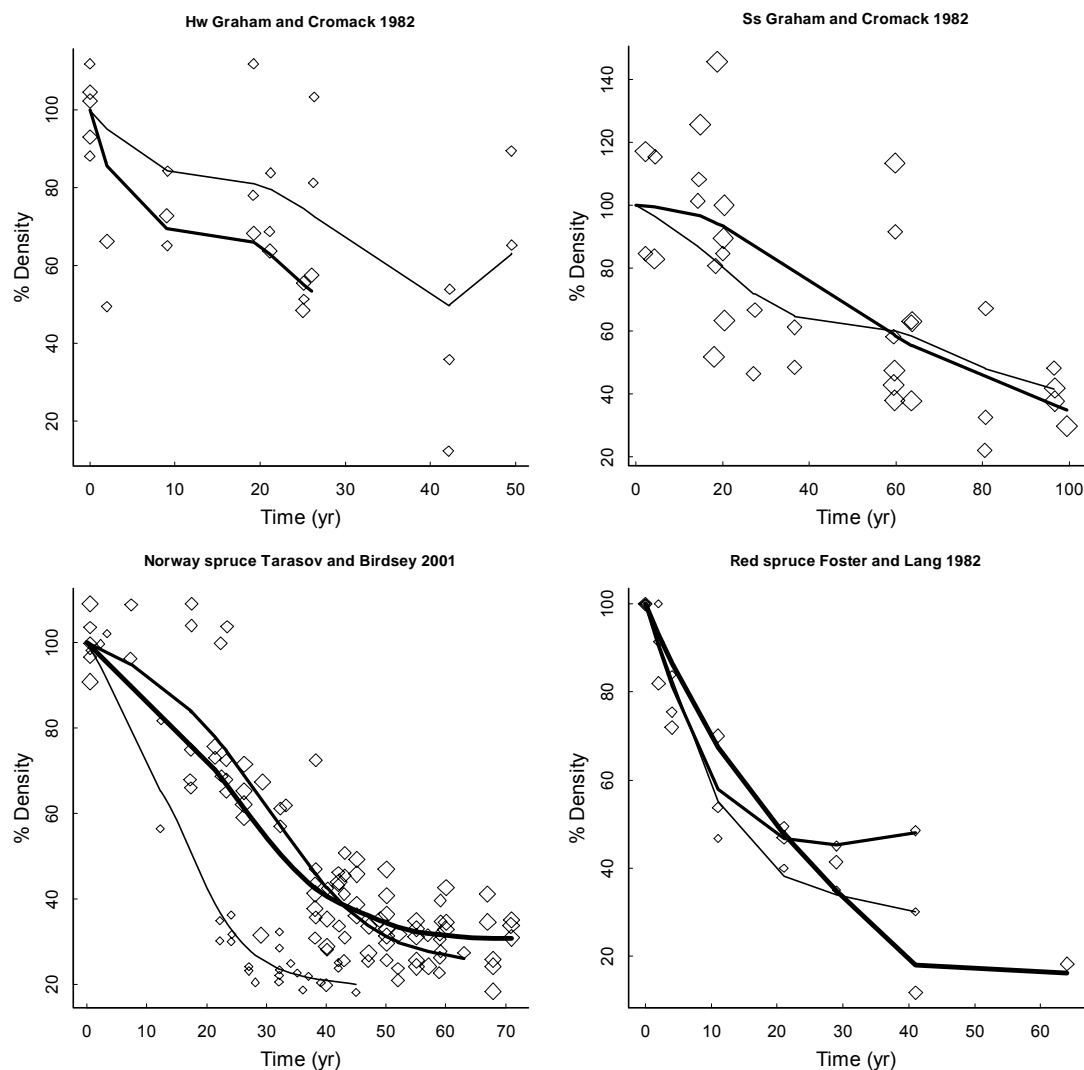
### 5.1.2. Results – Effect of log diameter on CWD decay

The data from the available studies are summarized in Figures 5.1-5.3. Note that the Figure 5.1 has studies that presented time since death for individual logs in 2-3 diameter classes; the graphs have time as the x-axis. Figures 5.2 and 5.3 have the other 6 graphs, which presented diameters of individual logs at 1-3 fixed times since death; diameter is the x-axis.

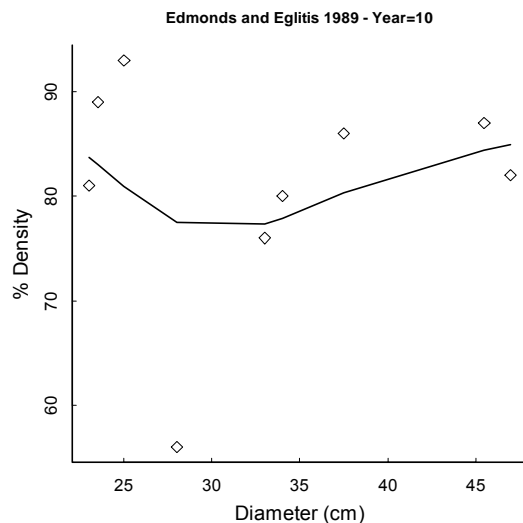
The 4 species x study combinations with individual times reported show generally sigmoidal or negative exponential loss of density with time, as expected (Figure 5.1). The smallest diameter class showed faster decomposition, at least initially, in 3 of the 4 combinations, but slower decay for hemlock in Graham and Cromack (1982). However, the diameter effect is generally not clear or pronounced in these cases.

The other species x study combination for density decomposition presented diameters of individual logs and their decay 10 years after death, but showed no clear trend with diameter (Figure 5.2).

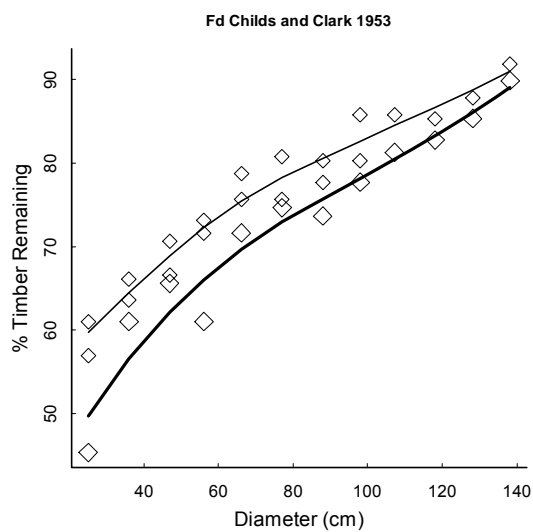
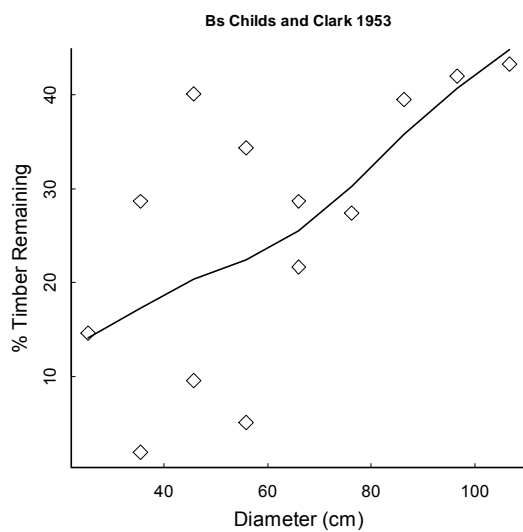
In contrast, the timber deterioration studies, which presented individual diameters and timber loss at 1-3 fixed times after death, showed clear trends with diameter (as well as consistently increasing timber loss over time) (Figure 5.3).



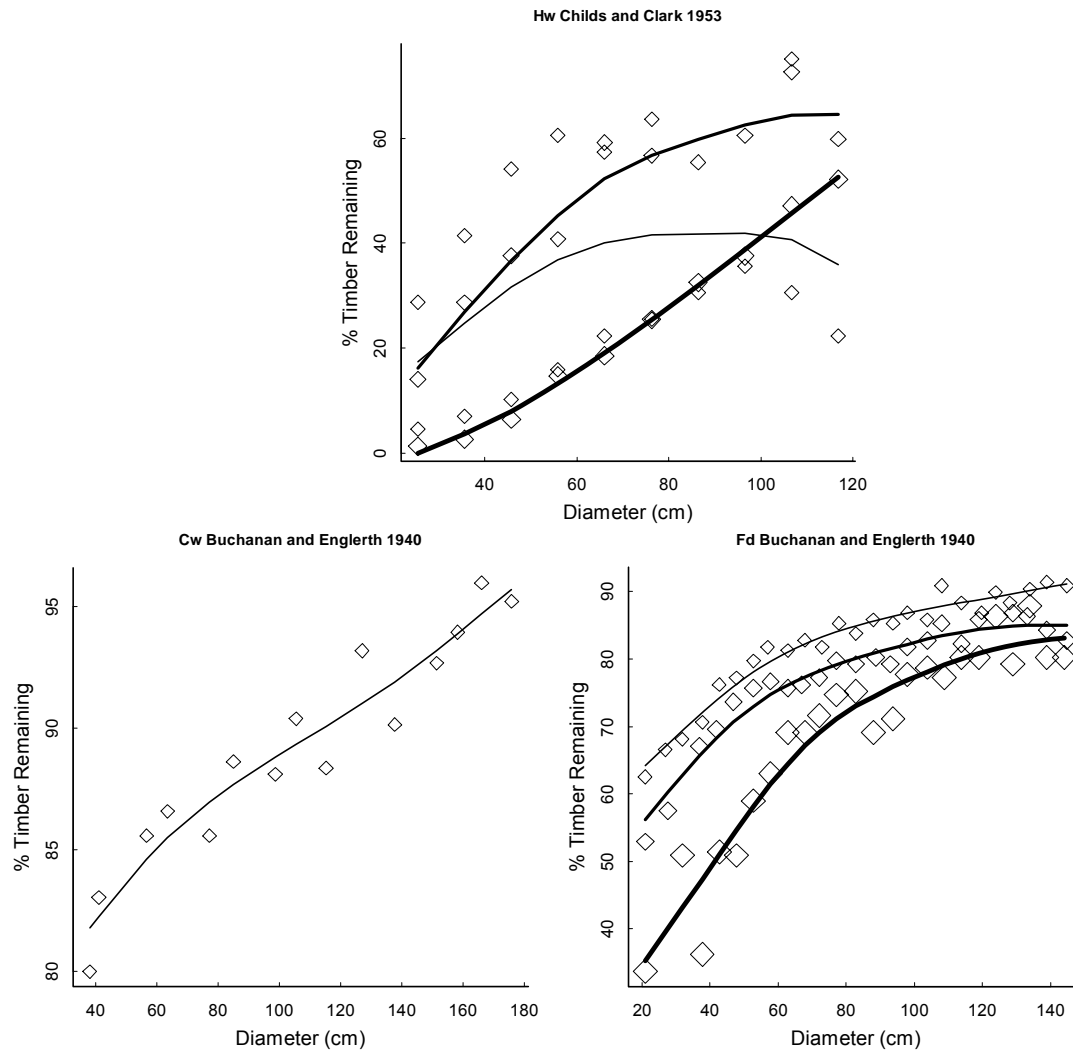
**Figure 5.1. Density decomposition over time, for 2-3 diameter classes. Larger symbols and thicker lines represent larger diameter classes. Fitted lines are spline curves showing the main trends in the data.**



**Figure 5.2. Density decomposition versus log diameter 10 years after death (Edmonds and Eglitis 1989). Fitted line is a spline curves showing the main trend in the data.**

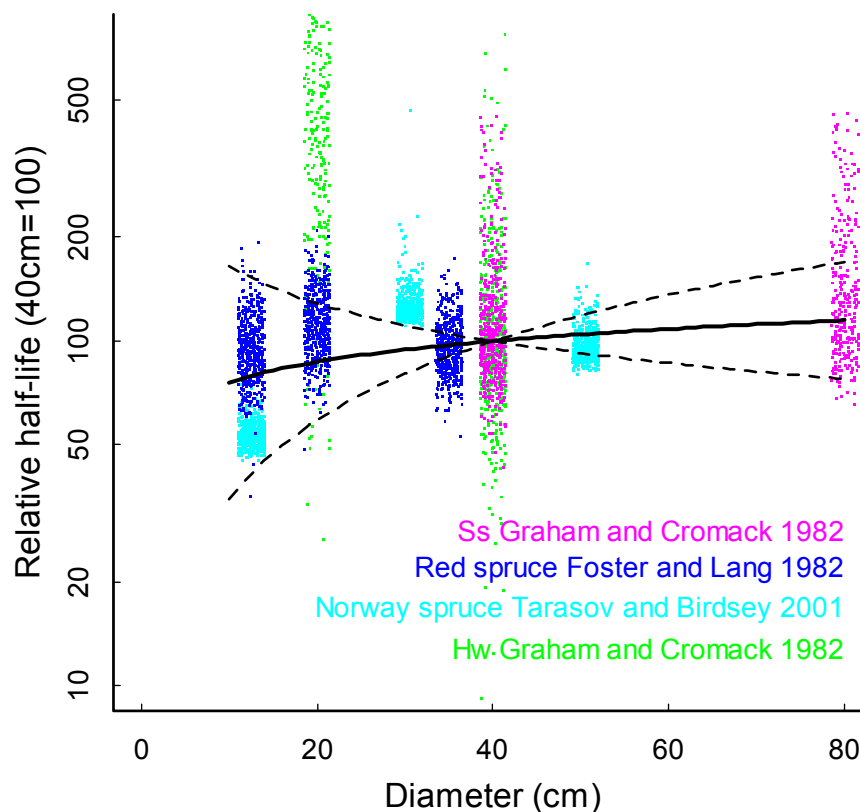






**Figure 5.3. Timber deterioration at 1-3 times since death, versus diameter of log. Larger symbols and thicker lines represent longer times since death. Fitted lines are spline curves showing the main trends in the data.**

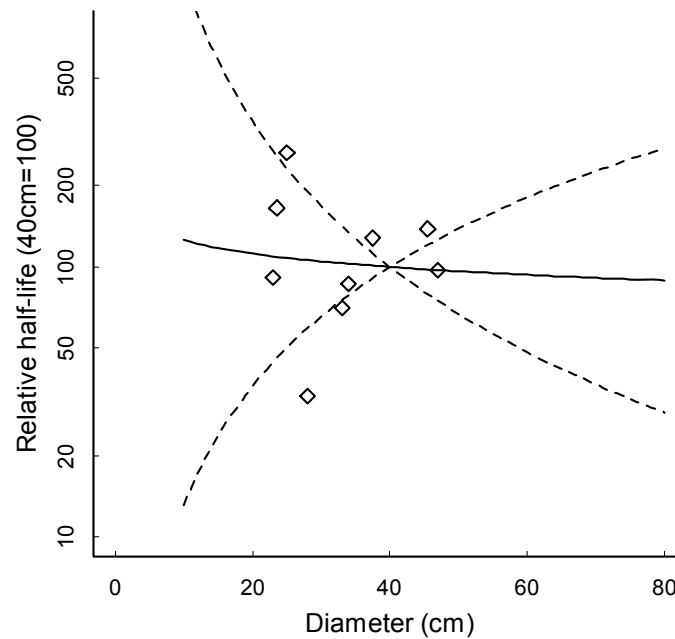
Figure 5.4 shows the distribution of half-lives for each of the species x study combinations and diameter classes for the 3 density decay studies that presented data on individual log ages.



**Figure 5.4. Relative half-life (standardized to 100 for a 40-cm log) of 2-3 diameter classes of logs in 4 species x study combinations. Solid line is log-log (power) regression; dotted lines are 95% confidence intervals (standardized to 100 at 40cm). Note logarithmic scale of y-axis.**

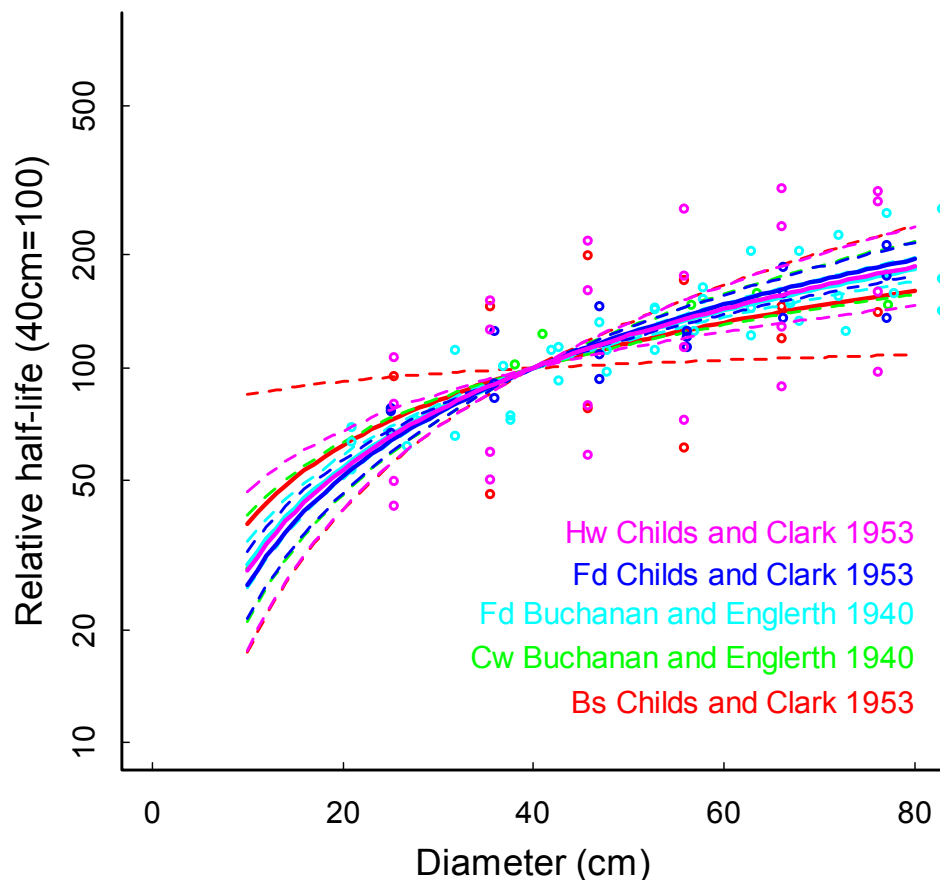
The half-lives from the different species x study combinations have been standardized to a value of 100 for 40-cm logs. The two species from Graham and Cromack 1982 showed considerably more variation in the half-lives than the other two studies, due to smaller sample sizes and more scattered density values. The power regression fit to the standardized distributions showed a slight increase in half-life with diameter (i.e., slower decay), but the 95% confidence intervals on the coefficients ranged from a modestly sharp increase in half-life with diameter to a moderate decline (i.e., faster decay of larger logs). A slope of 0 – no effect of diameter – is clearly a very plausible result.

The one study of density decay that presented diameters for individual logs (density at 10 years after death) had scattered half-life values, and an extremely wide range of possible slope coefficients in log-log regression (Figure 5.5).



**Figure 5.5. Half-life for each data point, log-log regression (solid line) and 95% confidence intervals (dotted line) for density decomposition from Edmonds and Eglitis 1989, all standardized to 100 for a 40-cm log. Note logarithmic scale of y-axis.**

In contrast to the density decay results, each of the 5 species x study combinations for the timber deterioration studies showed clearly increasing half-lives with increasing diameter (Figure 5.6). Slope coefficients ranged from 0.69 to 0.96 (i.e., a 20-cm log would have a half-life 51-62% as long as a 40-cm log).



**Figure 5.6. Half-life based on timber deterioration for 5 species x study combinations. Half-life values for individual data points (symbols), log-log-regression (solid line) and 95% confidence intervals (dotted line) have all been standardized to 100 for a 40-cm log. Note logarithmic scale of y-axis.**

The coefficients for the slope of the log-log regression for the four pooled density studies and the separately analyzed density results of Edmonds and Eglitis (1989) were averaged, weighting by precision. The coefficients for the 5 timber deterioration regressions were similarly averaged. The resulting best estimates of the coefficient clearly differ between the 2 data types (Table 5.1), with timber deterioration being strongly affected by log diameter, and density decay weakly affected, if at all. (Note: If these two averages were themselves combined in a weighted average, the result would be very close to the average from the timber studies, since these produced much more precise values. However, the distinct difference between the two data sources suggest that it would not make sense to do this average.)

Vanderwel et al. (2006), summarizing their own field data for a modeling paper, showed only minor and inconsistent effects of log diameters on rates of transition between CWD classes. Yin (1999) also found that wood diameter did not contribute to multivariate models of decay rate. (His review included smaller pieces than those used here, and deciduous species).

Stone et al. (1998) used long-term remeasurements of permanent plots to track CWD volume loss, which more closely relates to physical decay than biochemical decomposition. (Some volume is lost as logs shrink with decomposition, but most volume loss in the long-term comes from physical disintegration of logs into small wood fragments). Their results for volume loss of logs in 4 diameter classes produce a power exponent of 0.954 (SE 0.179), very similar to the timber deterioration studies.

The different types of data in this synthesis therefore provide different views on the relationship between decay and log diameter. We used the coefficient derived from the density decomposition studies for the analyses in the next two sections, because these are looking at decomposition as an initial step towards estimating time CWD spends in each decay class. Also, the decomposition studies covered a much longer range of times (from tree death to near complete loss of wood) than the timber deterioration studies. An additional argument for using this lower coefficient in these analyses (which has less of an effect on the results standardized for DBH) is that many studies analysed in subsequent sections only reported average log diameters, or we had to guess at the diameters from study area descriptions; the lower coefficient has less of an impact with uncertain diameters. For modeling decay of individual logs, we would use a coefficient intermediate between those derived from density decomposition and timber deterioration (and Stone et al. volume loss), similar to those used by the two modeling studies in Table 5.1. (In fact, the coefficient of 0.60 from the snag fall analysis is in this same ballpark).

**Table 5.1. Summary of slope coefficient (power exponent) for 5 species x study combinations of density decay, 5 of timber deterioration and 2 from a deadwood model.**

<b>Sp Study</b>	<b>Coefficient</b>	<b>SE</b>
<i>Density decomposition</i>		
Four pooled density decay studies	0.198	0.285
Fd Edmonds and Eglitis 1989	-0.165	0.814
<b>Average - density studies</b>	<b>0.158</b>	<b>0.269</b>
<i>Timber deterioration</i>		
Cw Buchanan and Englerth 1940	0.889	0.117
Fd Buchanan and Englerth 1940	0.874	0.052
Bs Childs and Clark 1953	0.688	0.285
Fd Childs and Clark 1953	0.963	0.075
Hw Childs and Clark 1953	0.900	0.175
<b>Average - timber studies</b>	<b>0.897</b>	<b>0.041</b>
<i>Model</i>		
Fd Mellen and Ager 2002	0.563	(0.109) <sup>1</sup>
Hw Mellen and Ager 2002	0.330	(0.015) <sup>1</sup>
<i>Volume chronosequence</i>		
Fd Stone et al. 1998	0.954	0.179

<sup>1</sup> Standard error only based on fit of log-log regression – does not reflect uncertainty in the individual data values.

## 5.2. CWD Decay – Species groups

*Question: How should species be grouped to estimate decay rates?*

As outlined above, we are first looking at density decomposition – even though we are interested in structural decay of CWD – so that we can convert reported densities for logs of different decay classes to how old those logs are. This allows us to supplement the few direct studies of CWD decay between structural classes with the more abundant information on wood decomposition rates and the density of CWD in different structural classes. With limited data on decomposition for each CWD species, better estimates of decomposition rates can be obtained by grouping similar species. This analysis uses an AIC-based model selection analysis to find the best way of grouping species, given the available data.

### 5.2.1. Methods – Species groups for CWD decay

Because our results are being used to convert information on density of logs in different decay classes to their age, we only used studies here that provide rates for density loss over time (not volume or mass loss). The analysis of diameter effects (section 5.1) showed some effect of diameter on decomposition rates. All data and analysed results used in this analysis were therefore corrected to a 40cm diameter. When studies reported separate results for different diameter classes, we pooled the results, all corrected to 40cm diameter, for the different size classes. Most studies reported mean diameters; when they didn't, we made a guess based on information provided in the paper. (The correction for diameter effects on decomposition is quite small, so the exact diameter is relatively unimportant). When studies reported separate values for CWD on versus off the ground, we only used values for wood on the ground.

Data on wood density versus time since tree fall were available for 16 studies, with a total of 24 species x study combinations. For these studies, we fitted a negative exponential curve, forced through the density of the wood at the time of death at time 0. The slope coefficient of this regression is the decomposition coefficient (and the SE of the slope is the SE of the decomposition coefficient). Six other studies provided the decomposition coefficient and SE for a species. Typically these regression were not forced through the initial wood density at time 0, and so have larger SE's than where we calculated the coefficient from the data.

The total of 30 species x study combinations included 13 different species, with 1 to 6 studies of each. An AIC-based model selection analysis was used to compare different plausible ways of combining these species to provide the best estimates of the decomposition coefficients. Candidate models were based on general background information and beliefs about relative rates of decomposition of different species, and included:

- Model 1: Each species separate (i.e., 13 separate estimates of coefficients)
- Model 2: Combine species within genus. This included 3 species of *Abies*, 5 of spruce, 2 of hemlock and 2 of pine.
- Model 3: Combine species within genus, except keep the 2 hemlock and 5 spruce species separate.
- Model 4: Combine species within genus, except the 5 spruce species.
- Model 5: By genus, but combine *Abies* and hemlock
- Model 6: By genus, but combine *Abies* and spruce
- Model 7: Group as fast-decaying, coastal slower-decaying and high-elevation/dry slower decaying. Fast-decaying includes *Abies*, hemlock, and Norway, red and black spruce; coastal slower includes Douglas-fir, Sitka spruce and cedar; high/dry slower includes Engelmann (or hybrid) spruce, and lodgepole and ponderosa pine.

Model 8: Fast-decaying, coastal and high-elevation/dry. This differs from model 7 in including western (but not eastern) hemlock in the coastal group. (There were no studies with Interior western hemlock).

Model 9: Model 8, but with cedar separate. Cedar is thought to have slow decay.

Model 10: Null. One decay coefficient for all species.

Decomposition coefficients (and SE) were calculated for each species, combining the results from the 1-6 studies with data on each. SE's here were calculated with the standard analytical formula for averaging more than one mean with SE's. Decay coefficients (and SE) were also calculated for each group in the AIC-best grouping model. In this case, there were 8-12 studies in the 3 groups (results below), so that SE's could be calculated with bootstrapping in which each study was a resampling unit. The bootstrapping approach better shows the uncertainty created by variation among study sites (and different ways of measuring density, time since fall, etc. in different studies). Different studies produced estimates of decomposition coefficients with different precisions. The means for the study groups were therefore calculated in two ways, with and without weighting by precision. Weighting by precision should give a better estimate of the one "true" decomposition coefficient for a species (if this concept applies). Unweighted means and SE's treat each study equally and show more directly the average of different sites and how variable results from different sites are.

