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# The Fate of Dead Spruce on the Kenai Peninsula

## A Preliminary Report



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**By**

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# TABLE OF CONTENTS

<b>EXECUTIVE SUMMARY</b> .....	<b>i</b>
<b>INTRODUCTION</b> .....	<b>1</b>
<b>BASIC METHODS OF THE STUDY</b> .....	<b>2</b>
<b>Location</b> .....	<b>2</b>
<b>Site and Sample Selection</b> .....	<b>4</b>
<b>DECOMPOSITION PATTERNS OF DEAD TREES</b> .....	<b>6</b>
<b>Snag Decay Classes</b> .....	<b>6</b>
<b>Log Decay Classes</b> .....	<b>6</b>
<b>RESULTS</b> .....	<b>7</b>
<b>Decay Class Ages</b> .....	<b>7</b>
<b>Salvage Considerations for Beetle-Killed Wood</b> .....	<b>8</b>
<b>Decomposition Rates</b> .....	<b>10</b>
<b>WHAT HAPPENS FOLLOWING BEETLE-KILL? A HYPOTHETICAL STAND</b> .....	<b>13</b>
<b>Carbon Storage</b> .....	<b>16</b>
<b>Future Studies</b> .....	<b>18</b>
<b>CONCLUSIONS</b> .....	<b>19</b>
<b>ACKNOWLEDGEMENTS</b> .....	<b>20</b>
<b>REFERENCES CITED</b> .....	<b>21</b>

## EXECUTIVE SUMMARY

Trees killed by beetle, fire, cutting, and the 1964 Earthquake-related flooding were sampled to determine loss of mass, volume, and soundness of wood. Preliminary estimates of the decomposition rates of primarily beetle-killed Lutz spruce trees on the Kenai Peninsula and the implications of these findings are presented. Snags created by beetle-kill (and fire and 1964 Earthquake-related flooding) have very low rates of decomposition except at their bases. Once these snags fall to the ground their decomposition rate increases and significant volume loss occurs. Based on the overall rate of decomposition estimated (1.5% per year), it would take close to 200 years for beetle-killed trees to disappear. In comparison to other species of spruce, Lutz spruce appears to have slower decomposition rates, but this is probably due to environmental and not species-related differences. Given the rates that decay penetrates dead trees, salvage would have to occur within 10 years to yield a high percentage of sound wood. Beetle-killed trees are likely to influence fire behavior and present a hazard for more than 75 years, but the nature of the hazard is likely to change significantly over this time. Based on a simple model of forest regrowth, and assuming that beetles kill an entire stand of spruce trees, it is likely that this disturbance will cause forests to lose carbon to the atmosphere for 60 to 70 years. The rate forests are regenerated would have a very large impact on the amount of carbon released during this time, and even a 20-year lag in tree establishment could double these losses.

## INTRODUCTION

The management of large dead and down trees has become a recent concern in Pacific Northwest forests, and especially in south-central Alaska where in the 1990s the spruce beetle, *Dendroctonus rufipennis* (Kirby), killed at least 3.4 million acres of Lutz, white and Sitka spruce forests (Ross et al. 2001). This outbreak has been most severe on the Kenai Peninsula and although the massive beetle outbreak has largely subsided, the level of tree mortality in affected forests is high, often exceeding 90 percent of the overstory (Ross et al. 2001).

Despite the large volume of dead wood created by beetle-kill (Van Hees 1992), we know very little about the fate of these dead trees. In the spruce forests of Alaska as much as 50 percent of the beetle-killed trees will still be standing after 16 years (Holsten et al. 1995). In addition, 20 years after a spruce beetle outbreak on the Kenai Peninsula, there was significantly more sound, dead wood (more than 3 inches in diameter) compared to uninfested areas (Schulz 1995). But the rate this material is decomposing, the length of time it will remain standing, and the time required for the majority of this wood to decompose, is not known.

Changes in the amount of dead wood in any forest influence a range of ecosystem characteristics important to management. Beetle-killed trees increase fuel loading and the related degree of fire hazard, increase the difficulty of fire control, influence nutrient cycling, and create wildlife habitat. The presence of beetle-killed trees represents a possible timber resource for a period of time after the attack, but eventually this material becomes unsalvageable. Dead wood also influences the overall carbon balance of the ecosystem in relation to the atmosphere.