### 5.2.2. Results – Species groups for CWD decay

The decomposition coefficients ( $\pm$  SE's) for each of the 30 species x study combinations are shown in Figure 5.7. All coefficients have been standardized to a diameter of 40cm. There is clearly considerable variation within species that are represented in several studies. Within spruce, low decomposition rates are found in the two studies of Engelmann spruce in high elevations, medium rates in Sitka spruce on the coast, and faster decomposition in eastern spruce and Norway spruce. The two studies of pine with the slowest decomposition are from dry fire-origin stands, but the ponderosa pine study and at least one of the lodgepole pine studies with faster decomposition were also from similar ecosystems. Except for the relatively fast decomposition rate of eastern hemlock, there is no obvious reason for the variation in decomposition rates within hemlock. Within Douglas-fir, the two fastest decomposition rates come from young, low-elevation stands and two slower rates come from old, higher-elevation stands (the other two studies do not specify stand age). However, there clearly are not enough studies of any given species for reliable post-hoc explanations of variation within a species.

Average decomposition rates and equivalent half-life values for each species are in Table 5.2.

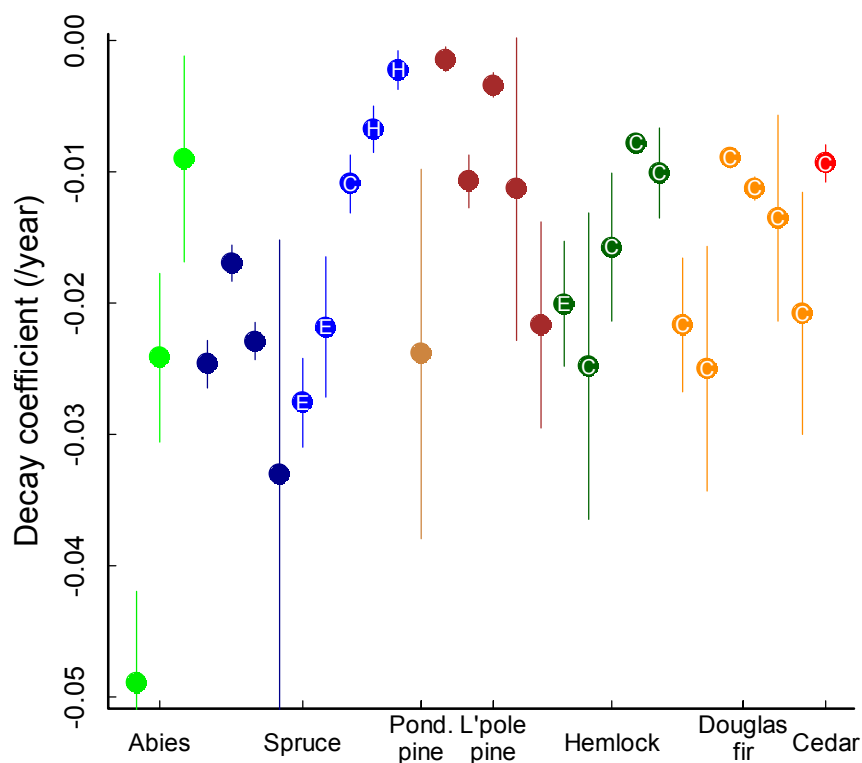


Figure 5.7. Decomposition coefficients ( $\pm 2$  SE's) for 31 species x study combinations. Colours indicate species or genera. Among spruce, darker blue is Norway spruce. E=eastern species that were included in the fast-decomposing group in some models. C=coastal species. H=high-elevation spruce (included with the pines in high/dry grouping in some models).

Table 5.2. Combined estimates of decomposition coefficients for each species, and equivalent half-life estimates.

Species	Decomposition coefficient (/year)		Half-life		Studies
	Mean	SE	Mean	95%CI	
Red fir	-0.0490	0.0035	14.1	12.4-16.5	1
Balsam fir	-0.0159	0.0027	43.6	32.6-66.0	2
Norway spruce	-0.0233	0.0008	29.8	27.8-32.1	4
Red spruce	-0.0276	0.0017	25.1	22.3-28.7	1
Black spruce	-0.0218	0.0027	31.7	25.5-42.0	1
Sitka spruce	-0.0109	0.0011	63.7	53.0-79.8	1
Engelmann spruce	-0.0045	0.0007	155.2	118.4-225.2	2
Eastern hemlock	-0.0201	0.0024	34.6	27.9-45.3	1
Western hemlock	-0.0177	0.0030	39.2	29.3-59.0	4
Ponderosa pine	-0.0238	0.0071	29.1	18.3-71.2	1
Lodgepole pine	-0.0064	0.0010	108.9	83.7-155.8	5
Douglas-fir	-0.0147	0.0011	47.3	41.2-55.5	6
Western red-cedar	-0.0093	0.0007	74.4	64.4-88.0	1



The AIC analysis did not support separate estimates by species or genus, or for any of the variations on these models (e.g., combining *Abies* and hemlock, or hemlock and spruce) (Table 5.3). Instead, the best model, with 80% of the AIC weight, separated species traditionally considered fast-decomposing (*Abies*, eastern and Norway spruces, eastern hemlock), coastal species (western hemlock, Sitka spruce, Douglas-fir and red-cedar) and high-elevation or dry Interior species (Englemann spruce, lodgepole pine, ponderosa pine). The only other model with moderate support separated red-cedar from the coastal group. These AIC analyses weighted studies by their precision, but similar AIC results were obtained without weighting.

**Table 5.3. AIC values and weights for the 10 candidate models.**

#	Model Name	AICc	AIC weight
1	Species	-177.4	0.0000
2	Genus, separate hemlocks and spruces	-187.6	0.0000
3	Genus, separate spruces	-190.4	0.0001
4	Genus	-180.9	0.0000
5	Genus, combine <i>Abies</i> and hemlocks	-179.7	0.0000
6	Genus, combine hemlocks and spruces	-182.6	0.0000
7	Fast, coastal slow, high-elevation	-193.6	0.0007
8	Fast, coastal, high elevation	-207.7	0.7996
9	Model 8, but with cedar separate	-204.9	0.1995
10	One mean (null)	-184.1	0.0000

The distributions of the estimates of decomposition rates for the 3 groups of the AIC-best model are shown in Figure 5.8. High-elevation and dry Interior species had the slowest decomposition rates, coastal species had moderate rates and the species expected to be faster-decomposing did indeed have faster decay rates.

These distributions use bootstrapping, with the study as the resampling unit, so they represent the variation among studies within a grouping. There are also two different sets of distributions in Figure 5.8, one based on weighting studies by the precision of their results, and one unweighted. Because estimates of higher decomposition coefficients (slower decomposition) tended to be more precise, the weighted means are higher than the unweighted mean. It is probably best to use the distributions based on unweighted means, given that there is apparently true variation among studies (not just sampling error), and it is unclear which study would best represent any future study site (i.e., the variation is not readily explainable).

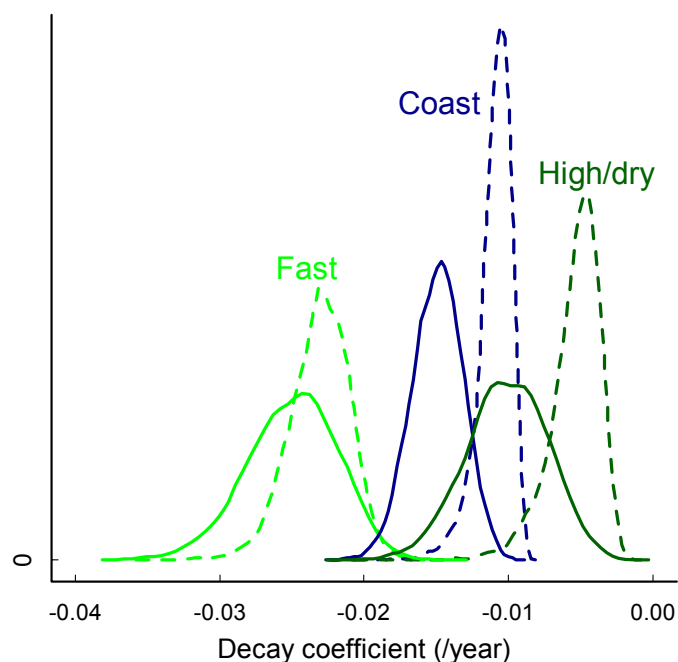


Figure 5.8. Estimates of the decomposition coefficients and their distributions for the 3 groupings in the AIC-best model. Solid lines are unweighted (each study treated equally). Dotted lines weight each study by the precision of its estimate.

The median and 95% quantile values for these distributions are presented in Table 5.4, along with the equivalent half-lives for each grouping.

Table 5.4. Medians and quantiles of the decomposition coefficients (/year; left) and equivalent half-lives (years; right) for the 3 groupings in the AIC-best model, weighting by an estimate's precision (top), or treating each result equally (bottom).

**WEIGHTED**

Group	Distribution of decomposition coefficient (/yr)			Distribution of half-life (years)		
	Median	2.5%'ile	97.5%'ile	Median	2.5%'ile	97.5%'ile
Fast	-0.0230	-0.0276	-0.0195	30.2	25.1	35.6
Coastal	-0.0108	-0.0140	-0.0093	64.3	49.6	74.6
High/dry	-0.0051	-0.0097	-0.0029	135.8	71.5	239.7

**UNWEIGHTED**

Group	Distribution of decomposition coefficient (/yr)			Distribution of half-life (years)		
	Median	2.5%'ile	97.5%'ile	Median	2.5%'ile	97.5%'ile
Fast	-0.0248	-0.0316	-0.0193	27.9	21.9	35.9
Coastal	-0.0149	-0.0185	-0.0116	46.6	37.4	59.7
High/dry	-0.0101	-0.0159	-0.0049	68.8	43.5	140.9

### 5.3. CWD Decay – Effect of ground position

*Question: How does the rate of decomposition of CWD differ for logs that are above the ground versus logs on the ground?*

CWD is often assumed to decay more slowly when it held off the ground by previously fallen logs. If this is a strong effect, it needs to be included in deadwood models, which can require tracking overlap of different logs. It is also important for projecting the decay of slash piles, and in general for looking at the effects of management options that produce aggregated versus dispersed CWD.

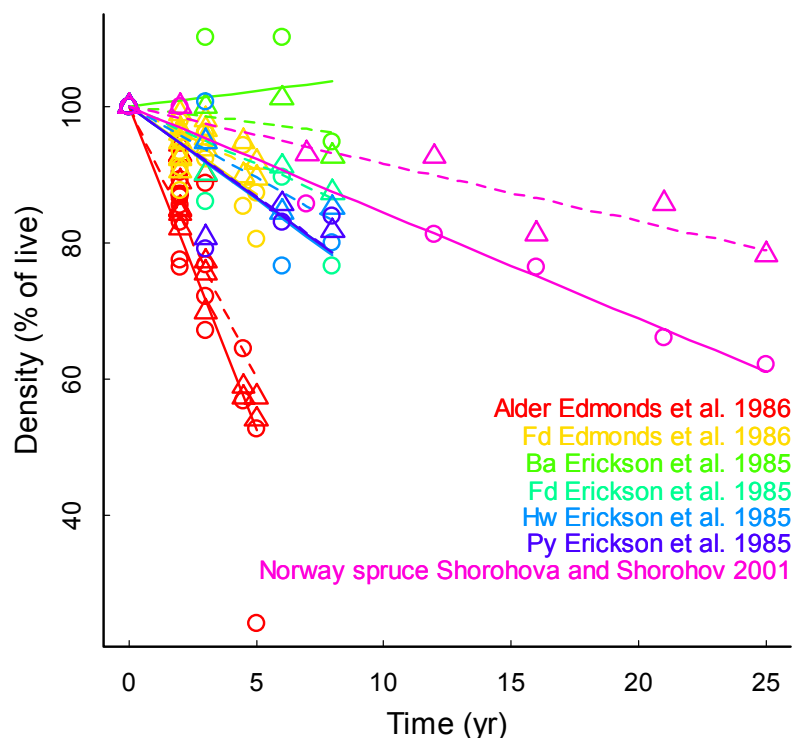
#### 5.3.1. Methods – Effect of ground position on CWD decay

Three papers were found which directly compared decomposition rates over time of CWD on versus above the ground. Several other papers measured decomposition of snags versus CWD, but these were not used, because we considered decomposition of vertical snags to be a different process than decomposition of horizontal but suspended logs. There were 7 species in the 3 available studies: Douglas-fir and alder in Edmonds et al. (1986); Douglas-fir, western hemlock, ponderosa pine and silver fir in Erickson et al. (1985); and Norway spruce in Shorohova and Shorohov (2001) (in which “leaned” logs were used as the sample of logs above the ground). Although alder typically decays considerably faster than conifers, the alder data from Edmonds et al. (1986) was used here, because the comparison is of the relative rates of decomposition on versus above the ground, not the absolute decomposition rates of different species.

Edmonds et al. (1986) included data for logs averaging 5cm diameter compared to 10cm. An initial step was to check if these 2 diameters showed decomposition rates that were different enough to justify treating the 2 size classes separately. AIC was used to compare 2 models for the change in wood density, expressed as a percentage of the initial density when the log fell, over time. Model 1: Density ~ Time + Time:(Species x Position x Diameter) – Density is a function of time and the interaction of time with species (Fd, alder), position (on, above ground) and diameter class (5, 10cm), and the 2- and 3-way interactions of the latter 3 factors. Model 2: Density ~ Time + Time:(Species x Position) – Density is a function of time and the interaction of time with species, position and species x position. Both models were forced through a relative density of 100% at time 0. Model 2 therefore differed from Model 1 only in lacking the effects of log diameter. A simple linear relationship with time was assumed, because the study only lasted 5 years and no non-linear form was apparent in the data. The resulting AIC weights were 0.010 for Model 1 and 0.990 for Model 2. This suggests the diameter effect is not worth estimating for this one study, and data from both size classes were pooled in the main analysis.

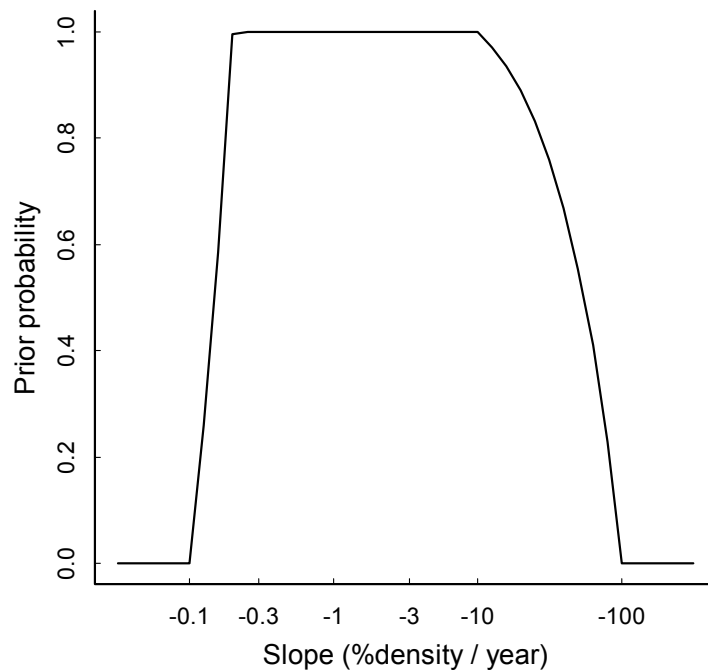
#### 5.3.2. Results – Effect of ground position on CWD decay

Figure 5.9 shows wood density, expressed as a percentage of the density when the log first fell, over time for the 7 combinations of study and species. Decomposition rates vary from extremely fast for alder in Edmonds et al. (1986), to relatively slow for Norway spruce in Shorohova and Shorohov (2001), with silver fir in Erickson et al. (1985) showing apparent “negative” decomposition with the limited available data. In all but the latter case, CWD on the ground decomposed faster than CWD suspended above the ground. None of the curves show any obvious non-linearity, but the results come from limited time spans (except Shorohova and Shorohov 2001).



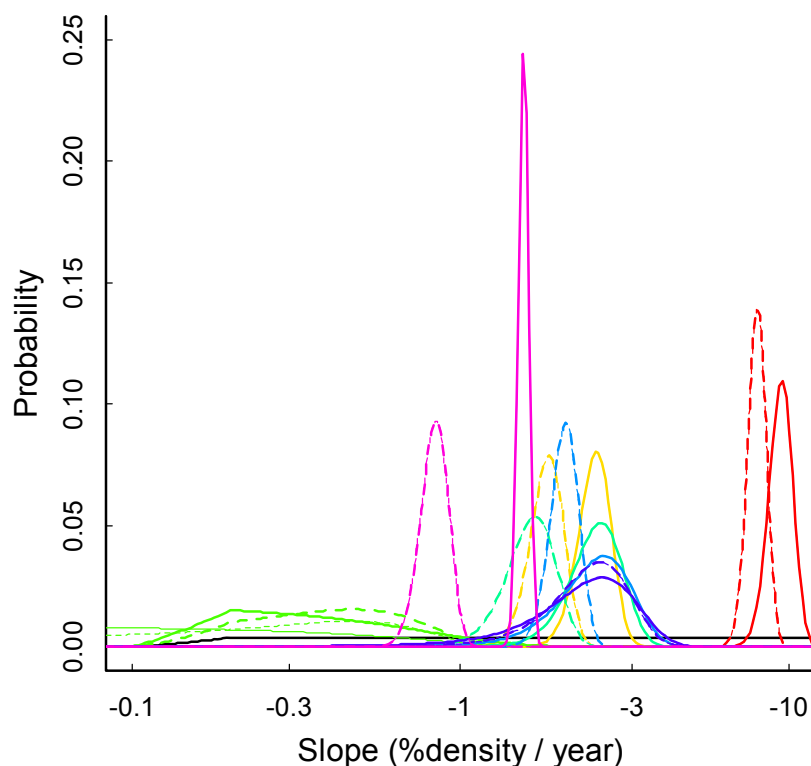
**Figure 5.9. Density (as a percentage of the density of the live log) over time for 7 species x study combinations, on the ground (circles, solid lines) and above the ground (triangles, dotted lines). Note that regression lines for 4 of the on-the-ground cases are essentially on top of each other: Fd from Edmonds et al. (1986), and Fd, Hw and Py from Erickson et al. (1985).**

Linear regressions, forced through 100% at year 0, were estimated for each species x study combination, separately for CWD on versus above the ground. This provided the mean slope (= linear decomposition rate) and its distribution for each case. A positive slope (= increasing density over time) is clearly nonsensical and occurs in the case of silver fir on the ground from Erickson al. (1985) simply from uncertainty due to the small sample size. The observed distributions of the slopes were therefore combined with a subjective prior distribution representing the broadest range of decomposition rates that were considered feasible (Figure 5.10). Possible slopes were considered to range from -0.1 (% density/year) to -100, which represent complete decomposition of the CWD requiring between 1000 and 1 years. The prior probability for decomposition rates increased from 0 for values outside this possible range to 1 for rates between -0.2 (500 years for complete decomposition) and -10 (10 years for complete decomposition). In practice, use of this prior distribution only affected the distribution of slopes for silver from Erickson et al. (1985) and the extreme lower end of the distribution for alder from Edmonds et al. (1986).



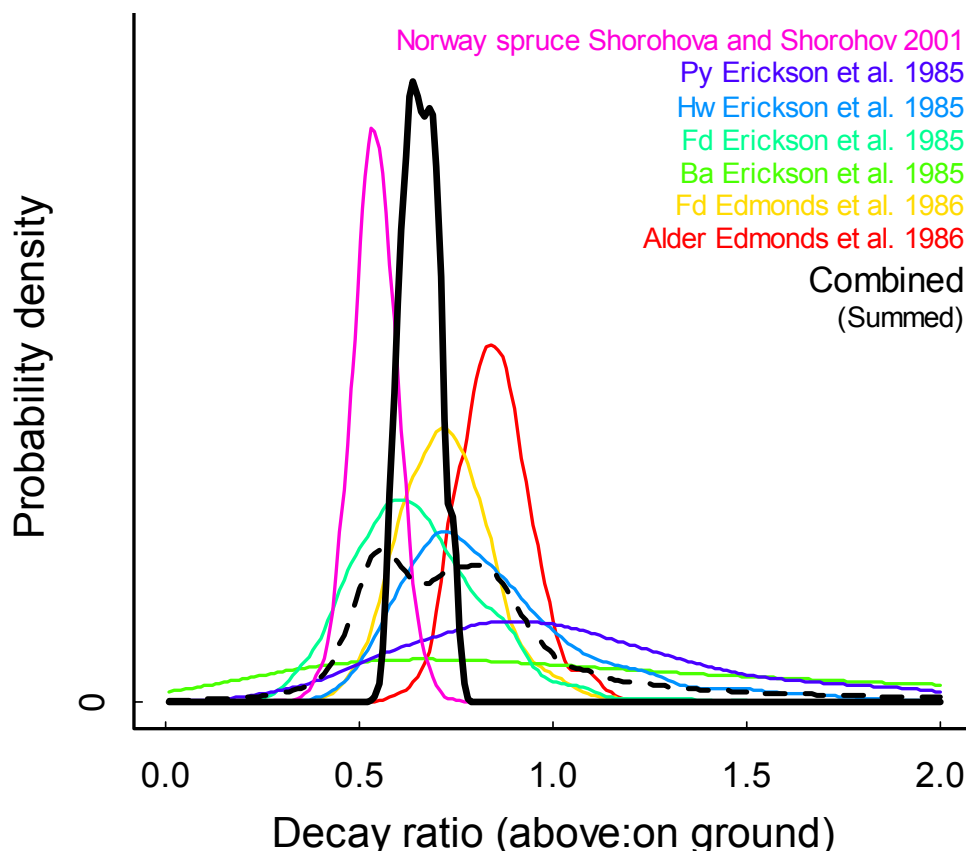
**Figure 5.10. Prior probability distribution for linear decomposition rate, used to truncate clearly infeasible parts of the empirical results that are based on small sample sizes. A slope of -0.1 corresponds to 1000 years for complete decomposition of CWD; -100 corresponds to complete loss in a single year. Note log-scale of x-axis.**

The slope distributions, both observed and posterior after combining with the prior (most of which are identical), are shown in Figure 3. The differences among the study x species combinations are apparent, and in most cases there are clear differences between the distributions for logs on the ground versus above the ground.



**Figure 5.11. Distribution of observed (thin lines) and posterior (thicker lines) distributions of decomposition rates for the 7 study x species combinations, for logs on the ground (solid lines) and logs above the ground (dotted lines). In most cases, the posterior distribution is unaffected by the prior (black line), so that the observed and posterior distributions are identical. Note log-scale of x-axis.**

These slope distributions were used to calculate the distributions of the ratio of the decay rate for logs above the ground to the rate for logs on the ground (Figure 5.12). A decay ratio of 0.5, for example, means that logs off the ground decayed at half the rate of logs on the ground. (Equivalently, it takes logs off the ground twice as long as logs on the ground to reach a particular decay stage). For 5 of the 7 cases, the ratio ranged between about 0.4 and 1. In two cases, ponderosa pine and silver fir from Erickson et al. (1985), wide uncertainty in the individual slopes produced broad distributions of the ratio, including values  $>1$  (which would mean faster decay off the ground).



**Figure 5.12. Distributions of the ratio of decomposition rate above the ground to decomposition rate on the ground. A ratio <1 means that decomposition is slower above the ground. The combined curve (solid black) is a Bayesian combination of the 7 cases; the summed curve (dotted black) is a simple sum of the distributions – see text for interpretation.**

There are 2 ways of combining the distributions of the decomposition ratios from the 7 case studies, with different interpretations:

1. Bayesian combination. The 7 distributions are multiplied together and the sum of the product scaled to 1. This gives a distribution that is suitable if there is one true decomposition ratio, and each of the 7 cases is an (independent) estimate of this true value. This Bayesian distribution has a median of 0.625, with 95% quantiles of 0.570-0.742. In other words, if there is one decomposition ratio, the best estimate is 0.625 – that is, CWD off the ground decays at 62.5% the rate of wood on the ground, and takes 1.6 times as long to reach a particular decay stage (95% quantiles – 1.35-1.75 times as long).
2. Simple sum. The curves are added together, and the sum scaled to 1. The resulting distribution indicates the distribution that could be expected in any particular future case, incorporating both the variation among the cases and the uncertainty of each (assuming the published cases are a representative sample of future cases). The median for an individual case is 0.738, with 95% quantiles 0.367-1.652 (with a long tail on the upper end, as shown in Figure 4 – 84% of the distribution of the ratio is <1). The wider distribution reflects the variation among cases, and the considerable uncertainty in some individual cases, particularly at higher ratios.

The conclusion is that logs do decompose substantially slower if they are suspended above the ground by underlying logs, lasting around 1.4-1.7 times as long. This effect is worth capturing in detailed deadwood models, even though it means tracking the positions and decay

stages of individual logs (and making some assumptions about how they break). Retained wood that cross on top of other logs should last longer into the rotation than wood spread more uniformly around cutblocks. Of course, there may be other values that also factor into decisions on whether to retain wood in uniform or aggregated patterns.

#### 5.4. CWD time in decay classes

*Question: At what times after tree death or fall do logs change between different structural decay classes?*

This is basic information for modeling CWD as habitat, especially for the maintenance or production of well-decayed CWD in managed cutblocks. This section combines the few direct sources of information on CWD structural decay with the previous analyses of density decomposition and information on log density in different CWD classes to estimate the transition times for different types of logs.

##### 5.4.1. Methods – CWD time in decay classes

There were 2 main sources of information to address this question: 1. Direct measurements of the age (=time since tree death or fall) of logs in different structural classes, and 2. Measurements of wood density in different classes, which can be combined with estimates of the rate of decay of wood density (section 5.2) to estimate the age of the logs in the different decay classes. Both sources of information have the difficulty that they do not measure transition times between classes directly; instead, they measure the actual age of logs, which may be at the beginning, middle or end of their time in the class. The analysis needs to use the observed ages to estimate the transition age. The second source of information has added uncertainty from having to estimate the density decay rate, but is useful to include because there are more studies on density than on age in structural classes.

Studies use different ways of describing CWD structural classes. All analyses here used the system of Thomas 1979. Decay classes in other systems were converted to this system by assigning each class to one or more Thomas classes, based on the class descriptions given in the paper. A decay class that appeared to be midway between Thomas class 3 and 4, for example, would be assigned a proportion of 0.5 in class 3 and 0.5 in class 4. (Equivalently, that observation would be considered half a class 3 observation, and half a class 4 observation). The assignment of proportions was subjective, but there is very little information to relate different classification systems quantitatively.

With both information types, some data were measurements of individual samples, while others were means of >1 sample. Data were therefore weighted by the sample size of each point.