In the past, the typical management step would be to remove and dispose of as much beetle-killed material as possible. However, that is not always economically feasible and this limitation coupled with new knowledge of the ecological roles that dead trees play in forested ecosystems suggests removal and disposal needs to be selectively targeted. We know, for example, that dead wood is associated with many ecological functions (plant and animal habitat, nutrient and water storage, and soil formation). These benefits all vary with the species of logs, the environment, and the volume of dead wood on a site (Franklin et al. 1987, Harmon et al. 1986, Triska and Cromack 1980, Harmon 2001). However, it is also clear that the scale and intensity of the current beetle outbreak is having a major ecological impact on the forest ecosystem. Fuel levels in the affected forests are extremely high and continuous over large areas. Also, the input of woody debris into stream channels will be changed for many years to come (Ross et al. 2001).

An essential component of managing dead wood in forested ecosystems (including those in Alaska), is the recognition that dead wood levels are controlled by a series of dynamic processes (e.g., input and decomposition) and that this resource requires long-term planning. A key to managing dead wood dynamically is having an understanding of the rate at which this material decomposes. Given this information managers can plan the silvicultural practices required to remove or add trees to maintain dead wood at desired levels. Unfortunately, decomposition rates have been determined for very few species and mostly in the Pacific Northwest where the main

species that have been sampled are Douglas-fir and Western hemlock (Graham 1982, Grier 1978, Means et al. 1985, Sollins et al. 1987). In 2002 we initiated a multi-phase study on the decomposition of beetle-killed Lutz spruce trees on the Kenai Peninsula. The objective of the first phase of this study was to determine, by the chronosequence method (Harmon et al. 1999), the rate at which Lutz spruce logs and snags decompose. This report describes the overall study and presents preliminary data on the changes these trees undergo as they decompose, the rate salvagable volume is lost, and time for this material to decompose. We also present preliminary estimates of how this dead wood will influence the carbon balance of these forests.