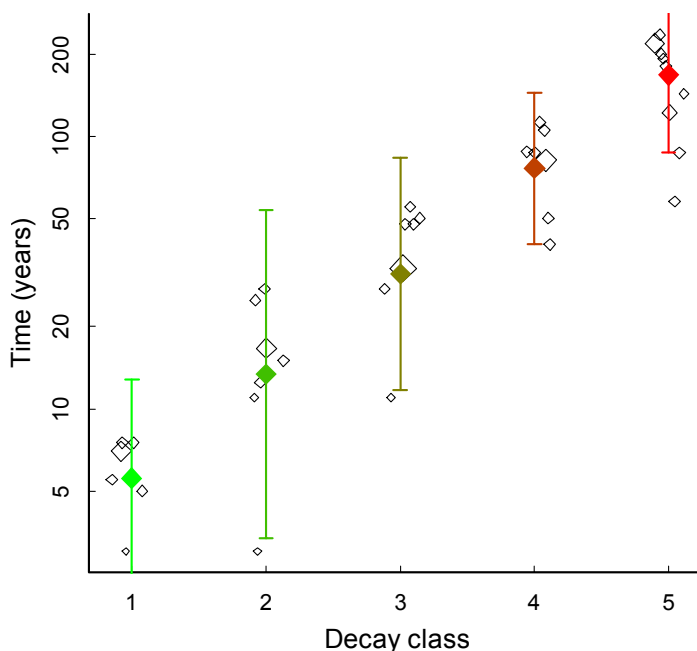
##### Data type 1. Analysis of measurements of log age by class

Analyses were standardized to a 40-cm diameter log. The time since death or fall (whichever the study reported) of logs was first standardized to a 40-cm diameter, using the equation:  $\text{Time}_{\text{EFFECTIVE}} = \text{Time}(\text{40}/\text{Diameter})^{0.5}$ . For example, a 20-cm diameter log that was 30 years old would be given an effective time of 42 years (i.e, equivalent to a 40-cm diameter log that was 42 years old). Log diameters were considered to be half of reported large-end diameters, or midway between reported large-end and minimum diameters. When log diameters were not reported directly in the study, they were guessed from study site descriptions. The exponent 0.5 was used for structural decay, as a compromise between the



lower value suggested for density decomposition and the higher values suggested for timber and volume losses (section 5.1).

For each species<sup>6</sup>, a log-normal distribution was fit to the data on effective times in each class (example in Figure 5.13). A log-normal distribution was used because the data appeared to follow this distribution in many cases. This distribution indicates the probability of a log in a particular class being a particular age. The cumulative distribution for a class indicates the probability that a log of that age will be in at least that class (i.e., in that class or a subsequent one). This is the relevant information for modeling transitions from one class to the next. We described the cumulative distributions with 3 points – the times when 10%, 50% and 90% of logs had reached that class (called  $T_{10}$ ,  $T_{50}$  and  $T_{90}$ ).  $T_{50}$  would be considered the median time it takes a log to get to that class, with  $T_{10}$  and  $T_{90}$  giving an indication of how variable the transition time is. The uncertainty of both the mean and the SD of the fitted log-normal distributions was used in Monte Carlo simulations to estimate the uncertainty around those 3 transition times for each class and species.



**Figure 5.13. Example of data points for time (since tree death or fall) and decay class, for Douglas-fir. Symbol size proportional to sample size of each data point. Coloured points and error bars are the mean  $\pm 2$  SD. Note log-scale of y-axis. Data have been standardized to a 40-cm diameter log.**

#### Data type 2. Analysis of wood density by class

The analysis of the information on wood density by class followed the same approach as the direct information on age of logs by class, with the addition of an initial step to convert density to age, based on the decomposition curves (section 2.2). Coefficients of negative-exponential decomposition rate curves (and their SE's) were previously estimated for 4 species groups: "fast" decomposing species, coastal species (excluding cedar), high-elevation and dry species, and cedar. These curves were used to convert the reported densities of logs – expressed, for each study and species, as a percentage of the density of the live tree – into

<sup>6</sup> *Abies* species were grouped, due to limited data for individual species.

ages (times since death or fall) for each data point. Monte Carlo simulations were used to incorporate the effect of uncertainty in the decomposition coefficients on uncertainty of the estimates of age. These distributions of age for each data point were then analysed in the same way as direct information on age (previous subsection). The  $T_{10}$ ,  $T_{50}$  and  $T_{90}$  values for each class of each species, and their 95% confidence were calculated.

Because this analysis assumes negative exponential density decomposition, there is no initial “lag time” (a period in which CWD may not decompose appreciably at all). The results for this analysis could therefore be considered the transition times *after* any initial lag time. However, inspection of the available data suggests that this lag time is short, if present at all.

#### Combining the results from the two data types

The  $T_{10}$ ,  $T_{50}$  and  $T_{90}$  values from the 2 data types were combined into an overall mean and SE. The estimates from the direct measurements of log ages were weighted twice as heavily as the indirect estimates based on density, because of the fewer assumptions involved in the former estimates. The SE's in these combined estimates reflect both the uncertainty in the estimates from each of the 2 information sources, as well as how different the 2 estimates were. Similar estimates from the 2 sources would reduce the uncertainty of the combined mean, while very different estimates would increase it.

[Note on other methods: An initial attempt at this analysis used a more comprehensive Bayesian model, which tried to include the fact that the transition times from sequential classes are dependent – a log cannot be in one class before it has been in the previous ones. (However, one individual log can clearly enter a later class earlier than another log enters a previous class, due to variation among logs). Unfortunately, the available data were not adequate to parameterize this full model (it couldn't be made to “converge”). A main limitation in implementing this full model is that many studies only present means and SE's, rather than individual data points. Individual studies with extensive data should be able to run analyses that better capture necessary relationships among the classes than the analyses used here based on studies' summary variables.

One result of not being able to the more comprehensive model is that transition times for each class are estimated independently here, so it is possible to get a transition time for one class that is less than for a preceding class. This is especially the case for the late-end tail of the distribution ( $T_{90}$ ). This impossible result simply reflects the limitations of the available data (including the fact that some studies did not provide data for all classes, so that differences between study sites are sometimes confounded with differences between classes).]

#### *5.4.2. Results – CWD time in decay classes*

The times (years since tree death or fall) at which 10%, 50% and 90% of logs reach decay classes 2, 3, 4 and 5<sup>7</sup> are presented in Table 5.5, and shown graphically in Figure 5.14. Our deadwood model uses these transition times, smoothed between the 10%, 50% and 90% values, to simulate transition rates among CWD of different species. The transition times are adjusted for log diameters other than 40cm, and also for logs that are suspended off the ground (section 5.3).

General patterns in the results include:

- Logs reach class 2 quickly, and class 3 fairly quickly thereafter. It generally takes about twice as long to reach class 4, and longer still to reach class 5 (which is considered “structural disappearance” of the log). In other words, classes 1 and 2 are relatively short-lived, class 3

<sup>7</sup> Class 1 not presented, since ~all logs start as class 1. (Some falling snags may enter later classes, but generally only logs derived from falling live trees are included in the studies summarized here).

lasts longer, and the log persists in class 4 even longer before becoming non-structural rotted wood.

- There is typically less time between the 10% and 50% times than between the 50% and 90% times. This means that there is a more extended tail of some logs that persist in a class longer than the mean time. This follows from the observed log-normal distribution of log ages in a class.
- Confidence intervals widen with longer times – i.e., for the later decay classes and for the 90% times versus 50% or 10%. This also follows from the log-normal distribution, and the fact that more variability can simply be generated over longer periods of time.
- Overall, there are not huge differences in the times to reach decay classes 2-4 for the different species. However, there are larger differences in times to reach decay class 5 (i.e., for the log to become non-structural rotted wood). This implies that there should be considerable differences in the proportion of CWD that is soft logs (class 4) among the species, with Douglas-fir, lodgepole pine and cedar having a higher proportion of soft wood, and spruce and Abies less. The differences may also, of course, partly reflect differences in how different people working on different species classify logs.
- Looking at the median times ( $T_{50}$ ), the differences are fairly small, but Abies and Norway spruce tend to have the fastest transitions among decay classes, while Douglas-fir is slowest. There is some variability in the relative times that different species spend in different decay classes. For example, Engelmann/white spruce is relatively slow to reach class 3, but relatively quick to reach class 4 compared to Douglas-fir or cedar.
- There is more difference among the upper tails of the times ( $T_{90}$ ) for the different species. Mostly this just reflects greater uncertainty for the species that had less available data and were highly variable in different studies (cedar, lodgepole pine). There are correspondingly wide confidence intervals on all the values for these species, so the differences in the tails should not be interpreted as very meaningful.
- The wide confidence intervals suggest that modelers using these numbers have considerable scope for adjusting the specific values to their particular ecosystems, based on local data. They should also incorporate the resulting uncertainty, rather than relying only on mean values.

**Table 5.5. Times (yr) at which 10%, 50% and 90% of logs have reached decay classes 2-5 ( $\pm 2$  SE).****Class 2**

	<b>10%</b>	<b>50%</b>	<b>90%</b>
<b>Fd</b>	6 (5-7)	13 (11-16)	31 (20-47)
<b>Hw</b>	7 (5-9)	14 (10-19)	28 (19-40)
<b>Sx</b>	8 (4-15)	13 (11-16)	22 (8-62)
<b>Cw</b>	3 (2-6)	13 (5-38)	61 (8-449)
<b>PI</b>	3 (2-5)	9 (5-19)	36 (6-228)
<b>Abies</b>	6 (3-12)	11 (8-17)	25 (13-49)
<b>Norway spruce</b>	3 (2-6)	8 (4-20)	22 (9-57)

**Class 3**

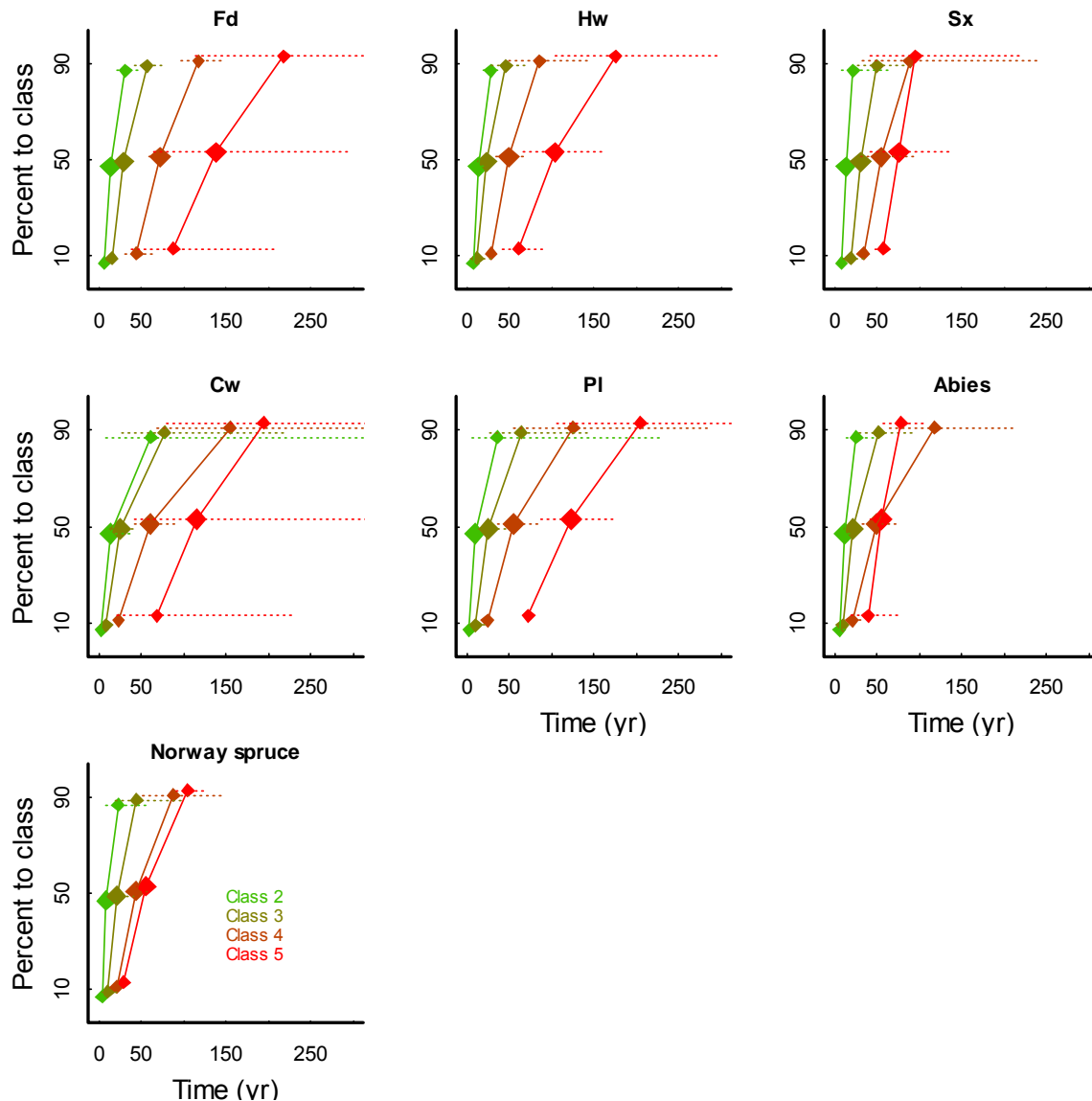
	<b>10%</b>	<b>50%</b>	<b>90%</b>
<b>Fd</b>	15 (11-21)	29 (22-39)	57 (42-76)
<b>Hw</b>	12 (5-31)	24 (17-33)	46 (29-73)
<b>Sx</b>	19 (10-37)	31 (26-36)	50 (27-92)
<b>Cw</b>	8 (6-11)	25 (15-43)	77 (27-221)
<b>PI</b>	11 (4-26)	26 (14-49)	64 (28-149)
<b>Norway spruce</b>	9 (7-11)	22 (17-28)	52 (28-94)
<b>Abies</b>	10 (5-21)	21 (10-44)	45 (20-100)

**Class 4**

	<b>10%</b>	<b>50%</b>	<b>90%</b>
<b>Fd</b>	45 (30-67)	72 (58-90)	118 (97-143)
<b>Hw</b>	29 (22-37)	50 (34-72)	86 (50-146)
<b>Sx</b>	34 (29-40)	54 (31-97)	88 (32-241)
<b>Cw</b>	23 (17-31)	60 (41-89)	155 (68-354)
<b>PI</b>	24 (23-26)	55 (36-85)	126 (55-287)
<b>Norway spruce</b>	20 (14-30)	49 (32-74)	118 (66-213)
<b>Abies</b>	21 (21-22)	43 (33-57)	88 (51-150)

**Class 5**

	<b>10%</b>	<b>50%</b>	<b>90%</b>
<b>Fd</b>	88 (38-207)	139 (65-293)	218 (113-421)
<b>Hw</b>	61 (42-90)	104 (67-161)	175 (104-296)
<b>Sx</b>	58 (48-71)	76 (42-138)	95 (41-220)
<b>Cw</b>	68 (21-227)	115 (41-322)	195 (80-476)
<b>PI</b>	72 (66-79)	123 (87-175)	205 (107-393)
<b>Norway spruce</b>	39 (20-77)	56 (43-73)	79 (56-110)
<b>Abies</b>	29 (24-36)	56 (48-64)	105 (90-123)



**Figure 5.14.** Times at which 10%, 50% and 90% of logs are at, or beyond, decay classes 2-5. For example, for Douglas-fir (Fd), 10% of logs have reached class 4 (dark red) 45 years after tree death or fall, 50% by 72 years and 90% by 118 years. All results are standardized to a 40-cm diameter log. (Horizontal) error bars on times are  $\pm 2$  SE's.

## 6. References

[This list includes all references used in the quantitative synthesis, as well as those cited in the text.]

- Aho, P.E. and J.M. Cahill. 1984. Deterioration rates of blowdown timber and potential problems associated with product recovery. USDA FS GTR PNW-167.
- Alban, D.H. and J. Pastor. 1993. Decomposition of aspen, spruce, and pine boles on two sites in Minnesota. Can. J. For. Res. 23:1744-1749.

- Arthur, M.A. and T.J. Fahey. 1990. Mass and nutrient content of decaying boles in an Engelmann spruce – subalpine fir forest, Rocky Mountain National Park, Colorado. *Can. J. For. Res.* 20:730-737.
- Boulanger, Y., L. Sirois. 2006. Postfire dynamics of black spruce coarse woody debris in northern boreal forest of Quebec. *Can. J. For. Res.* 36:1770-1780.
- Brown, P.M., W.D. Shepperd, S.A. Mata and D.L. McCain. 1998. Longevity of windthrown logs in a subalpine forest of central Colorado. *Can. J. For. Res.* 28:932-936.
- Bull, E.L. 1983. Longevity of snags and their use by woodpeckers. *In* Snag Habitat Management, USDA For. Serv. Gen. Tech. Rep. RM-99.
- Busse, M.D. 1994. Downed bole-wood decomposition in lodgepole pine forests of central Oregon. *Soil Sci. Soc. Am. J.* 58:221-227.
- Caza, C.L. 1993. Woody debris in the forests of British Columbia: a review of the literature and current research. BC Min. For. Land Manage. Rep. 78, Victoria, BC. 99pp.
- Chambers, C.L. and J.N. Mast. 2005. Ponderosa pine snag dynamics and cavity excavation following wildfire in northern Arizona. *For. Ecol. Manage.* 216:227-240.
- Clark, D.F., D.D. Kneeshaw, P.J. Burton and J.A. Antos. 1998. Coarse woody debris in sub-boreal spruce forests of west-central British Columbia. *Can. J. For. Res.* 28:284-290.
- Cline, S. P., A. B. Berg and H. M. Wight. 1980. Snag characteristics and dynamics in Douglas-fir forests, western Oregon. *J. Wildl. Manage.* 44:773-786.
- Conner, R.N. and D. Saenz. 2005. The longevity of large pine snags in eastern Texas. *Wildl. Soc. Bull.* 33:700-705.
- Dahms, W.G. 1949. How long do ponderosa pine snags stand? USDA FS Res. Notes PNW-57.
- Daniels, L. D., J. Dobry, K. Klinka, and M. C. Feller. 1997. Determining year of death of logs and snags of *Thuja plicata* in southwestern coastal British Columbia. *Can. J. For. Res.* 27:1132-1141.
- DeLong, S.C., J.M. Arocena and H.B. Massicotte. 2003. Structural characteristics of wet montane forests in east-central British Columbia. *For. Chron.* 79:342-351.
- DeLong, S.C., S.A. Fall and G.D. Sutherland. 2004. Estimating the impacts of harvest distribution on road-building and snag abundance. *Can. J. For. Res.* 34:323-331.
- Duvall, M.D. and D.F. Grigal. 1999. Effects of timber harvesting on coarse woody debris in red pine forests across the Great Lakes states, U.S.A. *Can. J. For. Res.* 29:1926-1934.
- Edmonds, R.L. and A. Eglitis. 1989. The role of Douglas-fir beetle and wood borers in the decomposition of and nutrient release from Douglas-fir logs. *Can. J. For. Res.* 19:853-859.
- Edmonds, R.L., D.J. Vogt, D.H. Sandberg and C.H. Driver. 1986. Decomposition of Douglas-fir and red alder wood in clear-cuttings. *Can. J. For. Res.* 16:822-831.
- Engelhardt, N.T., R.E. Foster and H.M. Craig. 1960. Pathological deterioration of wind-damaged white spruce and alpine fir in the Crescent Spur area of British Columbia. *Studies in For. Pathol.* XXIII, Dept. For., Ottawa.
- Erickson, H.E., R.L. Edmonds and C.E. Peterson. 1985. Decomposition of logging residues in Douglas-fir, western hemlock, Pacific silver fir, and ponderosa pine ecosystems. *Can. J. For. Res.* 15:914-921.
- Everett, R., J. Lehmkuhl, R. Schellhaas, P. Ohlson, D. Keenum, H. Riesterer and D. Spurbeck. 1999. Snag dynamics in a chronosequence of 26 wildfires on the east slope of the Cascade Range in Washington State, USA. *Intern. J. Wildland Fire* 9:223-234.
- Fahey, T.J. 1983. Nutrient Dynamics of Aboveground Detritus. *Ecol. Monogr.* 53:51-72.
- Feller, M.C. 2003. Coarse woody debris in the old-growth forests of British Columbia. *Environ. Rev.* 11:S157.

- Flanagan, P.T., P. Morgan and R.L. Everett. 1998. Snag recruitment in subalpine forests. *Northw. Sci.* 72:303-309.
- Foster, J.R. and G.E. Lang. 1982. Decomposition of red spruce and balsam fir boles in the White Mountains of New Hampshire. *Can. J. For. Res.* 12:617-626.
- Franklin, J.F. and D.S. DeBell. 1988. Thirty-six years of tree population change in an old-growth *Pseudotsuga-tsuga* forest. *Can. J. For. Res.* 18:633-639.
- Ganey, J.L. and S.C. Vojta. 2005. Changes in snag populations in Northern Arizona mixed-conifer and Ponderosa pine forests, 1997-2002. *For. Sci.* 51:396-405.
- Garber, S.M., J.P. Brown, D.S. Wilson, D.A. Maguire and L.S. Heath. 2005. Snag longevity under alternative silvicultural regimes in mixed-species forests of central Maine. *Can. J. For. Res.* 35:787-796.
- Graham, R.L. and K. Cromack, Jr. 1982. Mass, nutrient content, and decay rate of dead boles in rain forests of Olympic National Park. *Can. J. For. Res.* 12:511-521.
- Grier, G.C. 1978. A *Tsuga heterophylla* – *Picea sitchensis* ecosystem of coastal Oregon: decomposition and nutrient balances of fallen logs. *Can. J. For. Res.* 8:198-206.
- Harmon, M.E., K. Cromack, Jr. and B.G. Smith. 1987. Coarse woody debris in mixed-conifer forests, Sequoia National Park, California. *Can. J. For. Res.* 17:1265-1272.
- Harmon, M. E., J. F. Franklin, F. J. Swanson, P. Sollins, S. V. Gregory, J. D. Lattin, N. H. Anderson, S. P. Cline, N. G. Aumen, J. R. Sedell, G. W. Lienkaemper, K. Cromack, Jr., and K. W. Cummins. 1986. Ecology of coarse woody debris in temperate ecosystems. *Adv. Ecol. Res.* 15:133-302.
- Harmon, M.E., O. Krankina and J. Sexton. 2000. Decomposition vectors: a new approach to estimating woody detritus decomposition. *Can. J. For. Res.* 30:76-84.
- Harrington, M.G. 1996. Fall rates of prescribed fire-killed Ponderosa pine. USDA For. Serv. Res. Paper INT-RP-489.
- Harrod, R.J., W.L. Gaines, W.E. Hartl and A. Camp. 1998. Estimating historical snag density in dry forests east of the cascade range. USFS Gen. Tech. Rep. Pnw 428:1-16.
- Hely, C., Y. Bergeron and M.D. Flannigan. 2000. Coarse woody debris in the southeastern Canadian boreal forest: Composition and load variations in relation to stand replacement. *Can. J. For. Res.* 30:674-687.
- Hennon, P.E., C.G. Shaw III and E.M. Hansen. 1990. Dating decline and mortality of *Chamaecyparis nootkatensis* in southeast Alaska. *For. Sci.* 36:502-515.
- Hennon, P.E. and M.H. McClellan. 2003. Tree mortality and forest structure in the temperate rain forests of southeast Alaska. *Can. J. For. Res.* 33:1621-1634.
- Hinds, T.E., F.G. Hawksworth and R.W. Davidson. 1965. Beetle-killed Engelmann spruce: its deterioration in Colorado. *J. For.* 63:536-542.
- Huggard, D.J. 1999. Static life-table analysis of fall rates of subalpine fir snags. *Ecol. Applic.* 9:1009-1016.
- Johnson, E.A. and D.F. Greene. 1991. A method for studying dead bole dynamics in *Pinus contorta* var. *latifolia* – *Picea engelmannii* forests. *J. Veg. Sci.* 2:523-530.
- Jonsson, B.G. 2000. Availability of coarse woody debris in a boreal old-growth *Picea abies* forest. *J. Veg. Sci.* 11:51-56.
- Keen, F.P. 1929. How soon do yellow pine snags fall? *J. For.* 27:735-737.
- Keen, F.P. 1955. The rate of natural falling of beetle-killed ponderosa pine snags. *J. For.* 53:720-723.

- Keenan, R.J., C.E. Prescott and J.P. Kimmins. 1993. Mass and nutrient content of woody debris and forest floor in western redcedar and western hemlock forests on northern Vancouver Island, British Columbia. *Can. J. For. Res.* 25:1052-1059.
- Kellner, A.M.E., C.P. Laroque, D.J. Smith and A.S. Harestad. 2000. Chronological dating of high-elevation dead and dying trees on northern Vancouver Island, British Columbia. *Northw. Sci.* 74:242-251.
- Kruys, N., Jonsson, B.G. and Stahl, G. 2002. A stage-based matrix model for the decay class dynamics of deadwood. *Ecol. Appl.* 12:773-781.
- Kueppers, L.M., J. Southon, P. Baer and J. Harte. 2004. Dead wood biomass and turnover time, measured by radiocarbon, along a subalpine elevation gradient. *Oecologia* 141:641-651.
- Laiho, R. and C.E. Prescott. 1999. The contribution of coarse woody debris to carbon, nitrogen, and phosphorus cycles in three Rocky Mountain coniferous forests. *Can. J. For. Res.* 29:1592-1603.
- Laiho, R. and C.E. Prescott. 2004. Decay and nutrient dynamics of coarse woody debris in northern coniferous forests: a synthesis. *Can. J. For. Res.* 34:763-777.
- Lambert, R. E., G. E. Lang, and W. A. Reiners. 1980. Loss of mass and chemical change in decaying boles of a subalpine balsam fir forest. *Ecol.* 61:1460-1473.
- Lang, G.E. 1985. Forest turnover and the dynamics of bole wood litter in subalpine balsam fir forest. *Can. J. For. Res.* 15:262-268.
- Lee, P. 1998. Dynamics of snags in aspen-dominated midboreal forests. *For. Ecol. Manage.* 105:263-272.
- Lewis, K.J. and I.D. Hartley. 2005. Rate of deterioration, degrade, and fall of trees killed by mountain pine beetle: A synthesis of the literature and existential knowledge. MPBI Working Paper 2005-14.
- Lyon, L.J. 1977. Attrition of lodgepole pine snags on the Sleeping Child Burn, Montana. USDA For. Serv. Res. Note INT-219, Ogden Utah.
- Marra, J.L. and R.L. Edmonds. 1994. Coarse woody debris and forest floor respiration in an old-growth coniferous forest on the Olympic Peninsula, Washington, USA. *Can. J. For. Res.* 24:1811-1817
- Means, J.E., K. Cromack, Jr. and P.C. MacMillan. 1985. Comparison of decomposition models using wood density of Douglas-fir logs. *Can. J. For. Res.* 15:1092-1098.
- Means, J.E., P.C. MacMillan and K. Cromack, Jr. 1992. Biomass and nutrient content of Douglas-fir logs and other detrital pools in an old-growth forest, Oregon, USA. *Can. J. For. Res.* 22:1536-1546
- Mellen, K. and A. Ager. 2002. A coarse wood dynamics model for the western Cascades. USDA For. Serv. Gen. Tech. Rep. PSW-GTR-181:503-516.
- Mielke, J.L. 1950. Rate of deterioration of beetle-killed Engelmann spruce. *J. For.* 48:882-888.
- Mitchell, R.G. and H.K. Preisler. 1998. Fall rate of lodgepole pine killed by the mountain pine beetle in central Oregon. *W. J. Appl. For.* 13:23-26.
- Morrison, M.L. and M.G. Raphael. 1993. Modeling the dynamics of snags. *Ecol. Appl.* 3:322-330.
- Næsset, E. 1999. Relationship between relative wood density of *Picea abies* logs and simple classification systems of decayed coarse woody debris. *Scand. J. For. Res.* 14:454-461.
- Newberry, J.E., K.J. Lewis and M.B. Walters. 2004. Estimating time since death of *Picea glauca* x *P. engelmannii* and *Abies lasiocarpa* in wet cool sub-boreal spruce forest in east-central British Columbia. *Can. J. For. Res.* 34:931-938.
- Ohmann, J.L. and K.L. Waddell. 2002. Regional patterns of dead wood in forested habitats of Oregon and Washington. USDA For. Serv. Gen. Tech. Rep. PSW-GTR-181:535-560.
- Parks, C.G., D.A. Conklin, L. Bednar and H. Maffei. 1999. Woodpecker use and fall rates of snags created by killing ponderosa pine infected with dwarf mistletoe. U S Forest Service Research



Paper PNW 515:1-11.

- Passovoy, M.D. and P.Z. Fule. 2006. Snag and woody debris dynamics following severe wildfires in northern Arizona ponderosa pine forests. *For. Ecol. Manage.* 223:237-246.
- Payer, D.C. and D.J. Harrison. 2000. Structural differences between forests regenerating following spruce budworm defoliation and clear-cut harvesting: Implications for marten. *Can. J. For. Res.* 30:1965-1972.
- Ranius, T., B.G. Jonsson and N. Kruys. 2004. Modeling dead wood in Fennoscandian old-growth forests dominated by Norway spruce. *Can. J. For. Res.* 34:1025-1034.
- Raphael, M.G. and M.L. Morrison. 1987. Decay and dynamics of snags in the Sierra Nevada, California. *For. Sci.* 33:774-783.
- Russell, R.E., V.A. Saab, J.G. Dudley and J.J. Rotella. 2006. Snag longevity in relation to wildfire and postfire salvage logging. *For. Ecol. Manage.* 232:179-187.
- Schmid, J.M., S.A. Mata and W.F. McCambridge. 1985. Natural falling of beetle-killed ponderosa pine. USDA For. Serv. Research Note RM-454.
- Shorohova, E.V. and A.A. Shorohov. 2001. Coarse woody debris dynamics and stores in a boreal virgin spruce forest. *Ecol. Bull.* 49:129-135.
- Sollins, P. 1982. Input and decay of coarse woody debris in coniferous stands in western Oregon and Washington. *Can. J. for. Res.* 12:18-28.
- Spies, T. A., J. F. Franklin and T. B. Thomas. 1988. Coarse woody debris in Douglas-fir forests of western Oregon and Washington. *Ecol.* 69:1689-1702.
- Stone, J.N., A. MacKinnon, J.V. Parmenter and K.P. Lertzman. 1998. Coarse woody debris decomposition documented over 65 years on southern Vancouver Island. *Can. J. For. Res.* 28:788-793.
- Storaunet, K.O. 2004. Models to predict time since death of *Picea abies* snags. *Scand. J. For. Res.* 19:250-260.
- Storaunet, K.O. and J. Rolstad. 2004. How long do Norway spruce snags stand? Evaluating four estimation methods. *Can. J. For. Res.* 34:376-383.
- Storaunet, K.O. and J. Rolstad. 2002. Time since death and fall of Norway spruce logs in old-growth and selectively cut boreal forest. *Can. J. For. Res.* 32:1801-1812.
- Sturtevant, B.R., J.A. Bissonette, J.N. Long and D.W. Roberts. 1997. Coarse woody debris as a function of age, stand structure, and disturbance in boreal Newfoundland. *Ecol. Appl.* 7:702-712.
- Tarasov, M.E. and R.A. Birdsley. 2001. Decay rate and potential storage of coarse woody debris in the Leningrad Region. *Ecol. Bull.* 49:137-147.
- Tinker, D.B. and D.H. Knight. 2001. Temporal and spatial dynamics of coarse woody debris in harvested and unharvested lodgepole pine forests. *Ecol. Model.* 141:125-149.
- Thomas, J.W. (editor). 1979. Wildlife habitats in managed forest in the Blue Mountains of Oregon and Washington. USDA For. Serv. Agric. Handb. 553.
- Tyrrell, L.E. and T.R. Crow. 1994. Dynamics of dead wood in old-growth hemlock-hardwood forests of northern Wisconsin and northern Michigan. *Can. J. For. Res.* 24:1672-1683.
- Vanderwel, M.C., J.R. Malcolm and S.M. Smith. 2006. An integrated model for snag and downed woody debris decay class transitions. *For. Ecol. Manage.* 234:48-59.
- Waterhouse, M.J. and H.M. Armleder. 2004. Windthrow in partially cut lodgepole pine forests in west-central British Columbia, B.C. BC Min. For. Extension Note 70, Victoria, B.C.

- Wei, X., J.P. Kimmins, K. Peel and O. Steen. 1997. Mass and nutrients in woody debris in harvested and wildfire-killed lodgepole pine forests in the central interior of British Columbia. *Can. J. For. Res.* 27:148-155.
- Wilhere, G.F. 2003. Simulations of snag dynamics in an industrial Douglas-fir forest. *For. Ecol. Manage.* 174:521-539.
- Wright, K.H. and G.M. Harvey. 1967. The deterioration of beetle-killed Douglas-fir in western Oregon and Washington. USDA FS Res. Paper PNW-50. 20pp.
- Wright, E. and K.H. Wright. 1954. Deterioration of beetle-killed Douglas-fir in Oregon and Washington: a summary of findings to date. USDA FS Res. Paper PNW No 10.
- Yin, X. 1999. The decay of forest woody debris: Numerical modeling and implications based on some 300 data cases from North America. *Oecologia* 121:81-98.

## Appendix 1. Description of deadwood model

The synthesis of parameters needed for projecting deadwood – snags and CWD as structural habitat elements – was guided by our deadwood projection model. This model has been used for habitat projections in a number of applications, including during implementation of variable retention harvesting (VR) in coastal BC by MacMillan-Bloedel and Weyerhaeuser, for projecting effects of alternative silvicultural systems on numerous resource values in the BC Interior, and for comparing management scenarios in montane forests. The model is described in detail here, because it provided much of the framework for deciding which deadwood parameters to summarize and which factors to examine. Some of the detail may be helpful to others developing models and using the snag and CWD information synthesized in the main report.

### A1.1. Deadwood model overview

The deadwood model is intended to project deadwood structures at the stand-level, although the “stand” can be arbitrarily large. It is also intended to be able to model realistically complex stands, including areas with different management, such as reserve patches or dispersed retention, and different site characteristics, such as outcrops, wetlands, etc. The model is therefore:

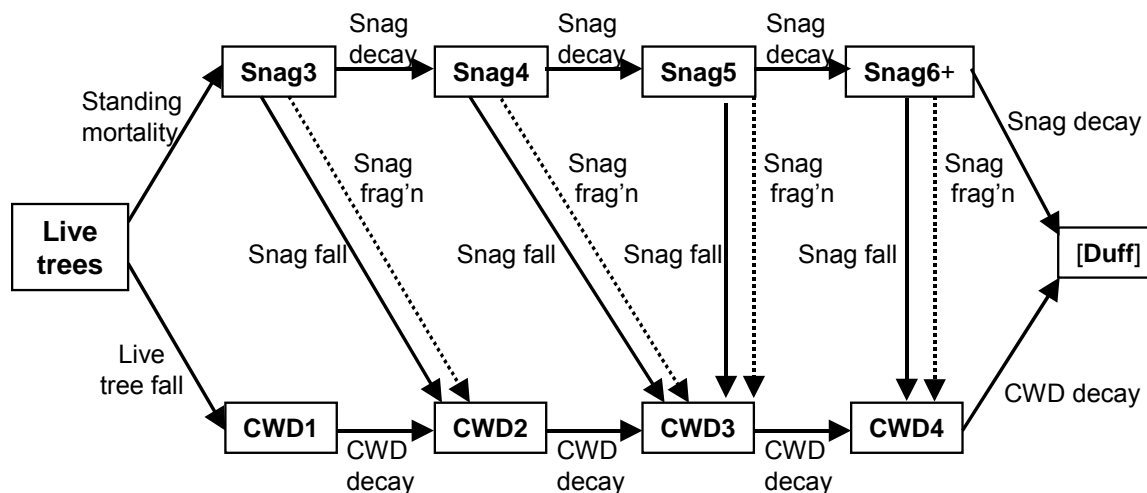
1. Individual-based. Each individual snag or log is tracked separately (rather than as classes). Each snag has a species, diameter at breast height, diameter at top break, height, decay class, time since death, and time in decay class. Logs have a big-end diameter, small-end diameter, length, height of ends above ground, decay class, time since death, time in decay class and direction. Only snags  $\geq 7.5$ cm DBH and logs with a diameter  $\geq 7.5$ cm are tracked.
2. Spatially-explicit. The harvest types and site types in the stand are mapped using a system of grid cells. Each snag or log has an x,y co-ordinate within the stand. Deadwood structures can therefore be mapped, as well as summarized numerically. Deadwood parameters can be modified by harvest type or site type (e.g., faster decay in wet sites; higher snag fall and fragmentation rates in exposed sites). Distance from edge can also be used to modify the results of management activities and the deadwood parameters.
3. Probabilistic. The chance of a snag or log undergoing a change (fall, fragmentation or decay) in an annual time step is a probabilistic function of the deadwood parameter, rather than deterministic. This is important in modeling the temporal and spatial variability in deadwood trajectories.
4. Based on parameters synthesized from the literature, and their uncertainty. Deadwood fall, fragmentation and decay rates were estimated from the published literature in the main report. Because many estimates are uncertain, the model incorporates parameter uncertainty using a Monte Carlo approach.

The deadwood model tracks snags and CWD (logs) from the death of the live tree through to the disappearance of the deadwood as a structure when it becomes “duff”. Trees that die are followed as individual structures through a series of snag and log decay classes. Decay classes follow Thomas (1979), and are used for their relevance to wildlife that use deadwood structures. The characteristics of different snag and CWD decay classes are described in Table A1.1.

**Table A1.1. Characteristics of decay classes of snags and CWD (following Thomas 1979)**

<u>Snag class</u>	
1 and 2	Live trees; modeled separately
3	Recently dead; bark intact or cracked; at least some fine branches present
4	Losing branches; 99-50% of bark present
5	Most branches lost; <50% bark present; wood still mostly hard
6+	Bark and branches lost; wood mostly or all soft
[duff]	Remaining unbroken part of snag decays into separate fragments of soft wood]
<u>Log class</u>	
1	Fresh wood; bark and at least some fine branches present
2	Fine branches and some larger branches lost; bark all present
3	Branches mostly lost; bark cracked or being lost; wood still hard
4	Wood soft; bark and branches mainly lost; log still has vertical sides
[duff]	Log has collapsed, sides less than vertical; wood broken into soft fragments]

Live trees can enter the deadwood model as class 3 snags if they die standing, or as class 1 logs if they die due to windthrow. Deadwood structures can undergo four kinds of changes: 1. Snag fall, 2. Snag breakage or “fragmentation” (producing a log and a shorter snag), 3. Snag decay (to the next decay class, or directly to duff for class 6+ snags), 4. CWD decay (to the next decay class, or to duff for class 4 logs). These processes are illustrated in Figure A1.1. Section 2 describes the form of the probability functions for these processes, how they are modified by various factors (such as the size of the deadwood piece), and the parameter values used for the coastal BC runs.



**Figure A1.1. Decay stages and deadwood processes in the model. Live tree growth and mortality are handled outside the deadwood model. “Frag’n” = fragmentation (breakage).**

The effects of management activities on deadwood are modeled with a series of rules, specifying the probability of an existing deadwood structure being retained, destroyed or modified (e.g., a snag fallen and left on site), and the amount, species, size, decay class and spatial distribution of new deadwood inputs from the activity (e.g., logging residue or thinning slash). The management rules can be based on species, decay class and size of deadwood, and also on height of snags to model retention of safe versus dangerous snags. Details of these management options are given in section A1.4.

The approach to incorporating the uncertainty of parameter estimates through Monte Carlo simulations is described in section A1.5. This section also discusses how the resulting

variation in predicted amounts of deadwood elements through time is summarized, and how these distributions are used in landscape projections.

Model output includes various options for summarizing snag and CWD attributes over time. These can be by species, decay class and/or size class, and their various combinations. The spatial distribution of snags and CWD can be indicated by coefficients of variation (scale of unit flexible), and by nearest neighbour distance for snags, and mean point-to-nearest-log for CWD. Some attributes that are more specific to particular groups of organisms, such as densities of logs projecting various heights above ground, have been added to the summaries. Because the model tracks individual deadwood elements, other deadwood attributes could be summarized when these are identified by studies of particular organisms. The model also produces graphical output showing a map view of the deadwood components of a stand. Details of the quantitative and graphical output are discussed in section A1.6.

### ***A1.2. Deadwood processes and parameters***

The four processes involved in deadwood dynamics (excluding management effects) are: 1. Snag decay, 2. Snag fragmentation, 3. Snag fall, 4. CWD decay. These are modeled as probabilistic functions, calculated annually for each snag or log. Unlike some simple probabilistic matrix-type models, probability functions in the deadwood model are age-specific (more precisely, time-since-death specific). For example, the probability of a class 4 snag decaying to class 5 is a function of how long the snag has been dead. This means that there can be a minimum and maximum age for the transition to class 5, and a “spread” of time over which a cohort makes the transition, which more closely matches field data than a fixed annual probability. The synthesis of snag decay rates was conducted to support this framework of a range of transition times. In contrast, some matrix models use fixed annual transition probabilities, which allow some individual snags to pass through several decay stages far too rapidly, while others remain too long in one stage. The probabilities in the deadwood model differ for different groups of species, and, except for snag fragmentation, are modified by the size of piece – snag DBH or log diameter primarily (sections 2.1 and 5.1), but also snag height and log length in some cases (discussed below). Probabilities can also be modified in different site types or positions relative to harvested edges.

The importance, values and distributions of the various deadwood parameters are outlined in sections of the main report. The following subsections explain how the parameters are used in our deadwood model.

#### ***A1.2.1 Snag fall***

Fall rates of snags are a function of their time-since-death, modified by their size, and possibly their mortality source and other factors. The rate in the model is not based on the snag decay class, except, of course, indirectly as both fall rate and likely decay class are related to age. The rate of fall is assumed to change (increase) continually with age of snag. This assumption was based on observations of fall rates of subalpine fir snags with age (Huggard 1999), other studies that indicate fates of snag cohorts over time or give interpretable static life-table information (e.g., Hinds et al. 1965), and the shape of the survivorship curves in the synthesis of fall rates (section 2.2). The parameters used by the model to describe the shape of this fall rate versus age curve are an initial annual fall rate for recently-dead snags and a half-life (age at which half the snags have fallen). The negative-exponential model often used in the literature, and seen for some fast-falling species in the synthesis, is a subset of this curve type, in which the fall rate is the same at all ages. This can be captured in the deadwood model by having the initial rate be the fitted negative exponential rate, and the mid-point being the calculated half-life. In this case, there would be no increase in the annual probability of fall over time. Some literature studies fit a model with a lag-time of no fall, followed by constant fall rate.

This could be approximated by an initial rate of 0 (or very low), and the mid-point as the reported half-life. However, looking at some of the original data in these studies suggests that there are, in fact, snags falling at a moderate rate initially. A better approximation to the actual data might be to use half the calculated negative exponential rate as the initial rate, with the mid-point the same as the reported half life. Most data, however, support a continuously increasing annual probability of fall as time-since-death increases.

The annual probability of snag fall is also affected by the height of the snag, with the fall rate decreasing at a given time-since-death as the snag becomes increasingly shortened by fragmentation. The fall probabilities decrease from the nominal value for a full-height (unfragmented) snag to  $\frac{1}{2}$  the probability for a snag that has fragmented near the ground. Snags of intermediate remaining height have intermediate probabilities. This decrease in fall rates after snags are fragmented reflects the lesser torque due to the shorter remaining bole, and is an important effect in allowing long-persisting well-decayed short snags seen in many forest types. Many of these fragmented old snags end up decaying directly to duff, rather than falling.

When a snag falls, it becomes CWD; class 3 and 4 snags become class 2 CWD, class 5 snags become class 3 CWD, and class 6+ snags become class 4 CWD. The time-since-death of a falling snag is set to the minimum transition date into the CWD decay class it enters. This is generally a younger time-since-death than the original snag. This reflects the fact that decay rates are assumed to be slower for a standing snag than for downed wood. For example, a snag that fell 20 years after it died might become a piece of CWD with an effective time-since-death of 10 years, reflecting the fact that the snag would only have decayed in its first 20 years as much as a log on the ground would have decayed in its first 10 years.

#### *A1.2.2 Snag decay*

The probability of a standing snag changing from one decay stage to the next is a function of how long the snag has been dead (modified by its DBH, etc.). A minimum and median age for each decay class transition are specified, taken from the literature synthesis of section 3.1. Because the distribution of the transition probability is symmetrical around the median, these 2 values also imply the maximum age a snag can remain in a particular class. The probability of a snag changing classes is normally distributed (truncated at 2 SD's) within the minimum to maximum ages, so that annual transition probabilities are lowest at the minimum and maximum, and highest at the median. Note that this means that the *conditional* probability of snag transition, given the snag remained in a decay class to a certain age, increases each year. The conditional probability is necessarily 0 at any age less than the minimum transition age, and 1 at the maximum possible age.

Transitions between decay classes tend to be quite imprecise, with different snags of the same size and species potentially leaving a particular class at considerably different ages. This means that the minimum and median transition ages (and hence the maximum) can be quite different. In fact, the maximum transition age out of one class can be greater than the minimum transition age out of the next class. Therefore, in a particular year a cohort of 10 snags of the same size and species that died in the same year, 2 might be in class 3, 6 in class 4 and 2 in class 5.

#### *A1.2.3 Snag fragmentation or breakage*

Fragmentation here refers to a snag breaking somewhere on the stem, producing a piece of CWD and a shorter snag. Annual probability of a snag fragmenting in the model is given for each decay class as a whole (i.e., fragmentation probabilities do not depend on how long the snag has been in the class). The synthesis of the limited information available in the literature on snag breakage showed considerable variability in rates, and in the factors that

create variation in the rates. Rates used in the model can therefore only be derived fairly loosely from this literature synthesis. Snag fragmentation in the model is a directly inverse function of how much of the snag is left unfragmented. For example, if the top third of the snag has already fragmented, the fragmentation rate for the remaining standing part is 2/3 the overall rate for the decay class. Fragmentation occurs at a random height on the remaining part of the snag. There is some physical justification for this, as the resistance to breaking is proportional to the cube of the diameter and the bending moment above a diameter in a conical snag is also proportional to the cube of the diameter. A conical snag is therefore equally likely to break at any height, all else being equal. This fairly simplified approach to fragmentation reflects that fact that very little empirical data are available to support a more complex model of fragmentation.

When a snag fragments, the top becomes a new piece of CWD. It is assigned a decay class and effective time-since-death in the same way as falling snags (section A1.2.1).

#### *A1.2.4 CWD decay*

Transition probabilities between CWD decay classes are treated in the model the same way as transitions between decay classes of snags – as a function of time-since-death, with minimum and median transition ages provided for each class of each species group, and a truncated normal distribution of transition probabilities within the class.

Two additional characteristics of logs affect their decay rates:

1. Log length. Short logs may undergo additional decay from their ends, which can hasten decay class transitions for short logs. Assuming that decay along the wood grain from cut or broken ends occurs 10 times more rapidly than decay in from the outside of the log, CWD decay rates are increased for logs that are <10 times as long as their widest diameter. This effect is implemented by treating these short logs as if their diameter was 1/10 of their length. For example, a 3m long log with a maximum diameter of 50cm would be treated like a 30cm diameter log.
2. Elevated logs. Logs with one or both ends suspended above the ground because they are on top of other solid logs undergo slower decay (section 5.3). The reduction factor is entered as a parameter. The synthesis of published information suggests that a suspended log will decay at about 2/3 the rate of a log fully in contact with the ground. The algorithm for calculating whether a log is being held off the ground is explained further in section A1.6.

#### *A1.2.5 Relationship with snag size or CWD diameter*

Snag fall rates and CWD decay rates decrease for larger diameter pieces (sections 2.1 and 5.1). In the deadwood model, we use the relationship: rate  $\propto 1/\text{diameter}^{0.60}$  (95%CI 0.41-0.83) for snag fall, taken directly from the literature synthesis. For CWD decay, where there were different values from different data sources (little relationship based on decomposition, strong inverse linear relationship based on timber deterioration and volume loss), we use an intermediate relationship of rate  $\propto 1/\text{diameter}^{0.50}$  (95%CI 0.25-0.75). With little direct information, it is less clear how snag decay rates respond to diameter, although the short-term remeasurements of tagged tree on Weyerhaeuser/WFP plots showed no obvious relationship. We use a relationship intermediate between the relationship for snag fall and no DBH relationship: rate  $\propto 1/\text{diameter}^{0.30}$  (95%CI 0.00-0.60).

#### **A1.3. Initial deadwood conditions**

Initial deadwood conditions in the model are set from field data for stands similar to those being harvested in the simulations. This provides the existing structures that can be

retained, modified or destroyed during management (section A1.4). It also provides “benchmark” values to compare with projected amounts in graphs of the simulation results.

The following values are entered in an “initial conditions” Excel workbook by the user of the model (with “CI” indicating that lower and upper 95% confidence intervals are also entered, to be used for incorporating uncertainty in initial conditions). Distinct values can be entered for each combination of harvest type (e.g., cut area, reserve, road, etc.) and site type in the stand, though in practice pre-harvest variables are likely to be the same across all harvest types. Separate values are entered for each species group, unless indicated.

Snag density (CI). Snags are currently generated in a moderately aggregated distribution, meeting the overall density in each harvest type specified by this parameter.

Reference to a table of size class x decay class proportions. These tables contain the proportion of snags in each cell of a matrix of 6 size classes (currently set to 7.5-20cm, 20-30cm, 30-40cm, 40-50cm, 50-80cm and 80-120cm DBH) and four decay classes (3, 4, 5, 6+). When individual initial snags are created, they are given an exact diameter from a uniform random distribution within their allocated size class. The upper limit of 120cm is simply to allow specific sizes to be assigned in the largest class; if larger dead trees are produced by the live tree model, they retain their larger diameters. The same or separate tables can be used for different species, harvest type and site types.

Proportion of snags that have broken tops, by decay class. Uncertainty is not simulated for this parameter, because it is relatively unimportant in deadwood dynamics.

Maximum height for broken snags. This value is used to allow only snags shorter than some safe working height, if the initial conditions represent a recently managed stand. A value of 0 is used to indicate no maximum height – i.e., broken snags have the break at a random height.

Initial CWD volume (CI).

SD of initial CWD volume. This parameter is used to generate initial CWD with distributions ranging from uniform to highly aggregated among individual pixels. The specific number represents a natural log factor. For example, a typical value of about 3 indicates that CWD volumes in individual pixels follow a log normal distribution with SD's equivalent to 1/20 to 20 times the mean ( $e^3 = \sim 20$ ).

Reference to a table of size class x decay class proportions. As with snags, these tables provide the distribution of the initial CWD by 6 size classes (large-end diameters) and 4 decay classes (1, 2, 3 and 4). Specific diameters are assigned to each initial log randomly from within the allocated size class.

In addition to these initial conditions, the user specifies a relationship between DBH and height for each species. The model uses a logarithmic function, in which height increases as the natural logarithm of diameter. The height of a 7.5cm tree and a 50cm tree are used to indicate the form of this curve. This relationship is used for setting the height of initial snags of a given DBH, and the length of initial CWD of a given large-end diameter.

#### **A1.4. Management effects on deadwood**

A separate Excel workbook is created by the user to indicate how deadwood is destroyed, modified and created during each management event (harvest entry). The following parameters are set (with “CI” indicating that lower and upper bounds are provided to allow for modeling of uncertainty). Values are set separately for each species, harvest type and site type combination, unless indicated.

Edge distance. Snags are fallen adjacent to harvest areas if they are within an “edge zone”.

The edge zone can be defined in one of two ways (or both ways together): by a fixed distance (e.g., 10m), or by a snag height multiplier (e.g., any snag within 1.5 times its



height of an edge is in the edge zone). Both or either of these parameters are entered by the user.

Safe snag heights and class. During snag falling, snags that are under a certain height may have a lower rate of falling (not 0, because many snags regardless of height are fallen because they are in the way of operations, or because they are hit by other falling stems). Some less-decayed snags (e.g., class 3) may also be considered safe regardless of their height. The user can set either or both of these parameters defining safe snags.

References to tables of percent retention of snags by size class and decay class. These tables indicate what percentage of existing snags in each harvest type x site type combination are retained at harvesting. Retention is a function of decay class and size class, because in some cases, a percentage of less-decayed snags will be considered safe to leave on a block, especially smaller snags. Separate tables are or can be specified for snags in the interior versus edge zone of a harvest type (as defined by the edge distance parameters, above), and for snags that are or are not safe heights or classes (as defined by those parameters, above). The use of references to tables makes it relatively easy to accommodate this flexibility for different snag falling in different situations, without requiring the user to enter endless numbers. Note that no uncertainty modeling is used with these parameters, but high variability is created by the existing variability in the density and types of snags existing at harvest.

Snag removal. The percentage of snags that are fallen during harvesting and removed (as opposed to being left as CWD) is specified for each species, harvest type and snag decay class. Typically, a high percentage of fallen snags in class 3 will be removed, as potentially merchantable wood, compared to low percentages of the most decayed snags. The numbers can differ by species, due to the different merchantability of snags of different species. Removal may differ by harvest type, if, for example, snags fallen along adjacent edges are removed less often, or if all snags fallen on roads are removed.