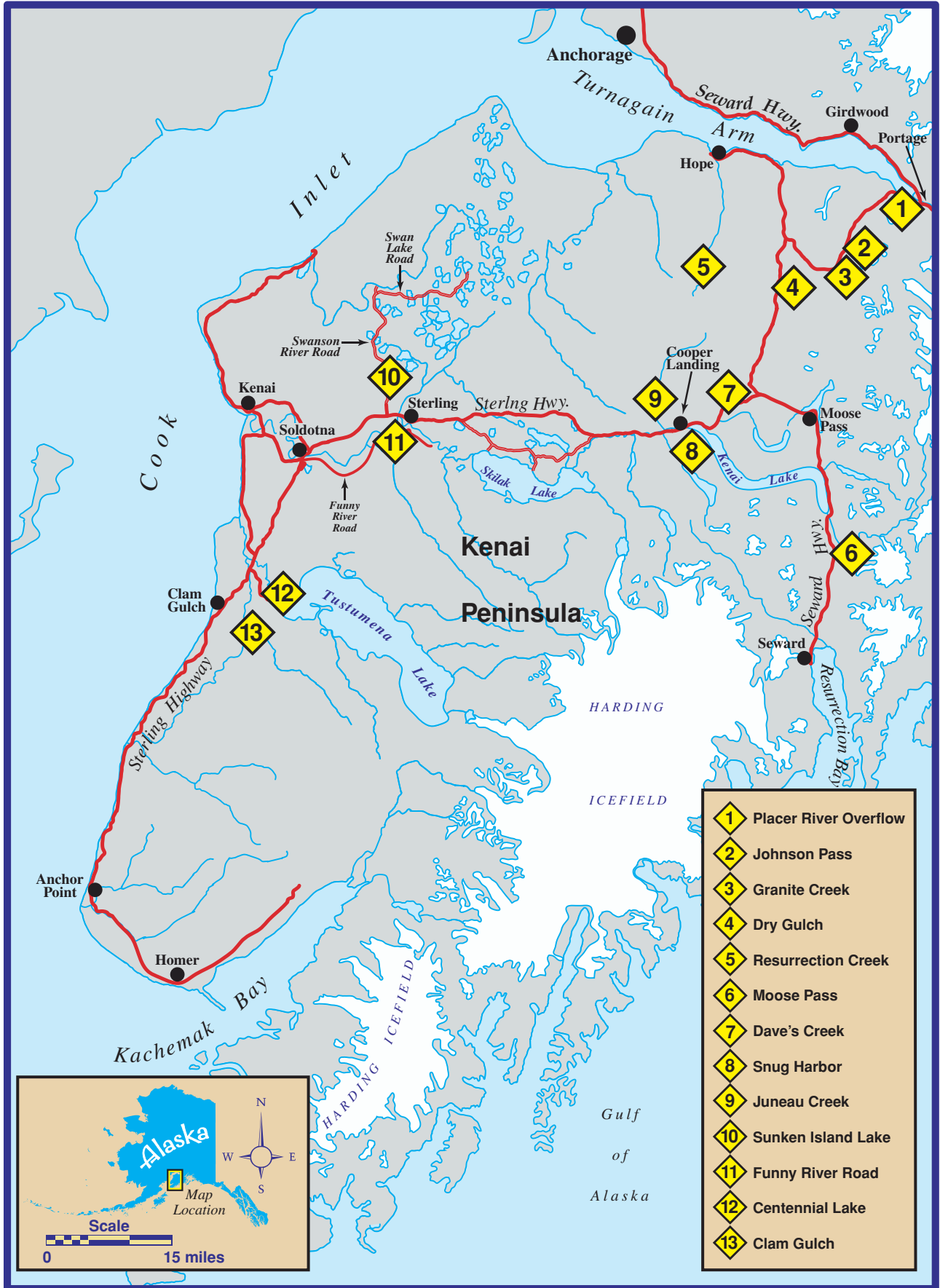
## BASIC METHODS OF THE STUDY

There are several methods that can be used to determine the decomposition and decay patterns in dead trees. Possibly the best method is a “time series” which examines a set of trees over time to determine how they change. Unfortunately this approach takes a great deal of time, perhaps hundreds of years (Harmon 1992). An alternative approach is a “chronosequence” which measures, at one time, trees that were killed at various times. In our study we used the chronosequence approach to determine decomposition rates of trees that remained vertical (snags) and trees lying on the ground (logs). In this chronosequence study, stands of dead trees were chosen based on the time since death. Wood and bark density were measured to determine the change over time. While this method is not as precise as a time series experiment (where individual pieces are followed through time) it provides an excellent first approximation of decomposition rates (Harmon et al. 1999).

### Location

The study was conducted on the Kenai Peninsula of Alaska on federal lands, including the Chugach National Forest and on Alaska State-managed lands (Figure 1). The maritime climate of the Peninsula supports a temperate, coniferous rainforest. The drier and colder climate inland from the coastal mountains supports forests dominated by white spruce (*Picea glauca* (Moench) Voss), black spruce (*Picea mariana* (Miller) Britt), and paper birch (*Betula papyrifera* Marsh). A fertile hybrid of white spruce and Sitka spruce (Lutz spruce, *Picea x lutzii* Little) is a common tree in maritime and mountainous areas of the Kenai Peninsula. The topography of our study area varies from lowlands to foothills. The lowlands of the Kenai Peninsula are a glaciated surface with gentle relief and a mean elevation of approximately 1000 ft. Throughout most of this lowland, glacial till is overlain by deep glacial lake and fluvial sediments and is mantled with loess. Our base of operation was in Cooper Landing. The Alaska Climate Research Center (ACRC) climatic summaries indicate the Cook Inlet Climatic Division, which represents much of our study area has a mean annual temperature of approximately 34 degrees (F) and annual precipitation 24.8 inches. Two specific climatic stations on the Kenai Peninsula, Homer and Kenai have long-term average temperatures of 38 degrees and 34 degrees, respectively. The same two stations have long-term annual precipitation averages of 25 and 19 inches, respectively.

Figure 1. Location of sample plot sites on the Kenai Peninsula.



## Site and Sample Selection

Field sites were selected to cover the full range of decomposition states (decay classes) and ages for logs and snags. As a preliminary screening, Forest Service records and local knowledge were used to identify forest stands that had been killed by beetles, earthquakes, or fire at a known time. Candidate sites were then examined in the field to judge if sufficient material existed to sample. Also sampled were trees within permanent plots established in Dry Gulch (Holsten 1984) and Resurrection Creek (Werner and Holsten 1983). Twenty-one plots within 13 sites were sampled for snags and logs with a total of 226 trees sampled. We were able to determine the time since death for 205 of 226 logs and snags. The dating of logs relied on local records of catastrophic events, data from permanent growth and yield plots, the age of young stands regenerating after a disturbance, and by examining the date of release from surviving trees.