CWD retention. The percentage of existing CWD that is retained at harvest is specified by species, harvest type and CWD decay class. Recent CWD is often removed to the landing as potentially valuable wood, while the most decayed CWD is often destroyed during logging. All existing CWD is typically retained in adjacent unlogged harvest types, while all CWD is removed from roads. As with snag falling, no uncertainty in these parameters is explicitly modeled, but variability in amounts and types of CWD existing at harvest is typically high.

CWD creation (CI). The user specifies the volume of additional CWD created by logging waste for each species and harvest type x site type combination, and a parameter indicating the degree of aggregation of the new CWD (as with the initial CWD in section 3). The user also indicates the size class distribution (large-end diameter) of this created wood. The newly created logs are equally allocated to decay classes 1, 2 and 3. The user also specifies what percentage of the newly created logs are broken, and the average number of breaks of broken logs. When these new logs are created at harvest, a "broken stick" model is used to determine the lengths of broken pieces: 1. For the proportion of logs that are broken, a random integer is drawn from a Poisson distribution (excluding 0) with the specified mean number of breaks. 2) If there is one break, it will be anywhere at random along the log; if there are 2 breaks, the first will be randomly along the log, and the second will be randomly along the longer segment from the first break; and so on for 3 or more breaks.

### ***A1.5. Effects of parameter uncertainty***

The effects of parameter uncertainty on the projected deadwood attributes are modeled using a Monte Carlo approach. 100 iterations of the model are run, each with a different value

of the uncertain parameters, drawn from the distribution specified by the mean and confidence intervals. A normal distribution is used, truncated at the 95% confidence intervals (i.e., 1.96 SD's from the mean). The upper and lower confidence intervals do not need to be symmetrical around the mean. The particular values of each parameter for a given run are drawn independently, except that the parameters guiding the decay times of snags or CWD are fully correlated (i.e., if the decay age from class 3 to class 4 snags is 0.7 SD's above the mean in a particular iteration, the earliest age for that transition is also 0.7 SD's above its mean, as is the decay from class 4 to class 5, etc.).

### ***A1.6. Deadwood summaries***

Summaries of the simulated deadwood are produced at user-defined intervals. Summary variables are recorded at each time period in each iteration. This allows plotting of "spaghetti plots", which show the trajectories of the different variables under the range of possible parameter values. The model also calculates the mean value of each variable at each time step, and the 2.5% and 97.5% percentiles. These 3 summary variables can then be used to specify the distribution for assigning deadwood attributes to particular stands in the landscape level simulations.

Because the model tracks individual deadwood pieces with all their attributes (location, species, size, age, etc.), the deadwood can be summarized in any way that could be measured in the field.

Total snag density.

Snag density by size class. Size classes of 7.5-20cm DBH, 20-30cm, 30-40cm, 40-50cm, 50-80cm and >80cm.

Snag density by decay class. Decay classes 3, 4, 5 and 6+.

Snag density by size class x decay class. The 24 combinations of the size and decay classes.

Total snag basal area.

Snag basal area by decay class.

Standard deviation of total snag density. Calculated using cells of user-defined size (all species combined only).

Mean snag nearest neighbour distance. The mean distance from a user-specified number of randomly chosen snags to the nearest adjacent snag (all species combined only).

Total CWD volume.

CWD volume by size class. Large-end diameters of 7.5-20cm, 20-30cm, 30-40cm, 40-50cm, 50-80cm, >80cm.

CWD volume by decay class. Decay classes 1, 2, 3 and 4.

CWD volume by decay class x size class. The 24 combinations of the size and decay classes.

CWD density. The number of separate logs per hectare.

Standard deviation of CWD volume. Calculated using cells of user-defined size (all species combined only).

Mean distance to nearest log. The mean distance from a user-specified number of randomly chosen points to the nearest log.

Density of logs projecting >50cm, >1m and >2m above ground. This calculates the overlap of logs, and the resulting heights of the ends of the logs. Only hard logs (class 1-3) are assumed to be capable of projecting above ground, and only hard logs support overlying logs. Calculating log overlap requires considerable simulation time, but is also necessary for adjusting CWD decay rates for logs suspended off the ground.

## **Appendix 2. Growth, mortality, fall and decay rates over 5 years for individually tagged trees and snags on the BC coast**

### ***Summary***

Trees and snags were measured and tagged in 87 variable retention (VR) cutblocks and uncut benchmark stands, and remeasured 5 years later, as part of a program monitoring habitat structure in MacMillan-Bloedel/Weyerhaeuser/Cascadia Forest Products/Western Forest Products tenure(s) on the BC Coast. The 7,821 remeasured trees and snags were used to calculate rates of diameter growth, mortality and mortality mode (standing versus fallen) of live trees, and fall and decay rates for different classes of snags. Growth, mortality and snag fall rates were compared between dispersed and group+mixed VR for Douglas-fir in CWHxm. With many more tagged trees in group+mixed VR, effects of DBH, tree species and ecosystem groupings on all these parameters were examined, as were any additional effects of distance from the edge of retention patches.

This information is a critical resource for long-term projection modeling of habitat structures, especially snags and CWD, in VR stands. Relatively little good information is otherwise available to support this modeling for VR stands and for the local ecosystem types on the BC coast. Some of the results also have more direct implications for VR management. Because of their importance for projection modeling, the methods and results are presented in detail.

The main findings include:

#### Live tree growth

- Measured diameter growth was generally low, but only differed between VR and uncut sites for hemlocks (higher in uncut).
- Growth rates of cedars increased with DBH, and were higher in the CWHmm+dm and CWHwh than in other subzones, while other species showed less effect of DBH and ecosystem.
- Diameter growth of larger Douglas-fir in CWHxm were 3-4 times as high in dispersed VR as in group+mixed VR, with highest rates in 80cm DBH trees in dispersed VR.
- Growth rates were slightly higher 0-10m into retention patches compared to further into the patch. This may reflect true edge effects from removing adjacent trees, but it may also reflect anchoring many patches on wetlands or outcrops that lower growth rates near the patch centres.

#### Tree mortality

- Mortality rates for retained Douglas-fir trees decreased with DBH, while cedar and hemlock showed little difference in mortality among small or large trees. Deciduous trees and true firs had very high mortality rates at larger sizes, possibly because they are prone to windthrow, but this is based on a small number of samples.
- Mortality was considerably higher in VR blocks than in uncut forest in most cases.
- Mortality rates of Douglas-fir in CWHxm were higher in dispersed VR than group+mixed VR for smaller trees, but lower for larger trees.
- Mortality was moderately higher 0-10m into retention patches, decreasing with distance into the patch.
- Douglas-fir trees that died in VR blocks – particularly large trees – were much less likely to remain standing than in uncut forest, which reduces how much the extra mortality in VR stands contributes to snag supply. Moderate-sized hemlocks and cedars in drier ecosystems were least likely to remain standing, which is unfortunate since these are the main potential source of snags useful to many wildlife species.

#### Snag fall

- Fall rates of snags generally did not differ between VR stands and uncut forest, and there was relatively little difference in fall rates among the species.
- Fall rates usually declined with increasing snag diameter. Because decay rates did not change consistently with diameter, large snags are more likely to remain standing long enough to become well-decayed snags.
- Fall rates were somewhat higher for class 6+ (soft) snags, but there was no consistent increase in fall rates from class 3 to class 5.
- There were no apparent edge effects on fall rates of snags, except somewhat elevated fall rates of recent (class 3) snags near edges, as expected from their higher susceptibility to windthrow.

#### Snag decay

- Decay rates of snags were higher in VR than in uncut forest in a few cases, but the pattern was inconsistent. Decay rates also showed inconsistent relationships with DBH.
- Douglas-fir snags typically decayed more slowly than other species, including red-cedar.
- There were no consistent edge effects on decay rates.

#### General relationships with DBH

- Averaged across species, ecosystems and treatments, growth and mortality rates increased slightly with tree DBH, snag fall rates decreased in inverse proportion to DBH (doubling DBH halved fall rates), and snag decay showed no relationship with DBH.

### **A2.1 Overview**

This appendix uses information from the habitat structure monitoring program initiated by MacMillan-Bloedel on the coastal BC tenure, and continued by Weyerhaeuser, Cascadia Forest Products, and now Western Forest Products. As one part of the structure monitoring, trees and snags were individually tagged immediately after harvest in variable retention (VR) cutblocks, and in uncut “benchmark” sites, and remeasured 5 years later. The analysis reported here uses this remeasurement data to estimate rates of growth, mortality and “mortality mode” (standing or fallen) of live trees, and fall and decay of snags, along with the factors that affect those rates. The results can help to fill large gaps in our knowledge of these rates in local ecosystems and in VR stands, critical for projection modeling of the long-term supply of deadwood in managed stands. Some of the information may also be immediately useful in deciding what stems to retain and how to retain them.

Potential factors influencing the rates include the species of tree, the ecosystem type, the diameter at breast-height (DBH) of the stem, the type of VR (dispersed versus group or mixed retention) and the distance to patch edge in group and mixed VR. Within group+mixed VR, these rates are calculated for 5 main species (Douglas-fir, western red-cedar, western + a few mountain hemlocks, amabilis and a few other true firs, red alder), and different ways of grouping the 4 main ecosystem types (combinations of similar BEC subzones: CDF+CWHxm, CWHmm+dm, CWHvm+vh and CWHwh). Effects of distance into the patch (edge effects) were also examined for group+mixed VR. Fewer plots were conducted and remeasured in dispersed VR. Rates in dispersed versus group VR are therefore only examined for Douglas-fir in CDF + CWHxm, for live tree growth, mortality and mortality mode, and for fall rates of hard snags (class 3-5).

## A2.2 Methods

### A2.2.1 Field sampling

Group and mixed VR blocks were surveyed with 10m-wide transects across the edges of retention patches, extending 50m into the patch (and 50m into the harvested matrix, but the few stems in the matrix are not examined here). Live trees and snags  $\geq 12.5$ cm DBH were marked with individually-numbered tags. The following were recorded for each stem: species, diameter at breast height (1.3m, DBH), height and decay class (following Thomas et al. 1979: class 1 and 2 are live; class 3 is recently dead; classes 4 and 5 are increasingly decayed but still hard; class 6+ is well-decayed with soft wood). Surveys in operational cutblocks were conducted 1-2 years after harvest, and in uncut benchmark sites in some ecosystems. The same characteristics were recorded for each tagged stem in remeasurements 5 years after the original measurements, allowing calculations of growth of live trees, rates of standing and fallen mortality of live trees, and rates of fall or decay (change of decay class) of snags.

A total of 103 sites have been remeasured, with 7,954 remeasured tagged stems of the 5 main species groups (Table A2.1). There were an average of 105 individual stems per site in group+mixed VR and mature stands, and 9 stems per site with dispersed retention. The difference in stems per site reflects more sampling effort in the patchy blocks, the focus on the retention patches (rather than the harvested matrix), and higher retention in group+mixed VR than in dispersed VR. Other species, such as yellow cedar, Sitka spruce, pines and western yew were rare, and were not included in the analyses. An additional 278 well-decayed (class 6+) snags that could not be identified to species were included in the analysis of fall rates of class 6+ snags. Using sites as the sample unit, comparisons of rates in mature control stands and VR blocks were possible in CWHvm+vh and CWHwh ecosystems. Comparisons of rates in dispersed and group+mixed VR were only possible in CWD+CWHxm.

**Table A2.1. Number of remeasured sites and individual stems by BEC group and harvest treatment.**

BEC group	Treatment	Sites	Individually-tagged stems					Total
			Douglas-fir	Red-cedar	Hemlock	True fir	Red alder	
CDF+CWHxm	Group+Mixed VR	18	453	187	510	17	235	1402
	Dispersed VR	15	133					133
	Mature control	1	187	10	35		7	239
CWHmm+dm	Group+Mixed VR	12	172	195	467	105	30	969
CWHvm+vh	Group+Mixed VR	39	131	362	1617	602	50	2762
	Mature control	7	125	138	643	144	20	1070
CWHwh	Group+Mixed VR	7		341	422			763
	Mature control	4		101	495		20	616
Total		103	1201	1334	4189	868	362	7954

### A2.2.2 Analyses

Analyses were conducted for the following rates:

- diameter growth of live trees,
- mortality of live trees,
- "mortality mode" of live trees (standing versus fallen),
- fall rates of class 3, 4, 5, 6+ and combined classes 3-5 (hard) snags,
- decay rates (change of decay class) of class 3, 4 and 5 snags.

Growth showed a bell-shaped distribution with extended tails, including negative values, which are possible due to measurement error in DBH. A square-root transformation, preserving the

sign for negative values, gave an approximately normal distribution for the analysis. All the other rates are binomial (1/0) variables, and were analysed using a binomial model with logistic link function (logistic regression).

For each rate, the analysis examined how to combine the 4 ecosystem groups, comparing the following possible models

1. Each separate: CDF+CWHxm; CWHmm+dm; CWHvm+vh; CWHwh
2. Wetter subzones combined: CDF+CWHxm; CWHmm+dm; CWHvm+vh+wh
3. Drier and wetter groups: CDF+CWHxm+mm+dm; CWHvm+vh+wh
4. Driest group separate: CDF+CWHxm; CWHmm+dm+vm+vh+wh
5. All combined: CDF+CWHxm+mm+dm+vm+vh+wh (i.e., same rate in all ecosystem groups)

When there was >1 mature control site in an ecosystem group, the analysis also examined whether the rate differed between VR and uncut blocks, and, for Douglas-fir in CDF+CWHxm, whether the rate differed between group+mixed and dispersed VR.

Within each ecosystem grouping and treatment (or combination of the two treatments), 3 or 4 possible relationships between the rate and DBH of the stem were examined:

1. No relationship: Same rate at all DBH values
2. Linear: A linear relationship between the square-root-transformed (growth) or logistic-transformed (others) rate and stem DBH.
3. Quadratic: A quadratic relationship between the square-root-transformed (growth) or logistic-transformed (others) rate and stem DBH. This could include increasingly high rates at the lowest or highest end of the DBH scale, or maximum or minimum values at intermediate DBH values.
- (4. Log DBH. For growth only, a model with logarithm of DBH was also used. A log-relationship was not examined for the other rates because, with their logistic transformation, the linear or quadratic models could already capture this form of relationship.)

This type of analysis would normally use an AIC-based model selection approach (Burnham and Anderson 1998). However, this requires calculation of the likelihood of each model, which is not currently possible for binomial models with random effects (due to the blocking by site). Instead, the underlying objective of finding the model with the best predictive ability was assessed using cross-validation. Each model (i.e., each DBH relationship within each way of combining or separating ecosystem groups and treatments) was fit to the data from all but one of the sites, then the sum-of-squares deviations between the model's predictions and the data for each stem in the withheld site were calculated. This was repeated with each site as the withheld test data. The model with the lowest total sum-of-squares across all sites was considered the best model for that rate; this is the model with the best cross-validation predictive ability. The analyses were done separately by species.

#### *A2.2.3 Standardized DBH*

The simulation model used by Weyerhaeuser and others to project deadwood over time inputs fall and decay rates for a standardized stem with DBH 40cm. Rates are adjusted for stems of other sizes using a power function. For example, fall rates might decrease as the square root of DBH increases, so that a snag with 80cm DBH would have half the fall rate as a snag with 20cm DBH. Therefore the value for each rate was summarized as the rate for a standardized stem with 40cm DBH, and the exponent of the power relationship for other DBH values. The rates for a 40cm DBH stem were the prediction for each component of the best model (i.e., each ecosystem grouping and treatment in the best model), along with the confidence intervals of the predictions. The exponent was calculated from a power curve fit through the predictions for 20cm- and 80cm DBH stems.

#### *A2.2.4 Edge effects*

Edge effects were examined by looking at the residual values for a rate after the best model of ecosystem effects, treatment effects and DBH had been removed, for stems within VR patches. A positive residual at a particular distance means that the rate is higher at that distance than expected from the best model. Mean residuals and their confidence intervals were plotted for 3 edge distances: 0-10m, 10-20m and >20m into the patch. Confidence intervals were generated with bootstrapping, using the site as the resampling unit.

#### *A2.2.5 Note on calculations of snag decay*

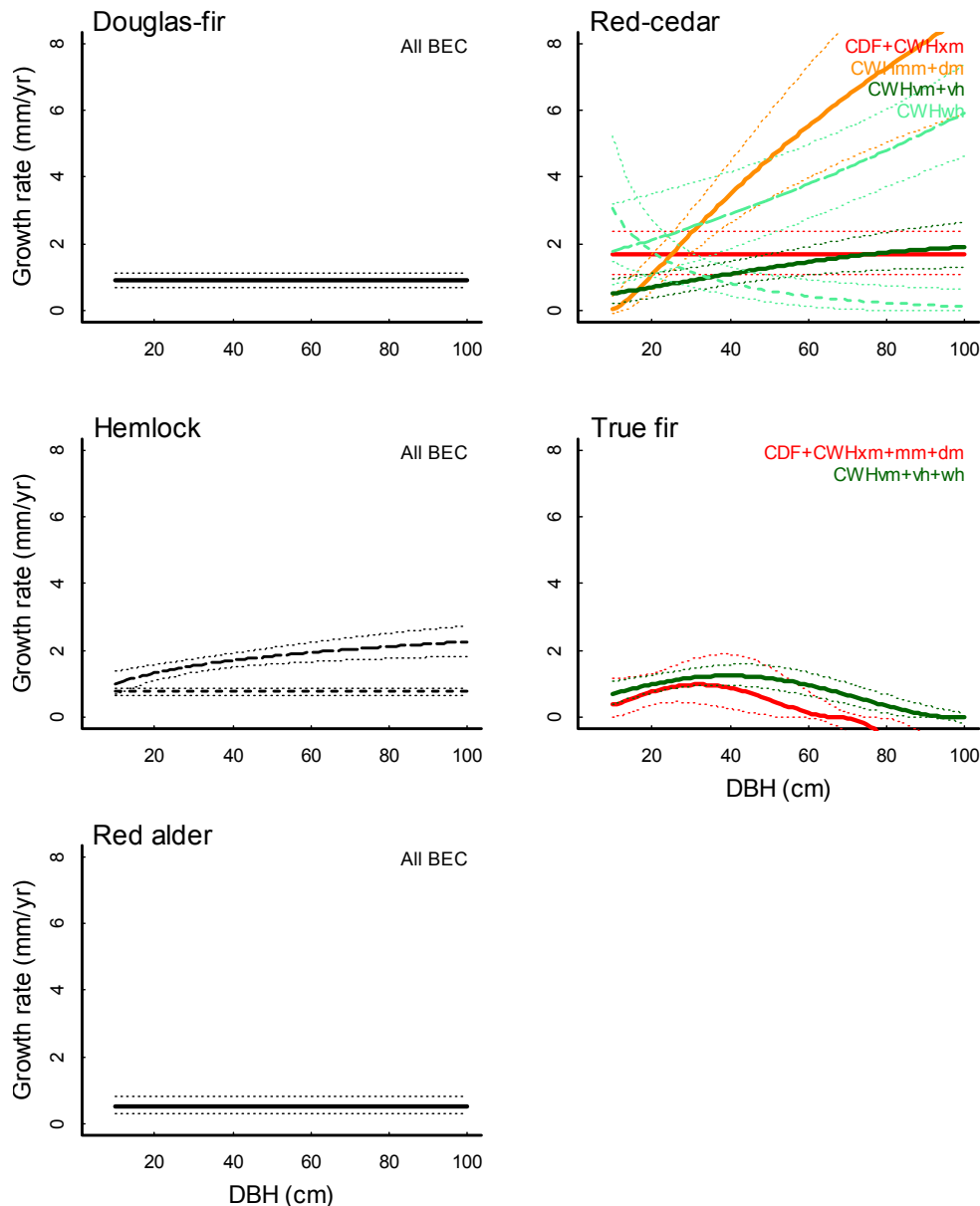
Classification of snags into decay classes 3, 4, 5 and 6+ is not always certain in the field, because each class is described by a mix of characteristics of branches, bark and wood. Some snags therefore decrease in decay class between the initial measurement and 5-year remeasurement. Because this is not possible in reality, the rate of such backward changes gives an indication of how much “measurement error” there is in classifications among adjacent decay classes. This measurement error also presumably operates in the forward direction – some snags that have not truly decayed to an older class are described as being in the older class. This inflates the apparent rate of decay of snags. The measurement error estimated from the impossible backward transitions was therefore used to correct for this inflation of decay rates.

Combining all species, 15.6% of class 4 snags were classified as class 3 in the remeasurements, 11.0% of class 5 were reclassified as class 4 or 3, and 8.8% of class 6+ were reclassified as class 5, 4 or 3. The values suggest that there is more uncertainty distinguishing class 3 and 4 snags than class 4 and 5 snags, and least uncertainty among well-decayed class 6+ versus younger snags. The error rates of 15.6%, 11.0% and 8.8% were used to reduce the apparent decay rates of snags from class 3→4, class 4→5 and class 5→6+, respectively (i.e., the calculated decay rate from class 3→4 was reduced 15.6%, etc.).

### **A2.3. Results**

#### *A2.3.1 Diameter growth of live trees*

Diameter growth rates were relatively low for all species (<2mm/yr), except for larger cedars in some ecosystems. Low growth rates may reflect some growth suppression due to disturbance in recently cut VR stands, but rates were typically the same in uncut mature stands. The exceptions were hemlocks in all ecosystems and cedar in CWHwh, where the mature uncut



**Figure A2.1.1. Diameter growth of live trees (mm/yr) as a function of tree DBH. Solid line = VR blocks and mature controls combined; long dashes = mature controls only; short dashes = VR blocks. Thin dotted lines are 95% confidence intervals. “All BEC” = all 4 ecosystem groups combined; otherwise, colours indicate the different ecosystem groups in the best model.**

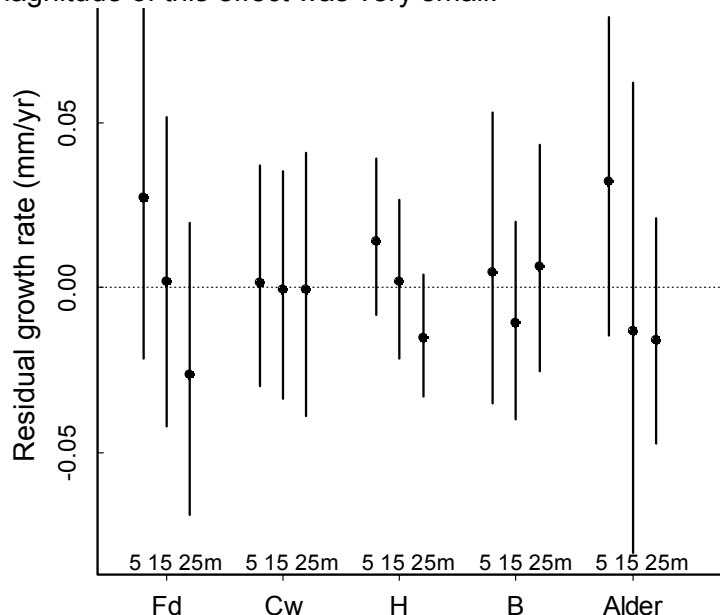
stands had higher growth rates, particularly of larger diameter trees. The lower growth in retention patches in these cases may reflect either retention of poorer trees or trees in poorer growing spots (wetlands, knolls), or reduced growth following harvesting. Slight changes in measurements of DBH could also alter apparent growth rates, although many of the initial and 5-year measurements were made by the same field crews. Because the emphasis of this monitoring was measuring habitat features, DBH measurements may not have been made as precisely as they would be in permanent sample plots for growth and yield.

**Table A2.1.1. Diameter growth (mm/yr) of live trees, standardized to 40cm DBH, and exponent for power relationship for other DBH values (see text).**



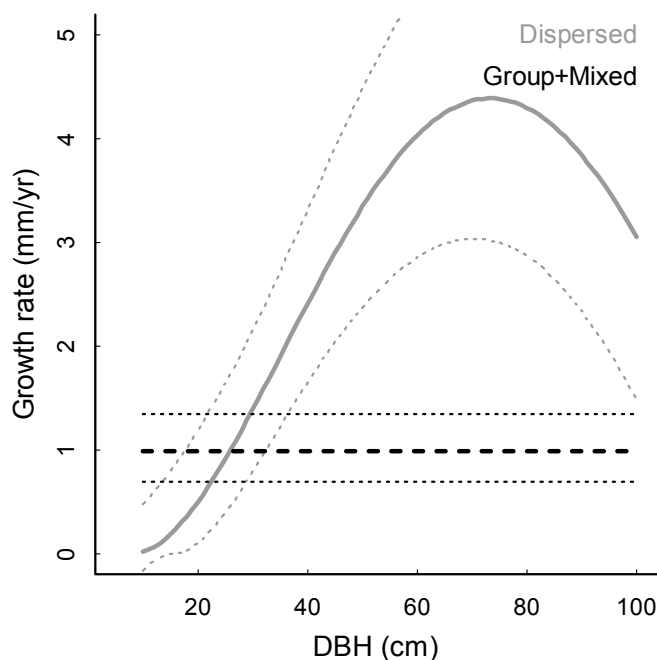
Species	BEC Group	Treatment	Growth (mm/yr)			Exponent
			Mean	LCI	UCI	
Douglas-fir		All	0.911	0.723	1.120	0
Red-cedar	CDF+CWHxm	All	1.684	1.098	2.396	0
	CWHmm+dm	All	3.487	2.624	4.472	1.376
	CWHvm+vh	All	1.110	0.790	1.483	0.648
	CWHwh	UC	2.901	1.859	4.172	0.586
		VR	0.831	0.462	1.308	-1.435
Hemlock	All	UC	1.704	1.499	1.922	0.338
		VR	0.776	0.675	0.885	0.000
True fir	CDF+CWHxm+mm+dm	All	0.888	0.262	1.883	
	CWHvm+vh+wh	All	1.254	0.963	1.584	-0.738
Red alder		All	0.533	0.302	0.829	0

There were only weak suggestions of edge effects on diameter growth of live trees, with slightly higher growth of Douglas-fir, hemlock and alder 0-10m into a patch. However, the absolute magnitude of this effect was very small.



**Figure A2.1.2. Edge effects on diameter growth of live trees (mm/yr).** Values are the residual growth rates after the predictions of the best model (Figure A2.1.1) have been removed, at 5, 15 and 25+m into retention patches. Error bars are bootstrapped 95% confidence intervals. Fd=Douglas-fir, Cw=western red-cedar, H=hemlocks, B=true firs. All ecosystem groups were combined for the analyses of edge effects.

Growth of Douglas-fir in dispersed retention in the dry CDF+CWHxm ecosystem exceeded growth in group+mixed VR, for trees >25cm DBH, with growth rates up to 4 times as high for 75cm DBH trees in dispersed retention.