In each study site we sampled snags or logs covering the full range of decomposition stages in Lutz spruce present at that site. The selected coarse woody debris (CWD) pieces were categorized into one of five decay classes based on visual characteristics linked to the degree of decomposition: the presence of leaves, twigs, branches, bark cover on branches and bole, sloughing of wood, collapsing and spreading of log (indicating the transition from round to elliptical form), friability or crushability of wood, color of wood, and mobility of branch stubs (Triska and Cromack 1980, Graham and Cromack 1982, Sollins 1982, Harmon and Sexton 1996). Biological indicators of decomposition such as moss cover, presence of fungal fruiting bodies, and the presence of insect galleries were also noted. In addition, at each site we sampled green trees to determine initial densities. Dimensions recorded for each tree sampled include total length, base and top diameters, and current DBH.

Most of the selected logs and snags were divided into five sections of similar length, and four cross-sections were cut. If the sampled log was short (e.g., in more advanced decay classes), it was divided into only three or four sections. The diameter at both ends of each section was recorded within 1 cm, and the section length and total tree length were recorded within 10 cm. From the end of each section, a disk (cross-section sample) was cut with a chainsaw to determine the density of wood and bark. The outermost diameter, longitudinal thickness, radial depth of rot, and radial thickness of bark were measured at four points on each disk to 0.1 cm and averages for each disk were calculated. Bark was separated from wood and the wet weight of each tissue was determined. Bark and wedge-shaped wood sub-samples (~100 g) were taken from each disk, weighed, placed in cloth bags, and air-dried to stop decomposition. All wet sample weights were measured in the field on a portable electronic scale to 0.1 g. Dry weights of sub-samples were determined in the laboratory after oven drying at 55°C to a constant weight (to 0.01g). The dry weight of wood and bark for each disk was calculated from the wet weights of these tissues and the ratio of dry-to-wet weight determined from the sub-sample. The density of the disk was calculated as the ratio of its dry weight to green volume (g/cm<sup>3</sup>).