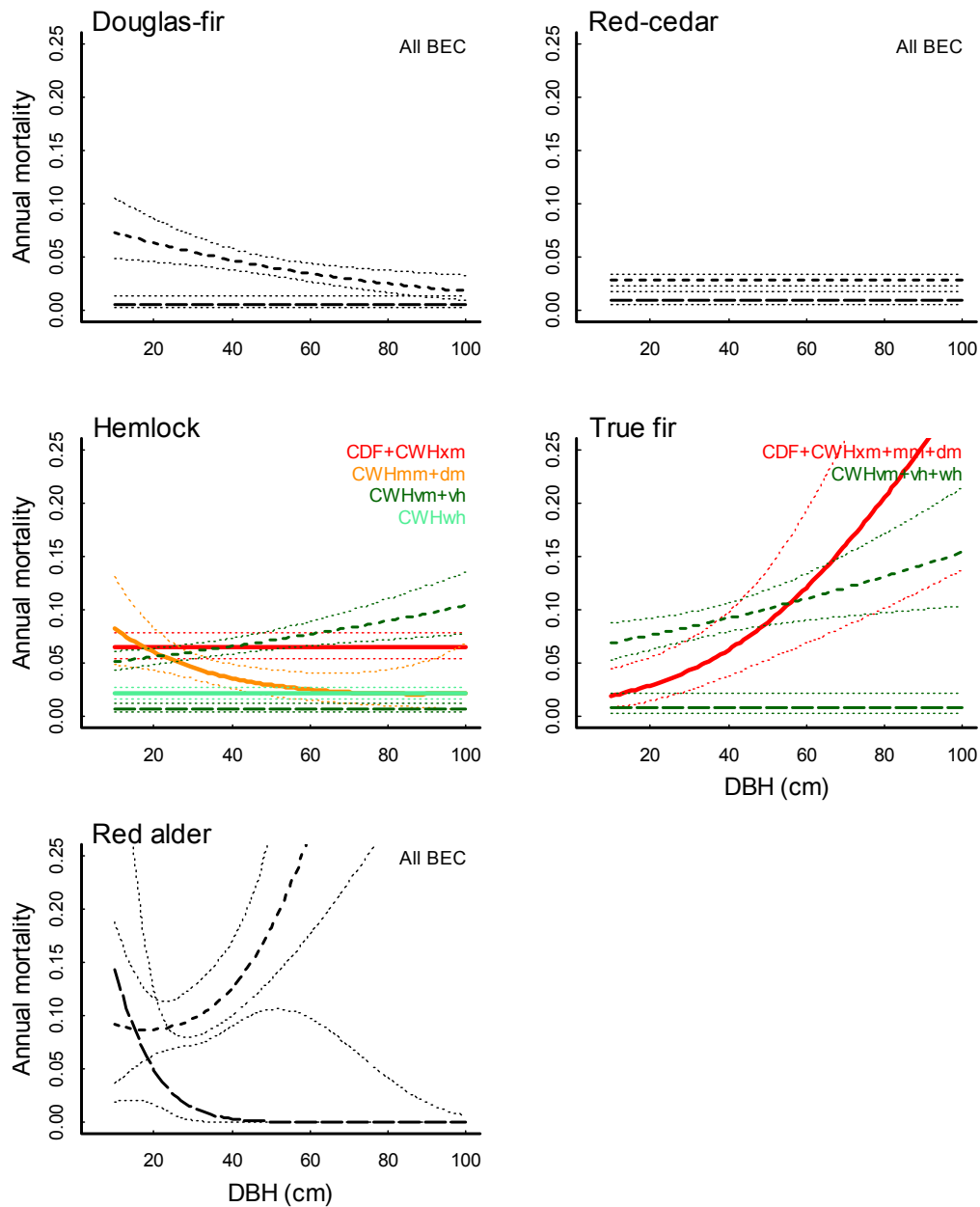
**Figure A2.1.3.** Diameter growth (mm/yr) of live trees in dispersed (grey solid line) and group+mixed (black dashed line) VR blocks, for Douglas-fir in CDF+CWHxm ecosystems. Thin dotted lines are 95% confidence intervals.

**Table A2.1.2.** Diameter growth (mm/yr) of live Douglas-fir trees in dispersed versus group+mixed VR in CDF+CWHxm, standardized to 40cm DBH, and exponent for power relationship for other DBH values (see text).

Treatment	Growth (mm/yr)			Exponent
	Mean	LCI	UCI	
Dispersed	2.41	1.65	3.31	1.55
Group+mixed	0.99	0.69	1.35	0.00

#### A2.3.2 Mortality of live trees

Mortality of live trees was considerably higher for all 5 species, overall or in certain ecosystems, in retention blocks compared to uncut stands. Loss of live trees over 5 years in VR stands ranged from 13.5% for cedar, 21.5% for Douglas-fir to 28.9% for hemlock (in CWHvm+vh), 38.4% for true fir and 49% for red alder (calculated for the standardized DBH of 40cm). Mortality rates are expected to be higher shortly after harvest, and should decline in subsequent remeasurement periods. Mortality rates in uncut control stands were mainly near the expected levels of somewhat less than 1%/yr.

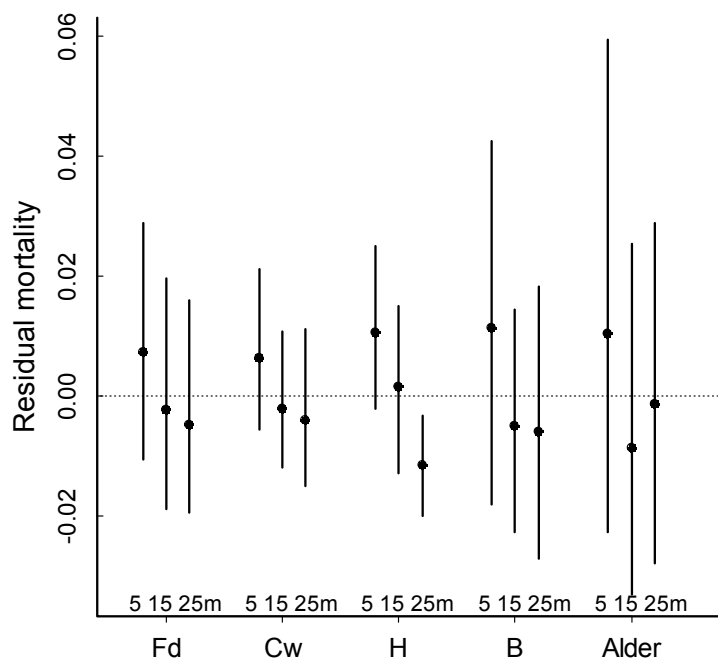


**Figure A2.2.1. Annual mortality rate of live trees as a function of tree DBH. Solid line = VR blocks and mature controls combined; long dashes = mature controls only; short dashes = VR blocks. Thin dotted lines are 95% confidence intervals. "All BEC" = all 4 ecosystem groups combined; otherwise, colours indicate the different ecosystem groups in the best model.**

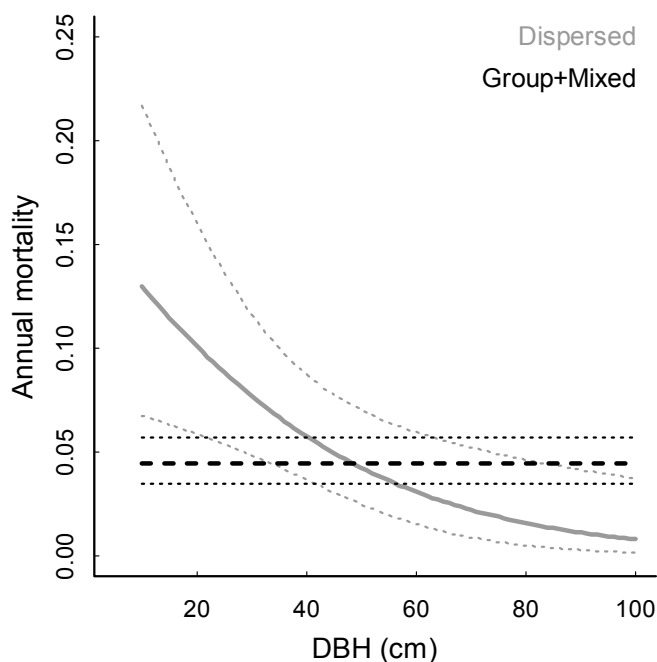
**Table A2.2.1. Annual (%) mortality rates of live trees, standardized to 40cm DBH, and exponent for power relationship for other DBH values (see text).**

Species	BEC Group	Treatment	Mortality (%/yr)			Exponent
			Mean	LCI	UCI	
Douglas-fir	All	UC	0.639	0.299	1.348	0
		VR	4.726	3.820	5.810	-0.662
Red-cedar	All	UC	0.962	0.510	1.792	0
		VR	2.848	2.332	3.466	0
Hemlock	CDF+CWHxm	All	6.508	5.390	7.805	0
	CWHmm+dm	All	3.603	2.617	4.907	-0.747
	CWHvm+vh	UC	0.749	0.461	1.210	0
		VR	6.583	5.892	7.338	0.340
	CWHwh	All	2.152	1.677	2.750	0
True fir	CDF+CWHxm+mm+dm	All	6.247	3.817	9.796	1.404
	CWHvm+vh+wh	UC	0.893	0.364	2.145	0
		VR	9.222	7.942	10.643	0.391
Red alder	All	UC	0.353	0.009	10.037	-5.911
		VR	12.609	9.000	16.981	1.286

Mortality was slightly elevated for all species 0-10m into retention patches, compared to further into the patch. However, there was considerable variation in overall mortality and its edge distribution between individual sites, resulting in wide error bars on the edge effects.



**Figure A2.2.2. Edge effects on annual mortality of live trees.** Values are the residual annual mortality after the predictions of the best model (Figure A2.2.1) have been removed, at 5, 15 and 25+m into retention patches. Error bars are bootstrapped 95% confidence intervals. Fd=Douglas-fir, Cw=western red-cedar, H=hemlocks, B=true firs. All ecosystem groups were combined for the analyses of edge effects.



**Figure A2.2.3.** Annual mortality of live trees in dispersed (grey solid line) and group+mixed (black dashed line) VR blocks, for Douglas-fir in CDF+CWHxm ecosystems. Thin dotted lines are 95% confidence intervals.

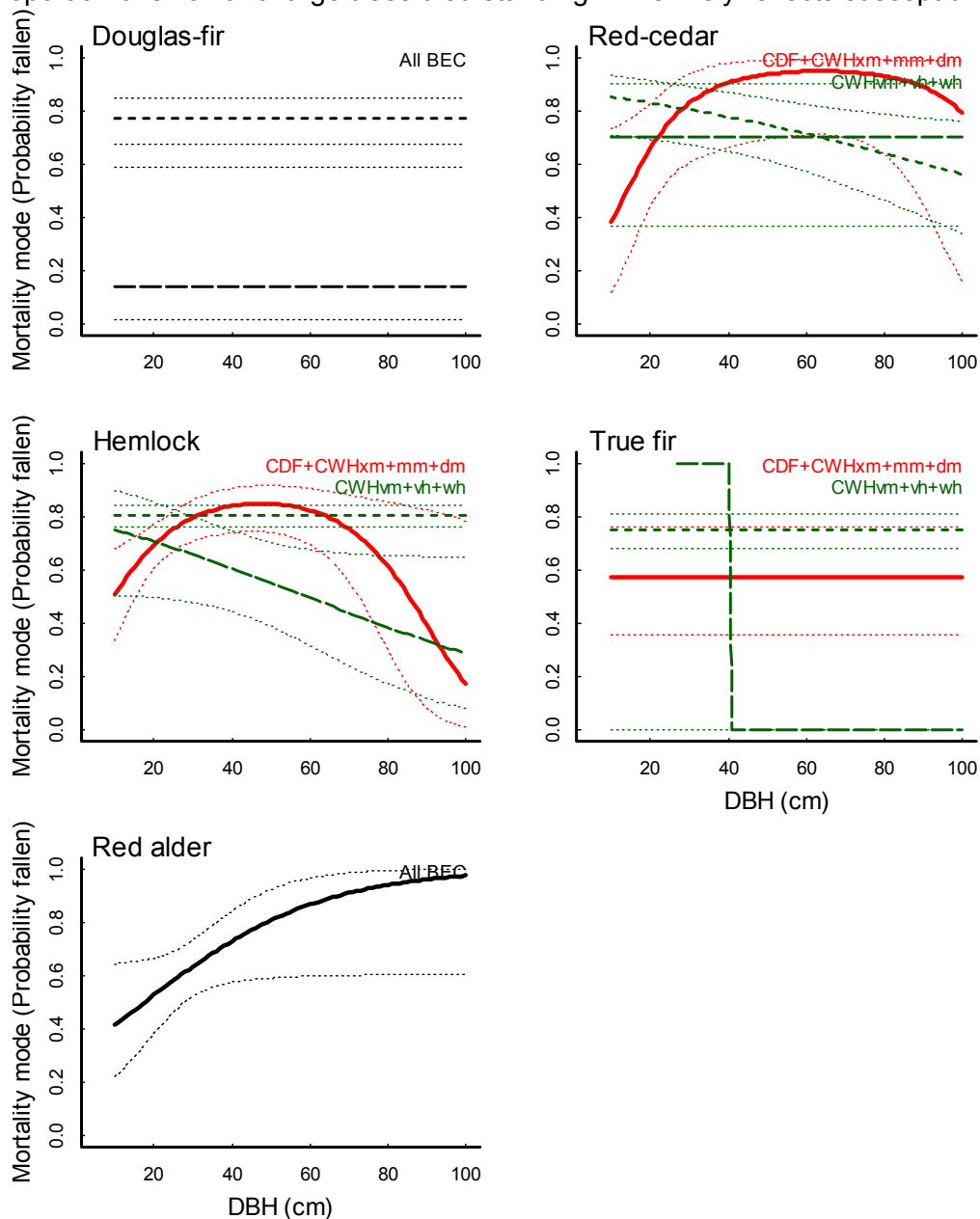
Retained live Douglas-fir trees in CDF and CWHxm showed higher mortality in dispersed VR for trees <50cm DBH, but lower mortality for large trees. The lower mortality of large Douglas-fir in dispersed retention likely reflects operational care in retaining healthy, wind-firm large firs for retention. Small trees retained in dispersed VR were likely not selected so carefully, and may have included poor-quality trees that did not survive in the open stands after harvest.

**Table A2.2.2.** Annual (%) mortality rates of live Douglas-fir trees in dispersed versus group+mixed VR in CDF+CWHxm, standardized to 40cm DBH, and exponent for power relationship for other DBH values (see text).

Treatment	Mortality (%/yr)			Exponent
	Mean	LCI	UCI	
Dispersed	5.76	3.67	8.74	-1.33
Group+mixed	4.49	3.50	5.69	0.00

### A2.3.3 Mortality mode for live trees

For Douglas-fir and for hemlocks in wetter ecosystems, a higher proportion of dying trees fell, as opposed to died standing, in VR stands than in uncut controls. In these cases, the additional mortality in VR stands will make less of a contribution to maintaining levels of snags. For cedars and hemlocks in the drier ecosystems, most mid-sized trees that died fell, while a higher proportion of small and large trees died standing. This likely reflects susceptibility of the



**Figure A2.3.1. “Mortality mode” of live trees as a function of tree DBH.** The value is the probability the tree will die fallen (e.g., windthrown) as opposed to dying standing. Solid line = VR blocks and mature controls combined; long dashes = mature controls only; short dashes = VR blocks. Thin dotted lines are 95% confidence intervals. “All BEC” = all 4 ecosystem groups combined; otherwise, colours indicate the different ecosystem groups in

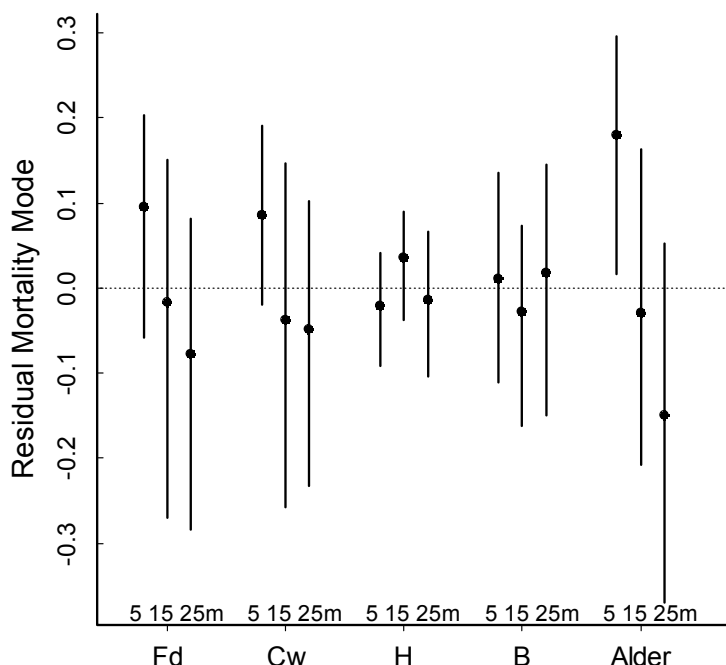
**the best model. Note: The result for true firs in uncut controls in wetter ecosystems is based on too few dying trees to be reliable.**

mid-sized trees to windthrow, while larger trees are more windfirm (and have already survived longer in the canopy) and small trees are more likely to die from effects of competition when their environment is changed at harvest.

**Table A2.3.1. Mortality mode (% of dying snags that die fallen) of live trees, standardized to 40cm DBH, and exponent for power relationship for other DBH values (see text).**

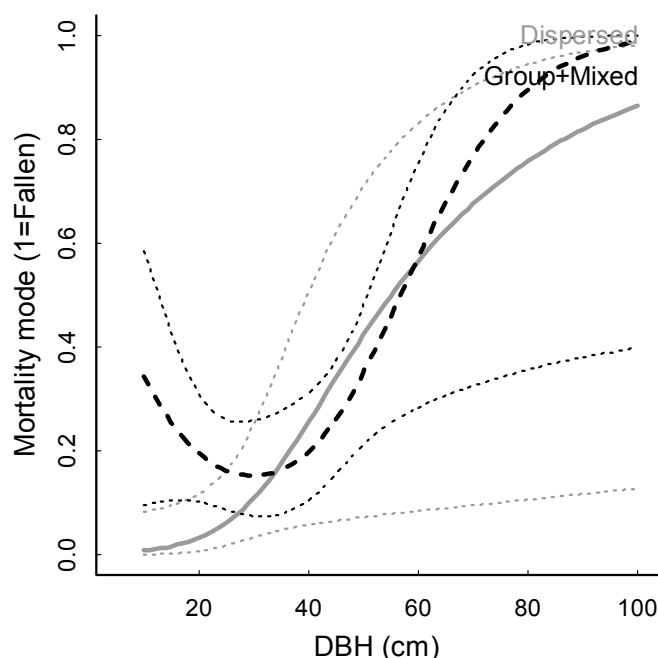
Species	BEC Group	Treatment	Mortality mode (% fallen)			Exponent
			Mean	LCI	UCI	
Douglas-fir	All	UC	3.036	0.380	16.377	0
		VR	25.676	20.246	31.304	0
Red-cedar	CDF+CWHxm+mm+dm CWHvm+vh+wh	All	37.593	19.545	53.801	0.543
		UC	21.400	8.822	37.247	0
		VR	25.945	18.798	33.424	-0.342
Hemlock	CDF+CWHxm+mm+dm CWHvm+vh+wh	All	30.668	23.629	37.689	-0.142
		UC	16.998	11.083	24.068	-0.613
		VR	27.976	24.882	31.097	0
True fir	CDF+CWHxm+mm+dm CWHvm+vh+wh	All	15.588	8.415	25.024	0
		UC	95.249			
		VR	24.214	20.343	28.224	0
Red alder	All	All	22.999	15.749	30.915	0.815

Dying trees near edges were somewhat more likely to fall, while more interior trees died standing, as expected from windthrow around edges of retention patches.



**Figure A2.3.2. Edge effects on mortality mode of live trees. Values are the residual mortality mode after the predictions of the best model (Figure A2.3.1) have been removed, at 5, 15 and 25+m into retention patches. Values >0 indicate that trees are more likely to die fallen (windthrow) at that edge position; values <0 indicate that they are more likely to die**

standing. Error bars are bootstrapped 95% confidence intervals. Fd=Douglas-fir, Cw=western red-cedar, H=hemlocks, B=true firs. All ecosystem groups were combined for the analyses of edge effects.



**Figure A2.3.3.** Mortality mode of live trees in dispersed (grey solid line) and group+mixed (black dashed line) VR blocks, for Douglas-fir in CDF+CWHxm ecosystems. The value is the probability the tree will die fallen (e.g., windthrown) as opposed to dying standing. Thin dotted lines are 95% confidence intervals.

Within the dry ecosystem group, Douglas-fir showed increasing tendency to fall at death with increasing DBH, in both dispersed and group+mixed VR. This contrasts with the main result for Douglas-fir, which combined all ecosystem groups and did not show a relationship with DBH. Smaller Douglas-fir trees may be more prone to dying standing in drier ecosystems, where they are generally growing under a canopy of vigorous second-growth Douglas-fir.

**Table A2.3.2.** Mortality mode (% of dying snags that die fallen – e.g., windthrow) of live Douglas-fir trees in dispersed versus group+mixed VR in CDF+CWHxm, standardized to 40cm DBH, and exponent for power relationship for other DBH values (see text).

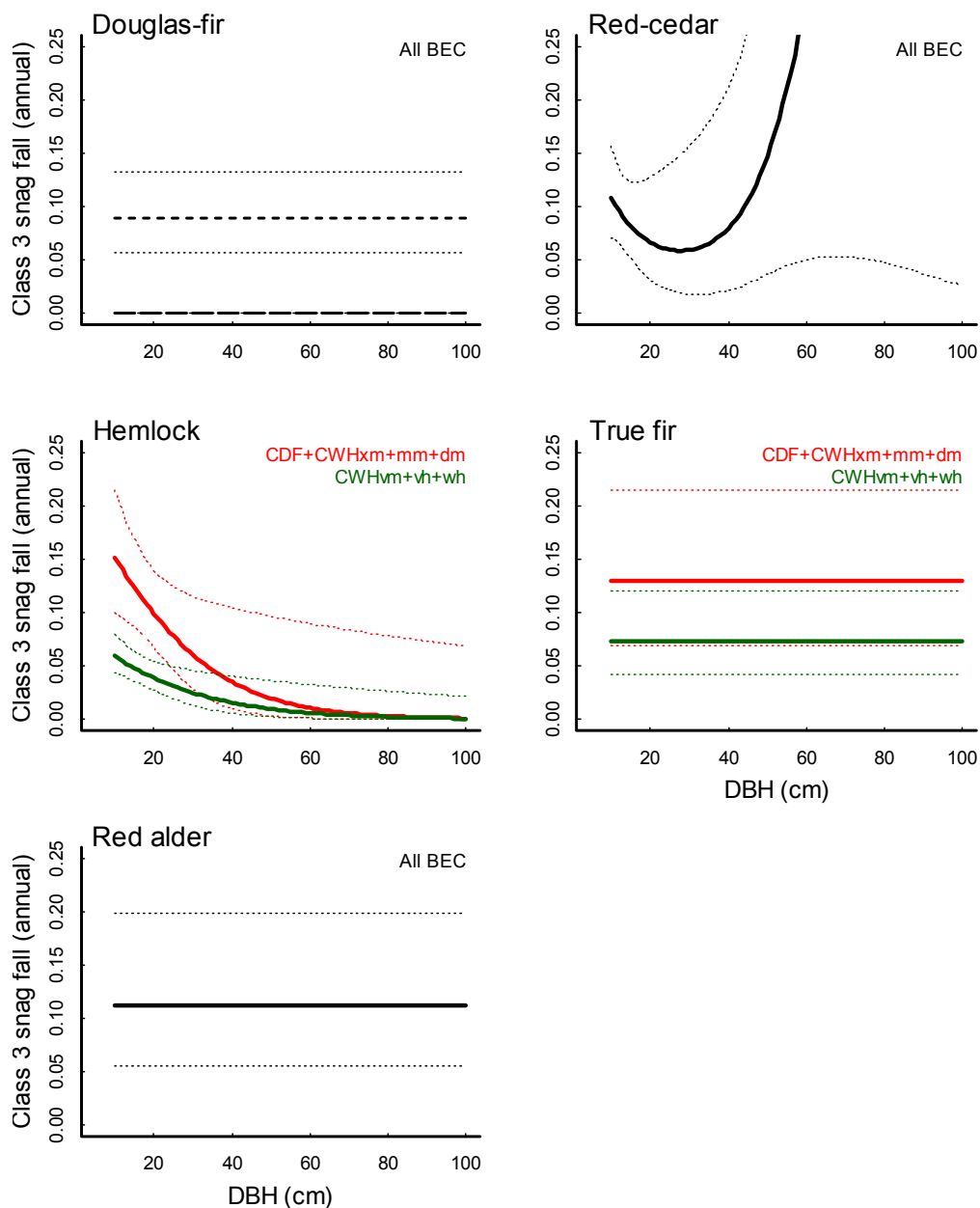
Treatment	Mortality mode (% fallen)			Exponent
	Mean	LCI	UCI	
Dispersed	25.59	5.76	50.65	2.27
Group+mixed	19.81	10.49	31.20	1.10

#### A2.3.4 Fall rates of snags – class 3

Fall rates of recent snags declined with DBH for hemlocks, but showed no changes in the other species. (The results for red-cedar have very wide confidence intervals, because few cedar snags were classified as class 3 – the snag classification system originated with Douglas-fir, and is less clearly applied to cedars). A declining fall rate with increasing DBH is generally



expected for snags, but recent snags may be more prone to windthrow, which tends to increase with snag size. No class 3 Douglas-fir snags fell in uncut sites, but this is likely due to the low numbers of recently dead trees in those stands, rather than substantial real differences in fall rates between VR and controls.

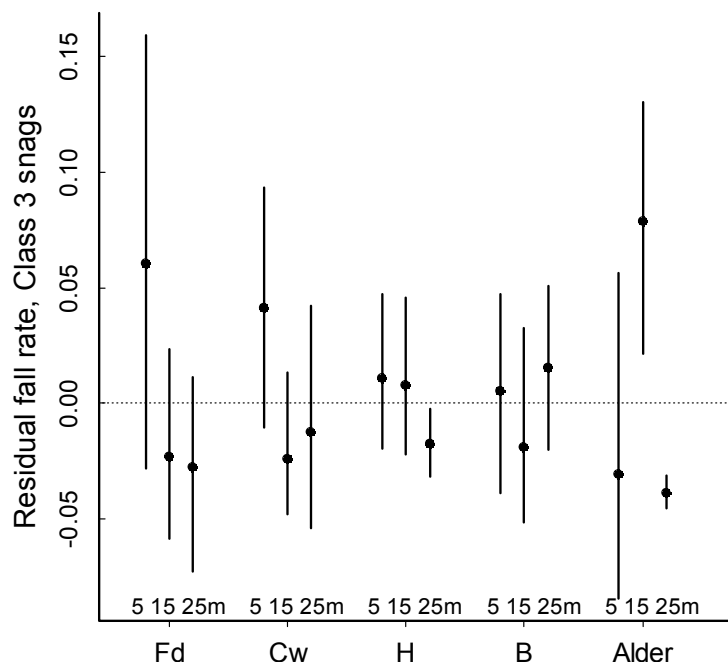


**Figure A2.4.1. Annual fall rates of class 3 (recently dead) snags as a function of snag DBH. Solid line = VR blocks and mature controls combined; long dashes = mature controls only; short dashes = VR blocks. Thin dotted lines are 95% confidence intervals. "All BEC" = all 4 ecosystem groups combined; otherwise, colours indicate the different ecosystem groups in the best model. Note: Results for red-cedar are highly uncertain, as there were very few class 3 cedar snags.**

**Table A2.4.1. Annual (%) fall rates of class 3 (recently dead) snags, standardized to 40cm DBH, and exponent for power relationship for other DBH values (see text).**

Species	BEC Group	Treatment	Snag fall - class 3 (%/yr)			
			Mean	LCI	UCI	Exponent
Douglas-fir	All	UC	0.000	0.000	0.000	0
		VR	8.972	5.762	13.307	0
Red-cedar	All	All	7.986	2.174	21.210	1.682
Hemlock	CDF+CWHxm+mm+dm	All	3.523	1.017	10.441	-2.471
	CWHvm+vh+wh	All	1.570	0.581	4.047	-2.032
True fir	CDF+CWHxm+mm+dm	All	12.945	6.854	21.460	0
	CWHvm+vh+wh	All	7.374	4.277	11.969	0
Red alder	All	All	11.270	5.587	19.781	0

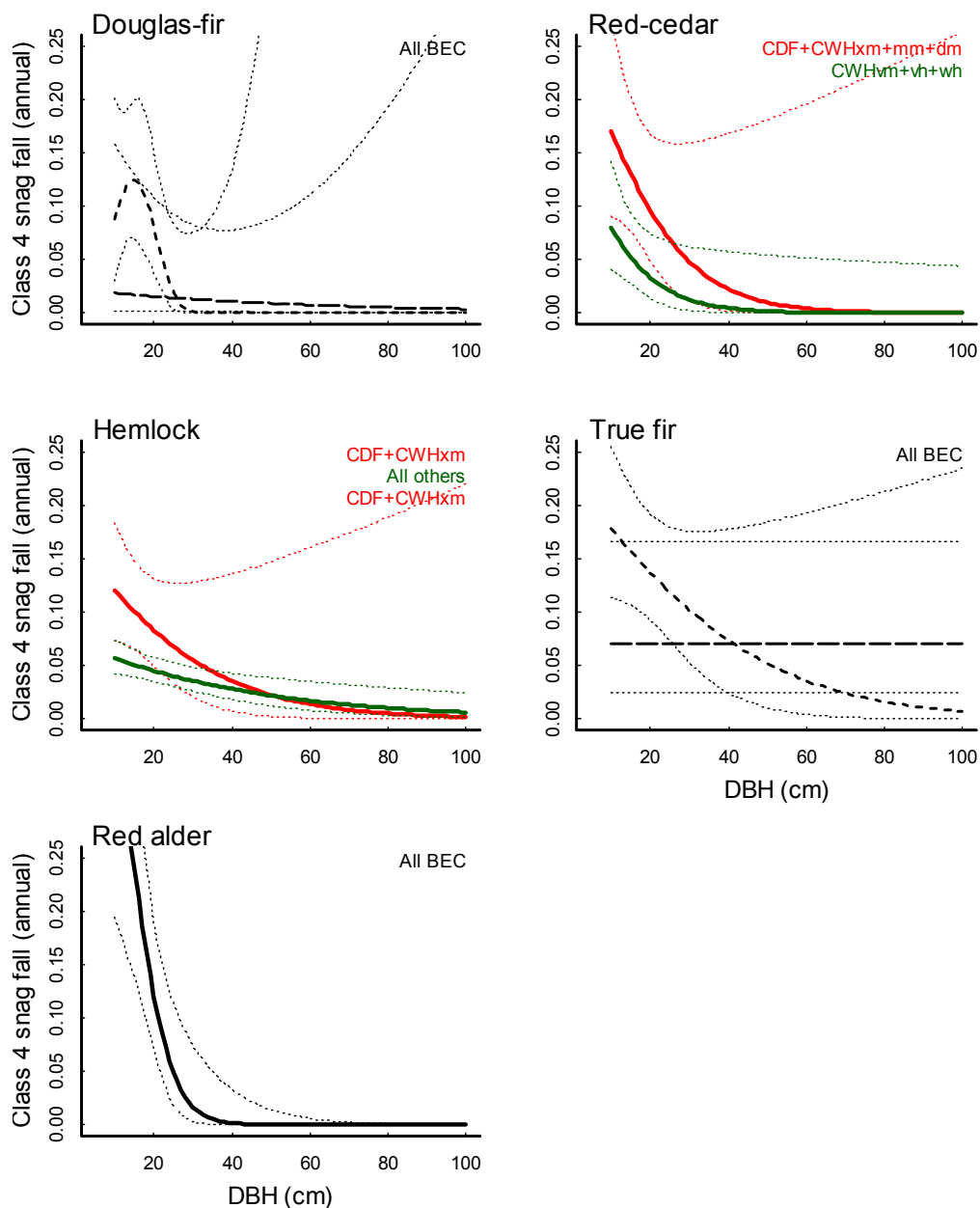
Fall rates of recent snags tended to be higher for Douglas-fir and cedar near the edges of patches compared to further from the edge. This may reflect susceptibility of these recently dead trees – which generally retain most of their branches – to windthrow.



**Figure A2.4.2. Edge effects on annual fall rate of class 3 (recently dead) snags.** Values are the residual fall rates after the predictions of the best model (Figure A2.4.1) have been removed, at 5, 15 and 25+m into retention patches. Error bars are bootstrapped 95% confidence intervals. Fd=Douglas-fir, Cw=western red-cedar, H=hemlocks, B=true firs. All ecosystem groups were combined for the analyses of edge effects.

### A2.3.5 Fall rates of snags – class 4

In most cases, class 4 snags showed declining fall rates with increasing DBH, with a very low proportion of class 4 snags >40cm falling for any species. Fall rates for the standardized 40cm DBH snag were considerably lower for class 4 than class 3 snags, except hemlock which had similar curves for the two classes. This result is contrary to the intuitive expectation that annual fall rates would increase with increasing decay of the snags.

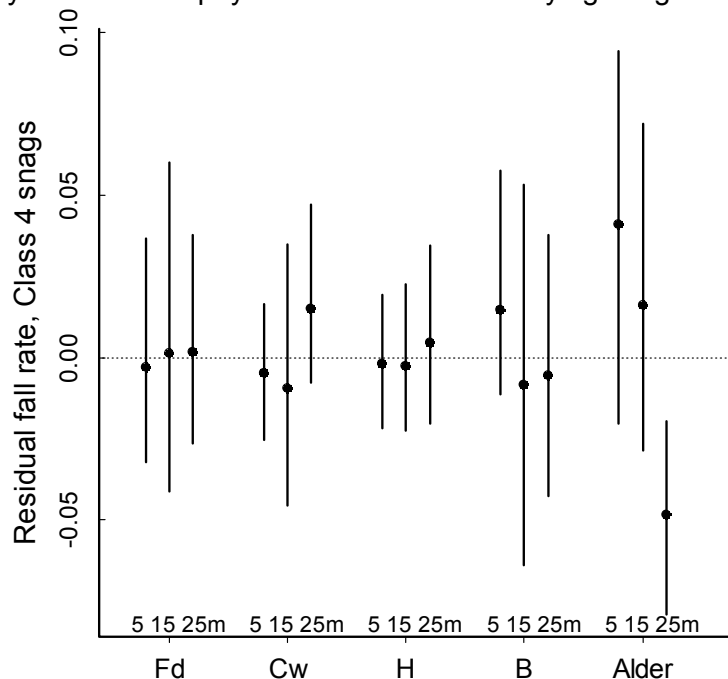


**Figure A2.5.1. Annual fall rates of class 4 snags as a function of snag DBH. Solid line = VR blocks and mature controls combined; long dashes = mature controls only; short dashes = VR blocks. Thin dotted lines are 95% confidence intervals. "All BEC" = all 4 ecosystem groups combined; otherwise, colours indicate the different ecosystem groups in the best model.**

**Table A2.5.1. Annual (%) fall rates of class 4 snags, standardized to 40cm DBH, and exponent for power relationship for other DBH values (see text).**

Species	BEC Group	Treatment	Snag fall - class 4 (%/yr)			
			Mean	LCI	UCI	Exponent
Douglas-fir	All	UC	1.090	0.127	7.760	-0.782
		VR	0.000	0.000	13.487	0
Red-cedar	CDF+CWHxm+mm+dm	All	2.234	0.188	16.816	-3.456
	CWHvm+vh+wh	All	0.468	0.033	5.744	-4.357
Hemlock	CDF+xm	All	3.548	0.712	13.598	-2.002
	CWHmm+dm+vm+vh+wh	All	2.804	1.811	4.273	-1.065
True fir	All	UC	7.091	2.477	16.600	0
		VR	7.376	2.438	17.764	-1.534
Red alder	All	All	0.175	0.008	3.322	-9.730

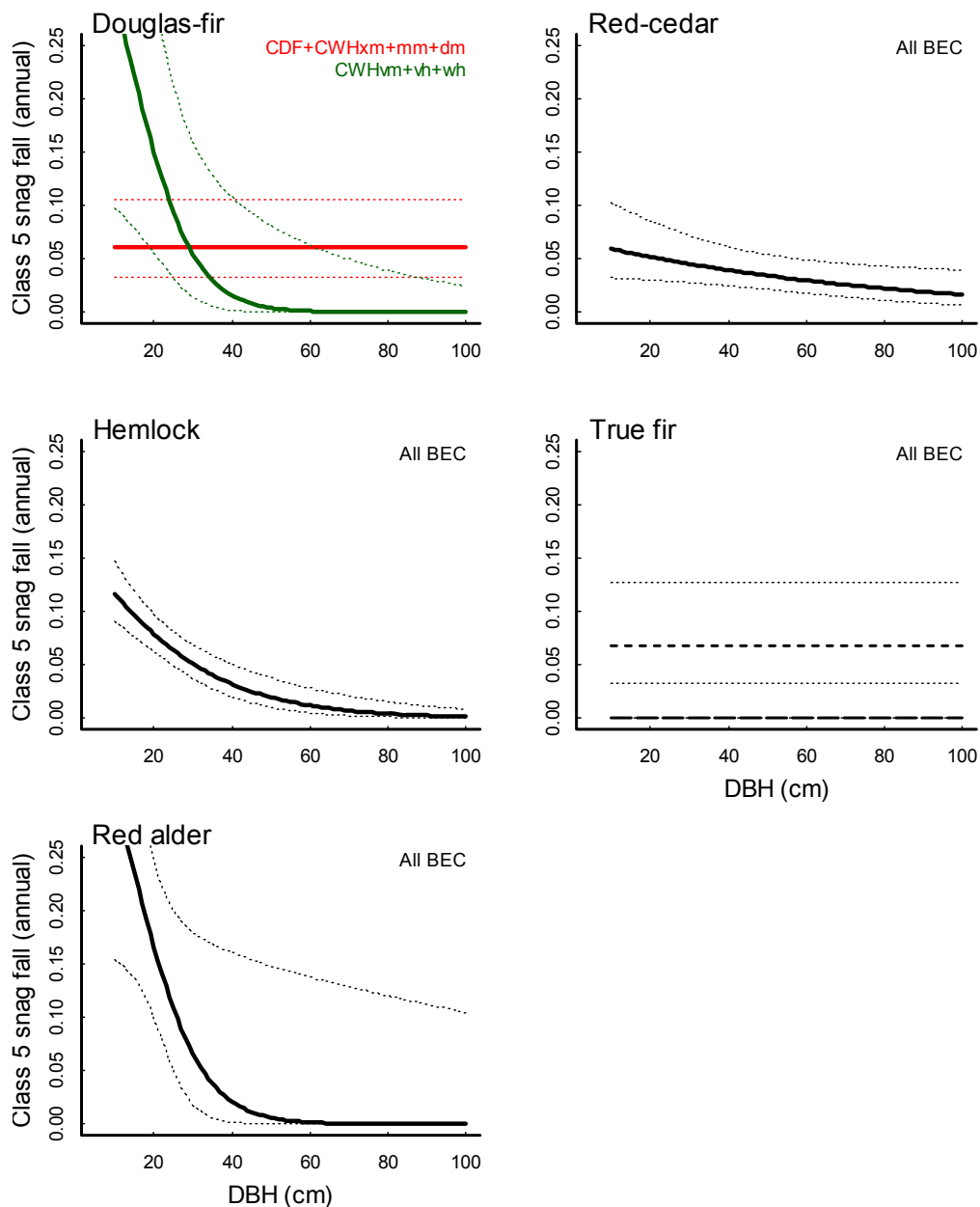
Fall rates of class 4 snags did not show any edge effects, except perhaps for alder snags. With increasing decay class, snag fall may be less affected by wind near an edge, and increasingly a function of physical failure of the decaying snag and its root system.



**Figure A2.5.2. Edge effects on annual fall rate of class 4 snags.** Values are the residual fall rates after the predictions of the best model (Figure A2.5.1) have been removed, at 5, 15 and 25+m into retention patches. Error bars are bootstrapped 95% confidence intervals. Fd=Douglas-fir, Cw=western red-cedar, H=hemlocks, B=true fir. All ecosystem groups were combined for the analyses of edge effects.

### A2.3.6 Fall rates of snags – class 5

As with class 4 snags, class 5 snags mostly showed decreasing fall rates with increasing diameter, except for Douglas-fir in drier ecosystems and true firs. Fall rates for the standardized 40cm snags were similar for class 5 and class 4 snags, and generally lower than for class 3, again contrary to expectation.

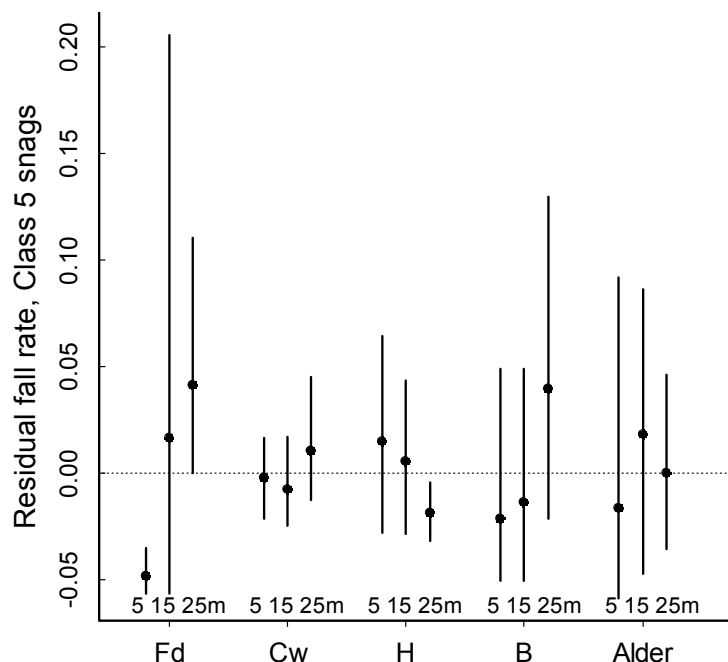


**Figure A2.6.1. Annual fall rates of class 5 snags as a function of snag DBH. Solid line = VR blocks and mature controls combined; long dashes = mature controls only; short dashes = VR blocks. Thin dotted lines are 95% confidence intervals. “All BEC” = all 4 ecosystem groups combined; otherwise, colours indicate the different ecosystem groups in the best model.**

**Table A2.6.1. Annual (%) fall rates of class 5 snags, standardized to 40cm DBH, and exponent for power relationship for other DBH values (see text).**

Species	BEC Group	Treatment	Snag fall - class 5 (%/yr)			
			Mean	LCI	UCI	Exponent
Douglas-fir	CDF+CWHxm+mm+dm	All	6.056	3.275	10.507	0
	CWHvm+vh+wh	All	1.577	0.177	10.768	-5.513
Red-cedar	All	All	3.950	2.477	6.144	-0.609
Hemlock	All	All	3.200	1.981	5.059	-2.105
True fir	All	UC	0.000	0.000	0.000	0
		VR	6.787	3.276	12.754	0
Red alder	All	All	2.104	0.179	16.031	-5.159

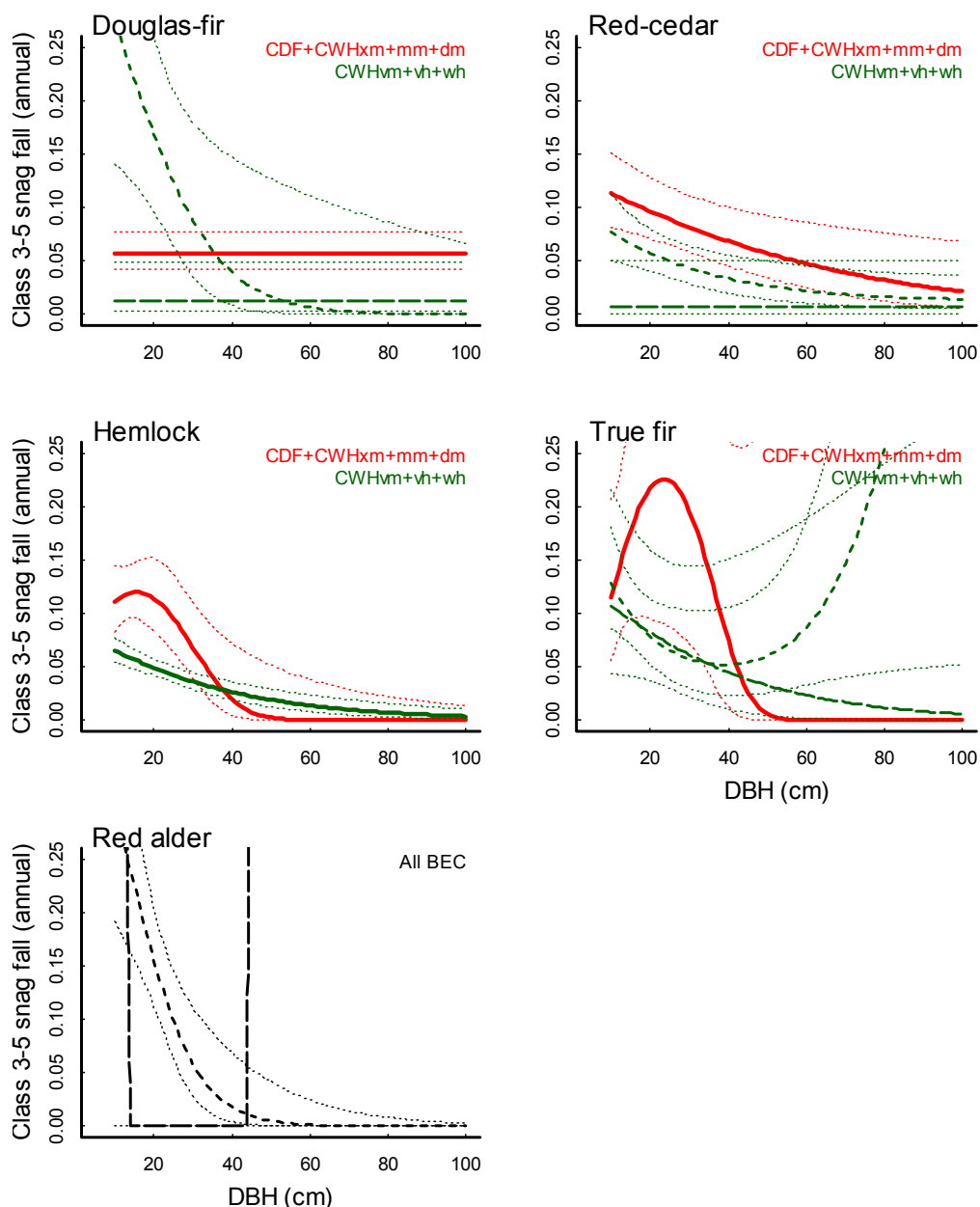
As with class 4 snags, there was no clear effect of edge position on fall rates of class 5 snags. The lower fall rate 0-10m into the patch for Douglas-fir is assumed to represent a chance occurrence, with a relatively small sample size of class 5 snags of this species.



**Figure A2.6.2. Edge effects on annual fall rate of class 5 snags.** Values are the residual fall rates after the predictions of the best model (Figure A2.6.1) have been removed, at 5, 15 and 25+m into retention patches. Error bars are bootstrapped 95% confidence intervals. Fd=Douglas-fir, Cw=western red-cedar, H=hemlocks, B=true firs. All ecosystem groups were combined for the analyses of edge effects.

### A2.3.7 Fall rates of snags – class 3-5 (hard snags)

Combining the three classes of snags with hard wood, fall rates mainly declined with increasing DBH. Exceptions were Douglas-fir in drier ecosystems where there was no apparent relationship with DBH, and Douglas-fir and cedar in uncut controls of wetter ecosystems, where fall rates were low at all DBH values. Hemlock and true fir in drier ecosystems may also show reduced fall rates for the smallest snags, but uncertainty is high because small snags of those species are relatively rare in dry ecosystems. The result for alder in uncut controls is again based on too few snags to be reliable.

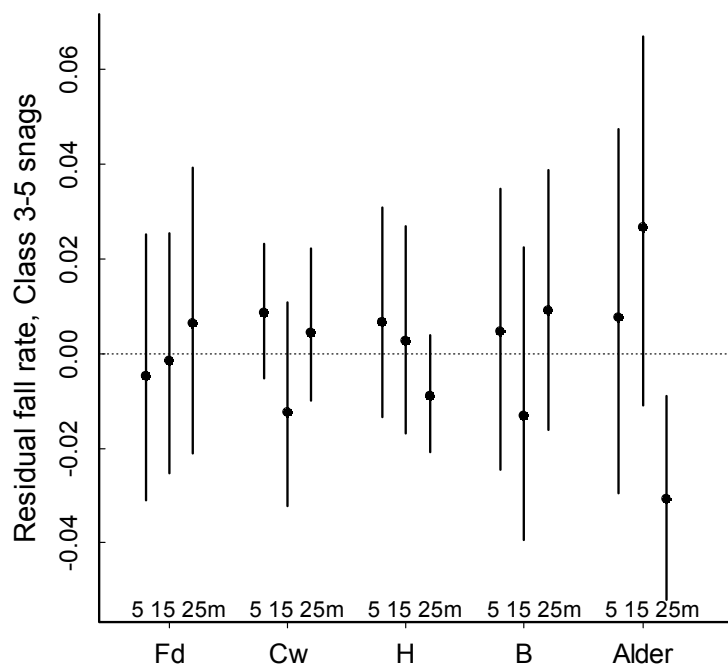


**Figure A2.7.1.** Annual fall rates of class 3-5 (hard) snags as a function of snag DBH. Solid line = VR blocks and mature controls combined; long dashes = mature controls only; short dashes = VR blocks. Thin dotted lines are 95% confidence intervals. “All BEC” = all 4 ecosystem groups combined; otherwise, colours indicate the different ecosystem groups in the best model.

**Table A2.7.1. Annual (%) fall rates of class 3-5 (hard) snags, standardized to 40cm DBH, and exponent for power relationship for other DBH values (see text).**

Species	BEC Group	Treatment	Snag fall - class 3-5 (%/yr)			
			Mean	LCI	UCI	Exponent
Douglas-fir	CDF+CWHxm+mm+dm	All	5.715	4.150	7.737	0
	CWHvm+vh+wh	UC	1.282	0.307	4.924	0
Red-cedar	CDF+CWHxm+mm+dm	All	6.844	4.523	10.016	-0.794
	CWHvm+vh+wh	UC	0.752	0.100	5.042	0
		VR	3.351	1.973	5.535	-0.894
Hemlock	CDF+CWHxm+mm+dm	All	1.960	0.470	7.222	-10.461
	CWHvm+vh+wh	All	2.648	1.935	3.596	-1.387
True fir	CDF+CWHxm+mm+dm	All	7.382	1.186	26.154	-13.761
	CWHvm+vh+wh	UC	4.506	1.031	15.074	-1.397
		VR	5.213	2.336	10.600	0.849
Red alder	All	UC	0.000	0.000	0.000	0
		VR	1.768	0.404	6.850	-5.349

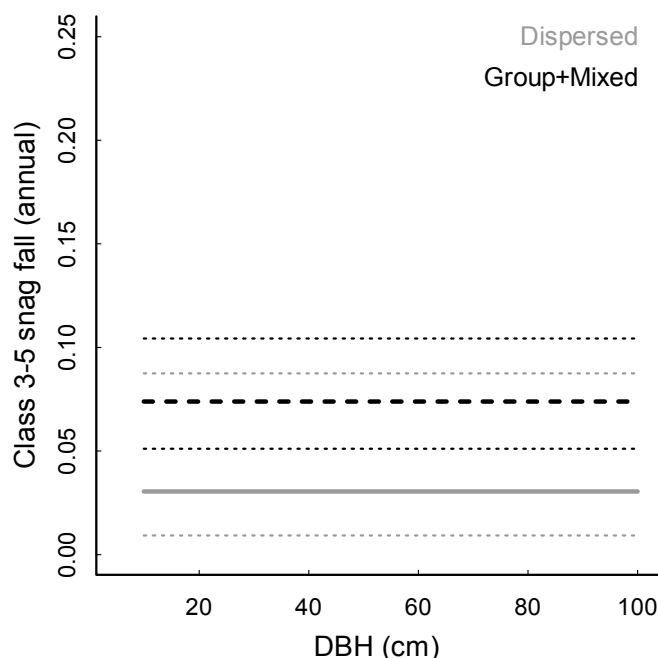
There were no obvious edge effects in the fall rates of the 3 combined classes of hard snags.



**Figure A2.7.2. Edge effects on annual fall rate of class 3-5 (hard) snags.** Values are the residual fall rates after the predictions of the best model (Figure A2.7.1) have been removed, at 5, 15 and 25+m into retention patches. Error bars are bootstrapped 95% confidence intervals. Fd=Douglas-fir, Cw=western red-cedar, H=hemlocks, B=true firs. All ecosystem groups were combined for the analyses of edge effects.



Hard Douglas-fir snags had lower fall rates in dispersed VR than in group+mixed VR in CDF and CWHxm. This likely reflects intentional selection of more stable snags for retention in dispersed VR, and also the fact that many of the snags retained within dispersed VR sites were short snags with broken tops.



**Figure A2.7.3.** Annual fall rate of class 3-5 (hard) snags in dispersed (grey solid line) and group+mixed (black dashed line) VR blocks, for Douglas-fir in CDF+CWHxm ecosystems. Thin dotted lines are 95% confidence intervals.