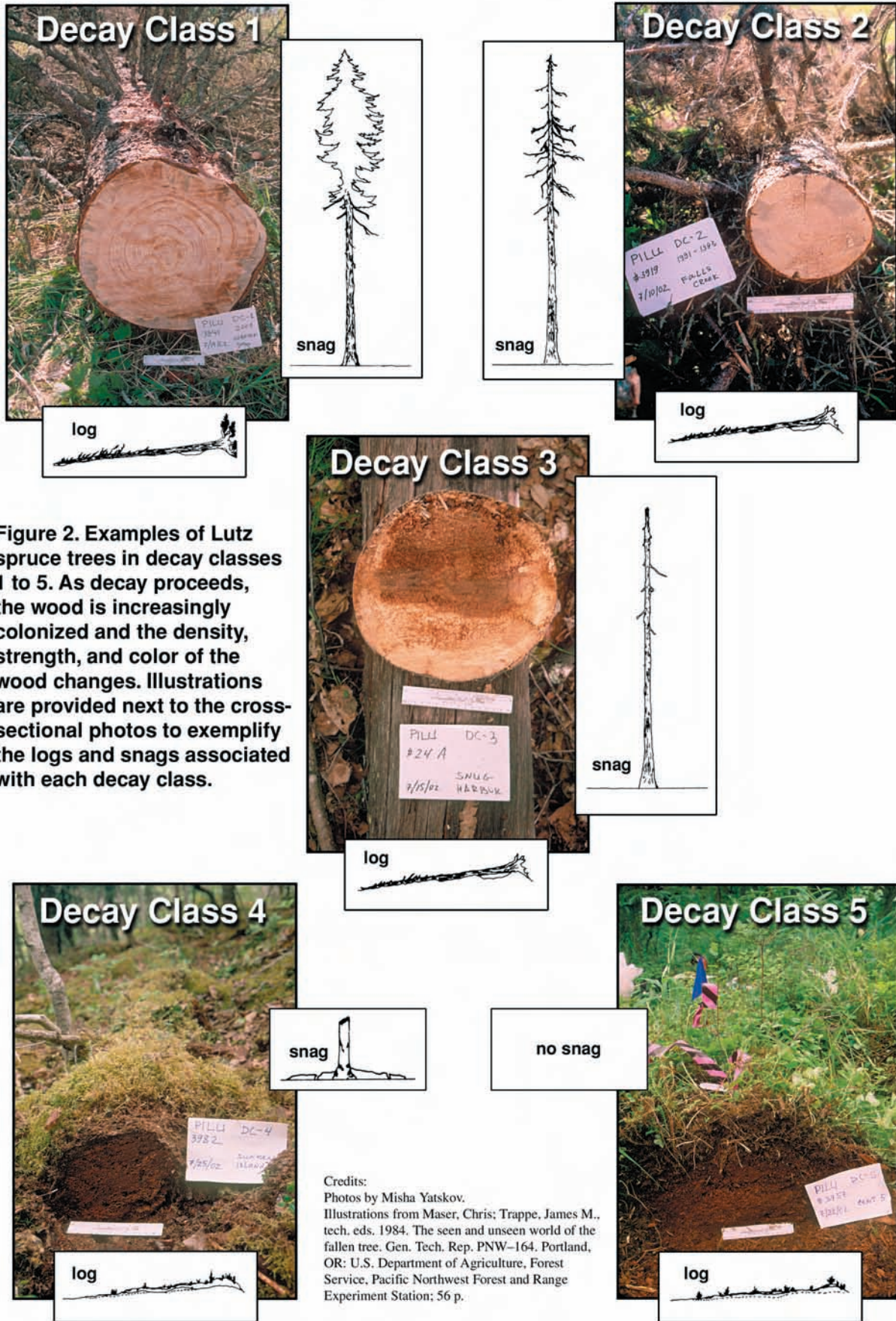


Figure 2. Examples of Lutz spruce trees in decay classes 1 to 5. As decay proceeds, the wood is increasingly colonized and the density, strength, and color of the wood changes. Illustrations are provided next to the cross-sectional photos to exemplify the logs and snags associated with each decay class.

Credits:  
 Photos by Misha Yatskov.  
 Illustrations from Maser, Chris; Trappe, James M.,  
 tech. eds. 1984. The seen and unseen world of the  
 fallen tree. Gen. Tech. Rep. PNW-164. Portland,  
 OR: U.S. Department of Agriculture, Forest  
 Service, Pacific Northwest Forest and Range  
 Experiment Station; 56 p.

To account for fragmentation and volume losses we gathered information to reconstruct the original tree volume from bole length and DBH either measured directly or after reconstruction in the field. Several methods were used for the latter purpose. For pieces missing bark at breast height, DBH was adjusted using bark/wood thickness ratios from other parts of the bole. For boles with missing bark and some wood fragmentation, DBH without bark, missing bark thickness, and radial thickness of missing wood were estimated (Harmon and Sexton, 1996). The original volume was determined using local volume tables based on the DBH and height of undecayed trees. The current mass of each log or snag was compared with its estimated initial mass to determine decomposition rates. The original total mass was calculated using the density and volume of undecayed wood and bark.

## **DECOMPOSITION PATTERNS OF DEAD TREES**

After trees die they undergo a continuous transformation from completely sound to completely decayed material. This continuum is often divided into discrete decay classes that are useful for inventorying the amount and quality of the dead wood as well as roughly determining the time the wood has been dead. In the system we used, decay class 1 is the least decayed and class 5 is the most decayed (Figure 2). A brief description of these decay classes for snags and logs follows.

### **Snag Decay Classes**

Decay class 1 snags are the least decomposed, with most having needles still attached and all having intact bark, fine twigs and branches. Any wood exposed by woodpecker activity has not turned gray due to sun bleaching. Decay class 2 snags are starting to decompose, needles are absent, and many of the fine twigs have fallen off the larger branches. Bark is typically loose and starting to fall off the snag. There is evidence that the surface layers of the wood are decomposing, but the inner, central region of the wood is undecayed unless previously infected with heart rots. Any exposed wood may be gray from sun bleaching. Decay class 3 snags have only a few large branches remaining, often in the form of stubs, the bark is falling off in large patches or completely removed, and evidence of sloughing of sapwood is also evident. The outer wood is easily crushed by hand, although the inner portions can be completely sound. Snags were usually not found in a decay class 4 or 5 condition as the wood is sufficiently decayed to be unable to support itself. For those wanting to match the classification system of Lowell and Willits (1998), the system presented here starts with their class 2 and their class 4 is roughly equal to our class 3.