**Table A2.7.2.** Annual (%) fall rates of class 3-5 (hard) Douglas-fir snags in dispersed versus group+mixed VR in CDF+CWHxm, standardized to 40cm DBH, and exponent for power relationship for other DBH values (see text).

Treatment	Snag fall - class 3-5 (%/yr)			Exponent
	Mean	LCI	UCI	
Dispersed	3.04	0.93	8.74	0.00
Group+mixed	7.39	5.09	10.42	0.00

#### A2.3.8 Fall rates of snags – class 6+ (soft snags)

The analysis of fall rates of soft snags combined all species (because species often cannot be determined for well-decayed snags) and ecosystems (because old snags are rare). Fall rates of soft snags declined with increasing DBH, with fall rates more than twice as high in VR stands than in uncut stands. Fall rates of soft snags were 2-3 times as high as fall rates of hard snags in a given treatment.

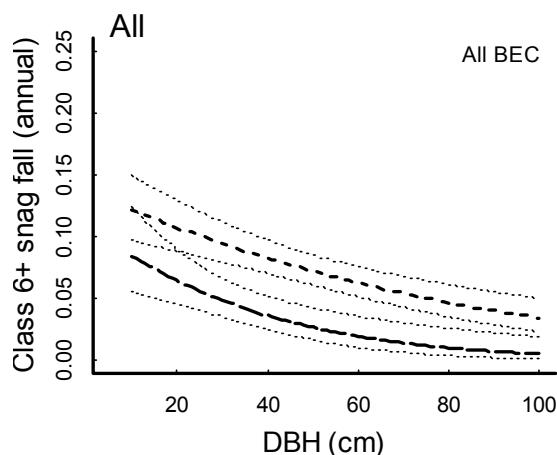


Figure A2.8.1. Annual fall rates of class 6+ (soft) snags as a function of snag DBH, combining all species. Long dashes = mature controls only; short dashes = VR blocks. Thin dotted lines are 95% confidence intervals. "All BEC" = all 4 ecosystem groups combined.

Table A2.8.1. Annual (%) fall rates of class 6+ (soft) snags, standardized to 40cm DBH, and exponent for power relationship for other DBH values (see text).

Species	BEC Group	Treatment	Snag fall - class 6+ (%/yr)			
			Mean	LCI	UCI	Exponent
All	All	UC	3.628	2.497	5.194	-1.324
		VR	8.288	7.026	9.712	-0.600

There were no obvious edge effects on fall rates soft snags, which are expected to fall due to structural failure from decay, rather than from the effects of wind along edges.

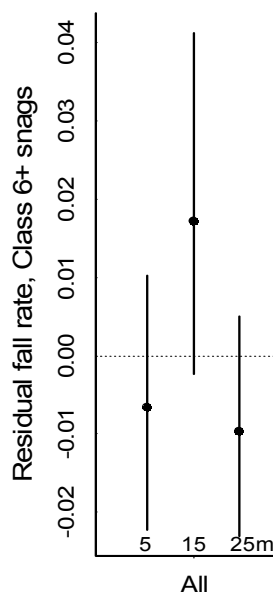
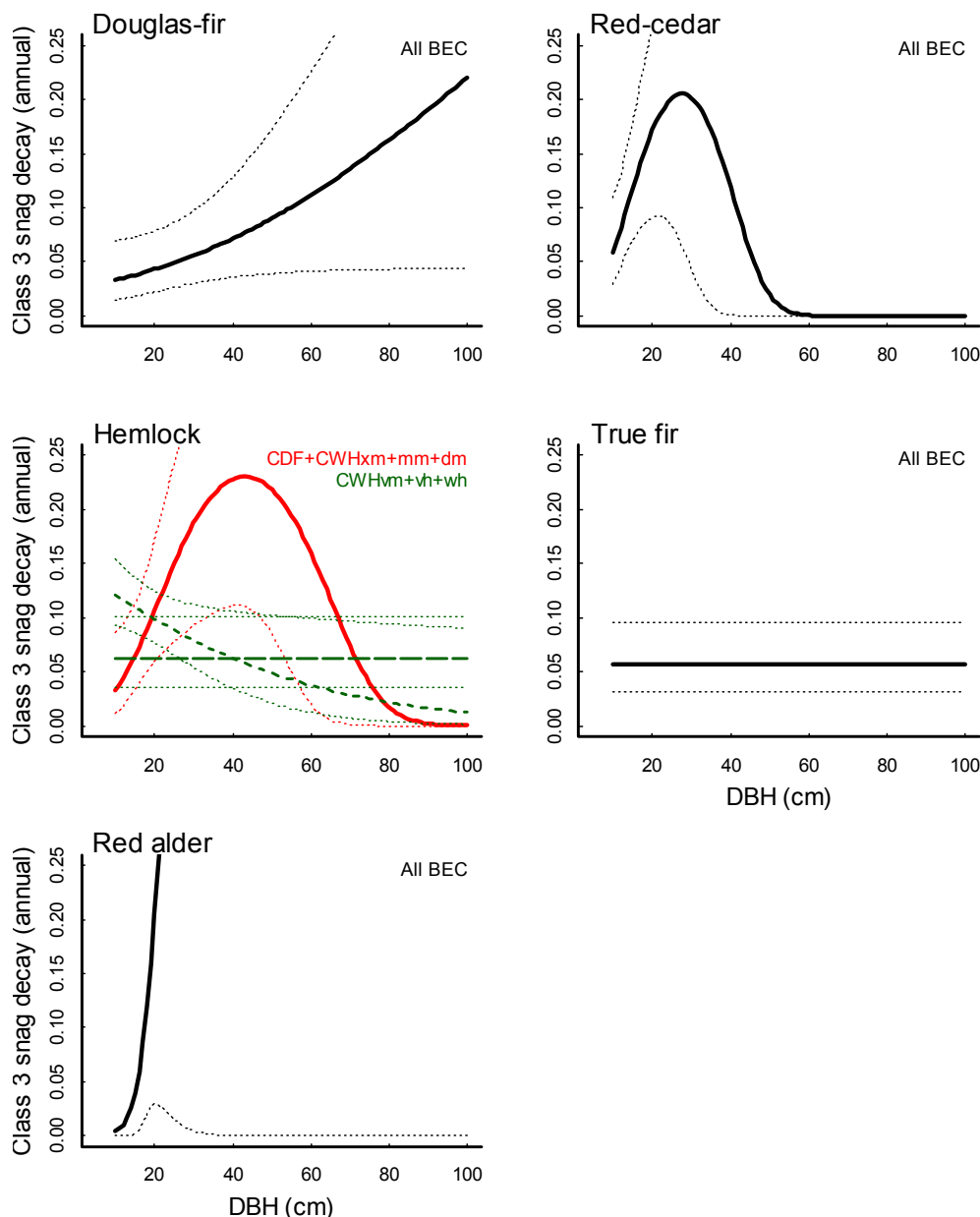


Figure A2.8.2. Edge effects on annual fall rate of class 6+ (soft) snags. Values are the residual fall rates after the predictions of the best model (Figure A2.8.1) have been removed, at 5, 15 and 25+m into retention patches. Error bars are bootstrapped 95% confidence intervals. Fd=Douglas-fir, Cw=western red-cedar, H=hemlocks, B=true firs. All ecosystem groups and species were combined for this analysis.

### A2.3.9 Decay rates of snags – class 3→4

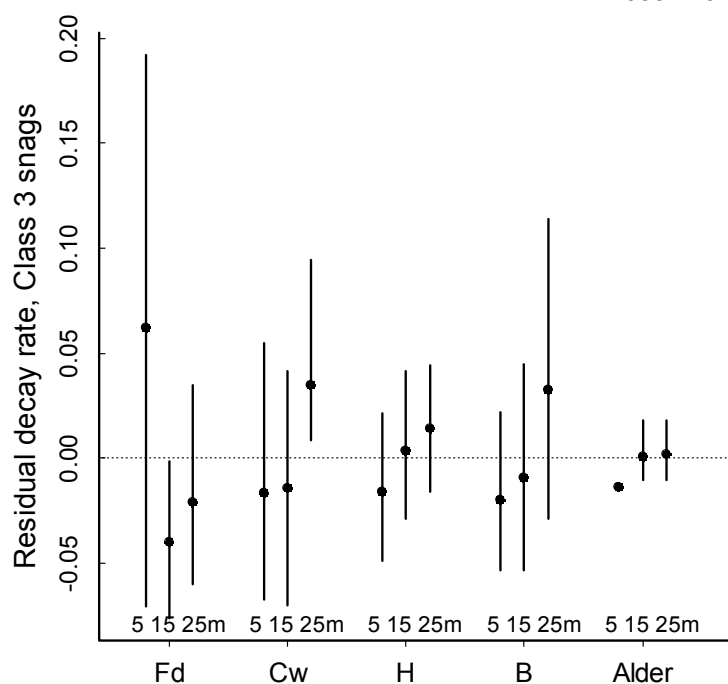
Decay rates from class 3 to class 4 snags showed a variety of relationships with DBH. In most cases, confidence intervals were wide, because there are relatively few class 3 snags. Edge effects were similarly variable, with wide uncertainty.



**Figure A2.9.1.** Annual decay rates from class 3 to class 4 snags as a function of snag DBH. Solid line = VR blocks and mature controls combined; long dashes = mature controls only; short dashes = VR blocks. Thin dotted lines are 95% confidence intervals. "All BEC" = all 4 ecosystem groups combined; otherwise, colours indicate the different ecosystem groups in the best model. Note: Rates for red alder are highly suspect, because there were very few class 3 alder snags that remained standing for the remeasurements.

**Table A2.9.1. Annual (%) decay rates of class 3 → class 4 snags, standardized to 40cm DBH, and exponent for power relationship for other DBH values (see text).**

Species	BEC Group	Snag decay - class 3-->4 (%/yr)				
		Treatment	Mean	LCI	UCI	Exponent
Douglas-fir	All	All	7.160	3.576	12.871	0.954
Red-cedar	All	All	11.899	0.096	55.905	-11.701
Hemlock	CDF+CWHxm+mm+dm CWHvm+vh+wh	All	22.829	11.105	35.548	-1.308
		UC	6.226	3.611	10.105	0
		VR	6.259	3.437	10.598	-1.093
True fir	All	All	5.649	3.135	9.547	0
Red alder	All	All	74.685	0.030	84.113	1.020

**Figure A2.9.2. Edge effects on annual decay of class 3 to class 4 snags. Values are the residual decay rates after the predictions of the best model (Figure A2.9.1) have been removed, at 5, 15 and 25+m into retention patches. Error bars are bootstrapped 95% confidence intervals. Fd=Douglas-fir, Cw=western red-cedar, H=hemlocks, B=true firs. All ecosystem groups were combined for the analyses of edge effects.**

### A2.3.10 Decay rates of snags – class 4→5

Decay rates from class 4 to class 5 snags were mainly either constant with DBH (Douglas-fir, true fir, alder; hemlock and cedar in some ecosystems). Decay rates of hemlock and fir in the drier ecosystems and in VR stands in wetter ecosystems apparently increased with increasing DBH, but confidence intervals are wide. Edge effects were not apparent.

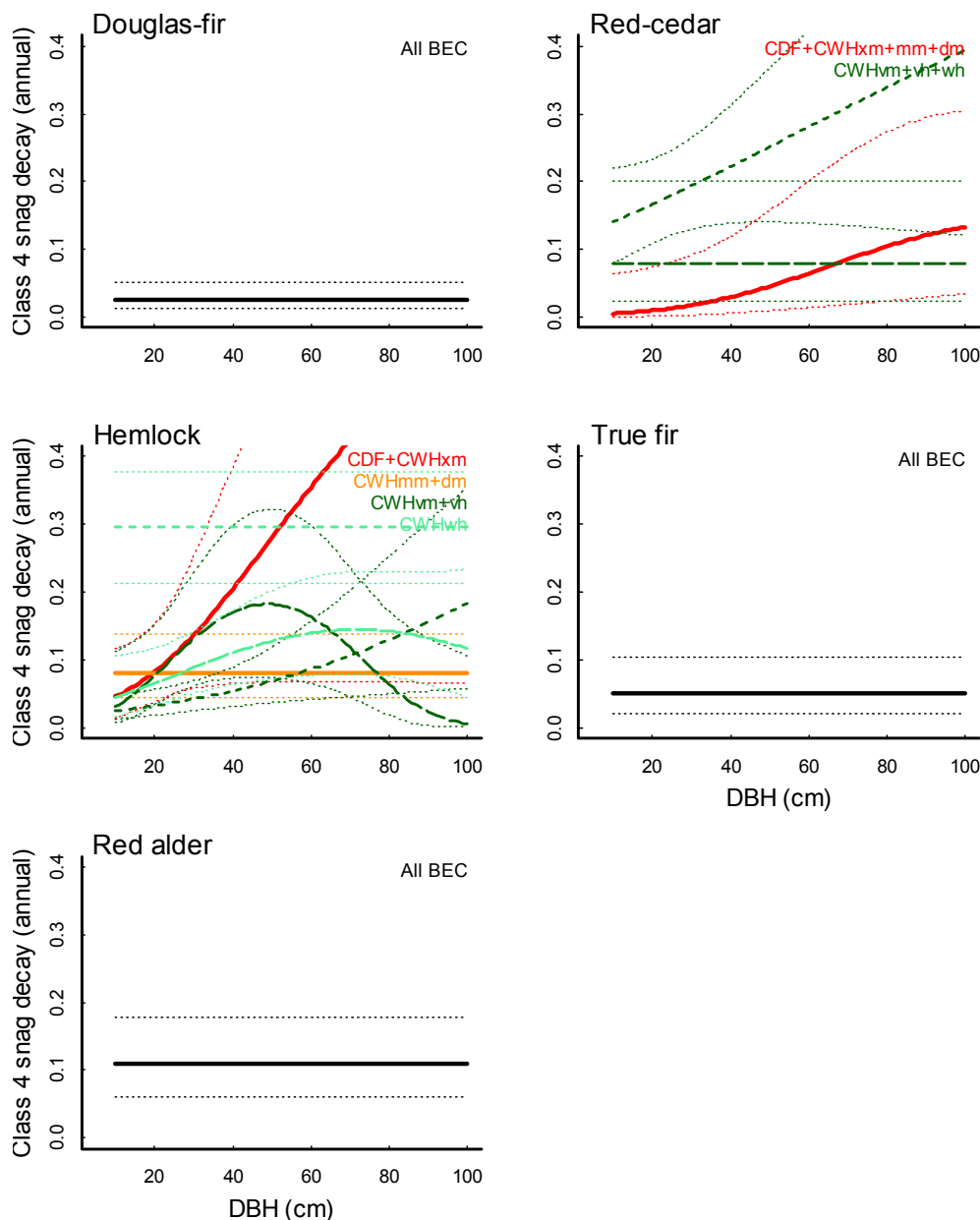
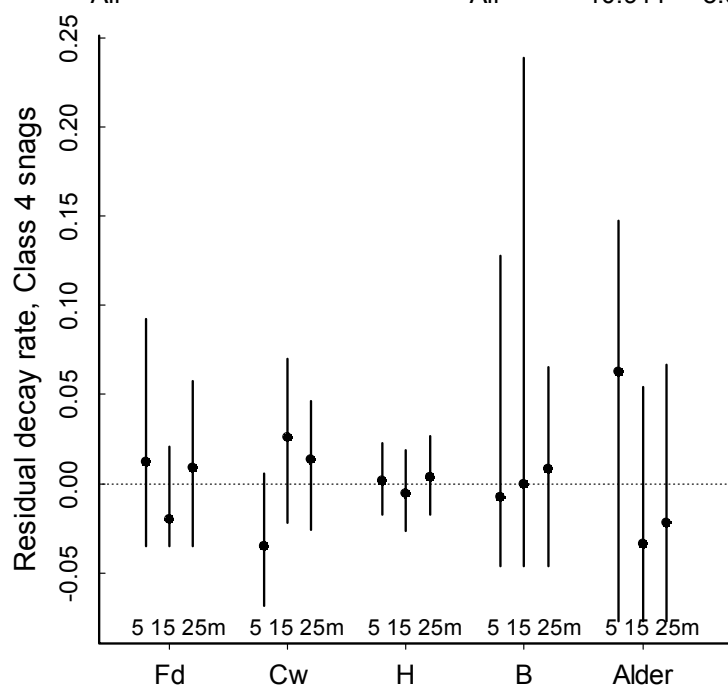


Figure A2.10.1. Annual decay rates from class 4 to class 5 snags as a function of snag DBH.

Solid line = VR blocks and mature controls combined; long dashes = mature controls only; short dashes = VR blocks. Thin dotted lines are 95% confidence intervals. "All BEC" = all 4 ecosystem groups combined; otherwise, colours indicate the different ecosystem groups in the best model.

**Table A2.10.1. Annual (%) decay rates of class 4 → class 5 snags, standardized to 40cm DBH, and exponent for power relationship for other DBH values (see text).**

Species	BEC Group	Snag decay - class 4→5 (%/yr)				
		Treatment	Mean	LCI	UCI	Exponent
Douglas-fir	All	All	2.537	1.180	5.192	0
Red-cedar	CDF+CWHxm+mm+dm CWHvm+vh+wh	All	2.926	0.550	11.921	1.731
		UC	7.985	2.291	20.057	0
		VR	22.220	13.865	31.272	0.513
Hemlock	CDF+CWHxm CWHmm+dm CWHvm+vh	All	20.494	6.470	38.447	1.283
		All	8.097	4.344	13.747	0
		UC	17.044	7.324	29.822	-0.135
	CWHwh	VR	5.391	3.095	8.913	1.001
		UC	10.989	6.326	17.323	0.564
		VR	29.632	21.275	37.749	0
True fir	All	All	4.976	2.147	10.352	0
Red alder	All	All	10.911	5.963	17.818	0

**Figure A2.10.2. Edge effects on annual decay of class 4 to class 5 snags. Values are the residual decay rates after the predictions of the best model (Figure A2.10.1) have been removed, at 5, 15 and 25+m into retention patches. Error bars are bootstrapped 95% confidence intervals. Fd=Douglas-fir, Cw=western red-cedar, H=hemlocks, B=true firs. All ecosystem groups were combined for the analyses of edge effects.**

### A2.3.11 Decay rates of snags – class 5→6+

Decay of snags from class 5 to class 6+ (from hard to soft) occurred at a constant rate of approximately 0.08/yr for all DBH values of the conifers, except for lower rates for Douglas-fir in uncut stands and higher rates for hemlock in VR stands. Results for red alder are based on few class 5 snags for this species and are likely unreliable. Edge effects in decay rates for these snags were again not apparent.

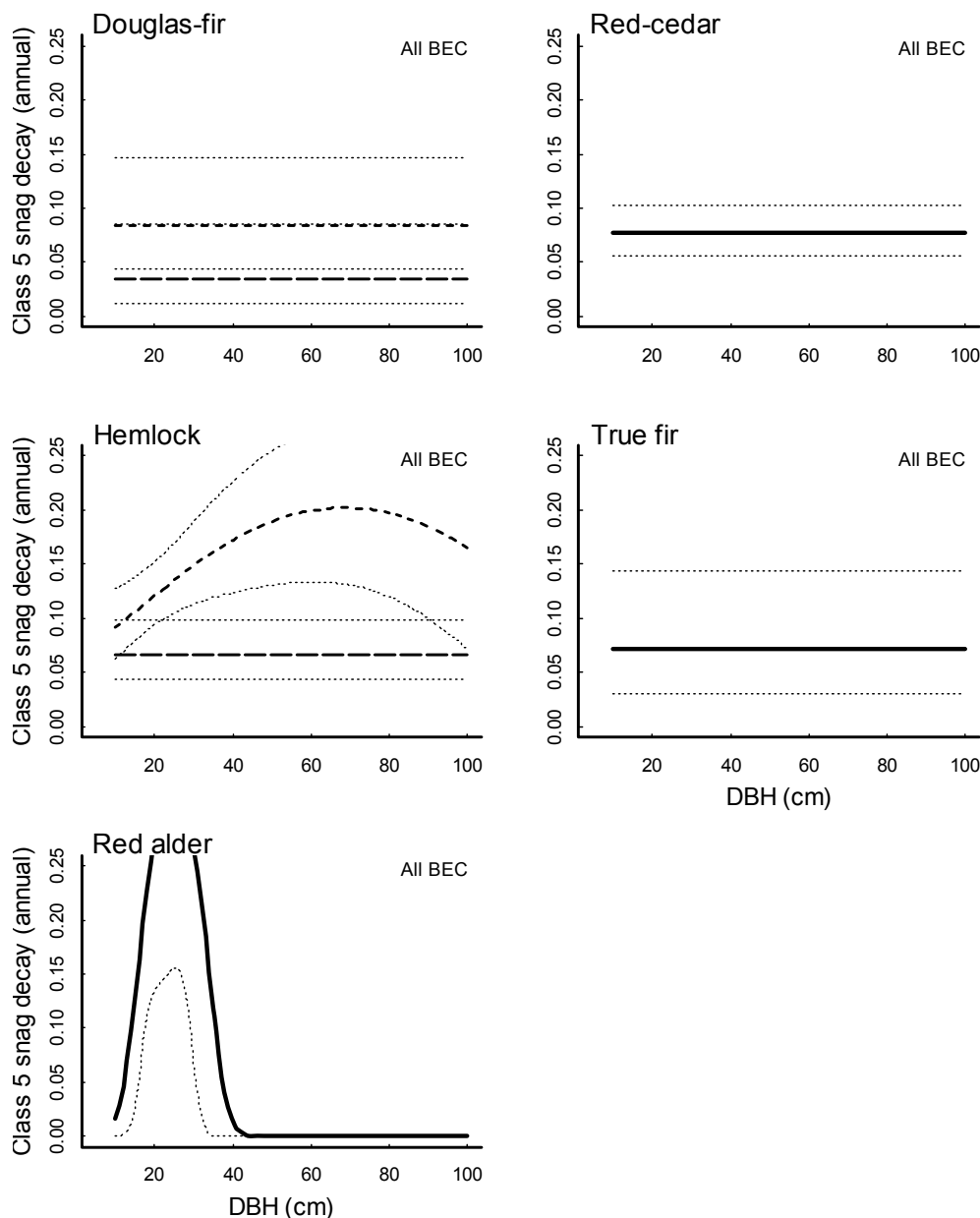
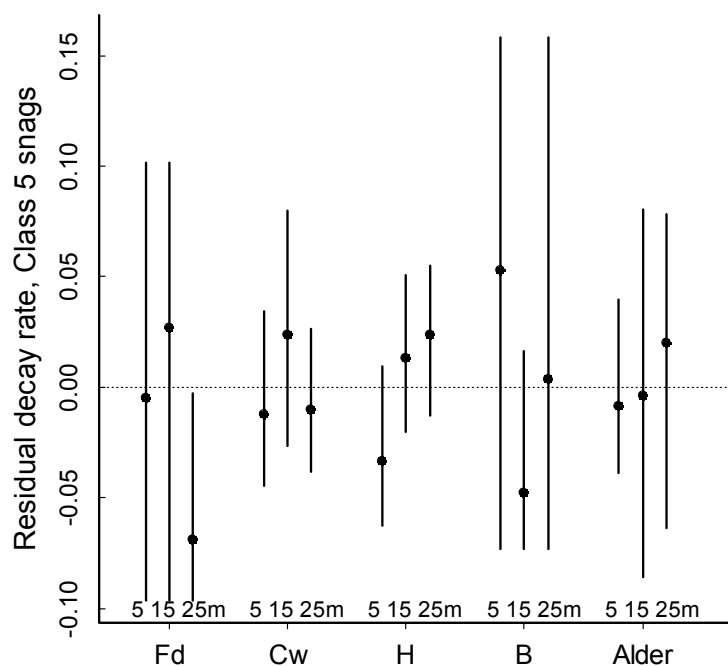


Figure A2.11.1. Annual decay rates from class 5 to class 6 snags as a function of snag DBH.

Solid line = VR blocks and mature controls combined; long dashes = mature controls only; short dashes = VR blocks. Thin dotted lines are 95% confidence intervals. "All BEC" = all 4 ecosystem groups combined.

**Table A2.11.1. Annual (%) decay rates of class 5 → class 6 snags, standardized to 40cm DBH, and exponent for power relationship for other DBH values (see text).**

Species	BEC Group	Snag decay - class 5-->6+ (%/yr)				
		Treatment	Mean	LCI	UCI	Exponent
Douglas-fir	All	UC	3.420	1.227	8.518	0
		VR	8.441	4.382	14.650	0
Red-cedar	All	All	7.715	5.622	10.333	0
Hemlock	All	UC	6.630	4.311	9.817	0
		VR	17.201	12.381	22.636	0.353
True fir		All	7.105	3.029	14.389	0
Red alder		All	1.345	0.000	75.823	

**Figure A2.11.2. Edge effects on annual decay of class 4 to class 5 snags. Values are the residual decay rates after the predictions of the best model (Figure A2.11.1) have been removed, at 5, 15 and 25+m into retention patches. Error bars are bootstrapped 95% confidence intervals. Fd=Douglas-fir, Cw=western red-cedar, H=hemlocks, B=true firs. All ecosystem groups were combined for the analyses of edge effects.**

#### A2.3.12 Combined relationships of rates with DBH

To support deadwood modeling work, the exponents of the DBH relationship for the various species, ecosystems and treatments were combined into a weighted mean, for 4 different processes: growth of live trees, mortality of live trees, fall rates of snags and decay rates of snags, and also for fall+decay of snags combined. The exponent is "X" in the equation: Rate at DBH Y = (Rate at 40cm DBH) x (DBH Y / 40cm)<sup>X</sup>. An exponent of -0.5, for example, means that the rate decreases as the square root of the DBH; an 80cm stem would have a rate 0.71 times the rate at DBH 40cm. Each of the exponents for a given process reported in the tables above was used in a weighted average, where the weight was inversely proportional to the variance of the estimate.



Live tree growth and mortality showed a slight increase with increasing DBH. Growth would be about 12% higher for an 80cm tree compared to 40cm, and mortality 10% higher. Confidence intervals of these estimates include 0, so no relationship with DBH is also feasible.

Fall rates of snags decreased on average in about inverse proportion to DBH, so that an 80cm DBH snag would have a fall rate just less than half that of a 40cm snag. Decay rates of snags, on the other hand, did not change with DBH on average. Although the rates for these two processes are quite different, with non-overlapping confidence intervals, deadwood modeling sometimes uses the same DBH relationship for both snag fall and decay. The combined rate is close to a decrease inversely proportional to the square root of DBH – with the combined rate, an 80cm snag would fall or decay at 66% the rate of a 40cm snag.

**Table A2.12. Weighted mean and standard error of exponents for the DBH relationship for 4 processes (and for snag fall+decay combined).**

Process	DBH Exponent	
	Mean	SE
Growth	0.166	0.162
Mortality	0.142	0.156
Fall	-1.054	0.327
Decay	0.018	0.246
Fall+Decay	-0.603	0.226