### **Log Decay Classes**

The pattern of decomposition observed for Lutz spruce logs was quite similar to that of white fir in the California Sierra Nevada Mountains (Harmon et al. 1987). Decay class 1 logs are formed by disturbance such as windthrow or cutting. For the sake of completeness we include them. As with decay class 1 snags, they are least decomposed, with most having needles still attached and all having intact bark, fine twigs and branches. Logs originating from cutting may not have

branches and twigs, however, and the cuts appear fresh and have not yet been bleached gray by the sun. Decay class 2 logs lack needles, and many of the fine twigs have fallen off the larger branches. Bark is typically loose, but only starting to fall off the log. There is evidence that the surface layers of the wood are decomposing, but the inner, central region of the wood is undecayed, unless previously infected with heart rots. Decay class 2 logs can be formed from beetle-killed trees that have decomposed at their base and fallen over. For logs originating from cutting, the ends are bleached gray. Decay class 3 logs have only a few large branches remaining, often in the form of stubs, the bark is falling off in large patches, and sloughing of the sapwood is also evident. The outer wood is easily crushed by hand, although the inner portions can appear completely sound. Despite the large amount of decay, Decay class 3 logs are able to support their own weight along most of their length. Decay class 4 logs are very decayed, unable to support their own weight, and most of their length conforms to the contours of the underlying ground. Although circular cross-sections can remain, much of the log forms an elliptical cross-section. Branches, if present, are short stubs, that move when pulled. This indicates decay has spread to the innermost portions of the log and has weakened the wood considerably. Bark, if present, is in small loose patches on the log and found in piles alongside or under the log. Decay class 5 logs are the most decomposed, of elliptical shape (the long axis is often many times that of the short axis) and are beginning to be incorporated into the forest floor. The wood is extremely decayed, usually in the form of cubical brown rot that can be easily crushed by hand. Bark is not evident from the surface, however, in most cases bark underlies the extremely decomposed wood. After the decay class 5 stage some wood is incorporated into the organic soil layer.

## RESULTS

### Decay Class Ages

The mean age of the decay classes increased with age for both logs and snags (Table 1). For example, decay class 1 logs and snags averaged 6 years of age, whereas decay class 4 logs and decay class 3 snags averaged 40 years of age. As a rough guide, the time trees stay in a decay class nearly doubles from one decay class to the next higher class.

The current log density (not adjusted for fragmentation losses) decreased with the decay classes for bark, wood, and tissues combined (Table 2).

Decay Class	Position							
	Logs				Snags			
	Mean	Min.	Max.	N	Mean	Min.	Max.	N
1	6.2	2	11	6	4.1	1	13	21
2	13.2	3	32	32	14.7	3	32	38
3	24.5	13	43	59	40.5	38	43	10
4	39.7	33	43	9				
5	76.0	76	76	20				

**Table 2. Mean density (g/cm<sup>3</sup>) of log bark and wood sampled for each decay class.**

Decay Class	Log					
	Bark			Wood		
	Mean	Std. Error	N	Mean	Std. Error	N
1	0.320	0.006	65	0.387	0.006	65
2	0.254	0.005	118	0.366	0.004	125
3	0.206	0.004	175	0.265	0.006	228
4	0.195	0.014	24	0.153	0.006	88
5				0.103	0.003	78

The current density of snags, however, decreased for bark, but slightly increased for wood possibly indicating that excessive drying of snags resulted in volume shrinkage (Table 3). Overall declines in tree density for snags are similar to those of wood (Table 4).

**Table 3. Mean density (g/cm<sup>3</sup>) of snag bark and wood sampled for each decay class.**

Decay Class	Snag					
	Bark			Wood		
	Mean	Std. Error	N	Mean	Std. Error	N
1	0.361	0.012	81	0.387	0.009	81
2	0.296	0.011	135	0.411	0.006	141
3	0.247	0.012	2	0.421	0.028	35

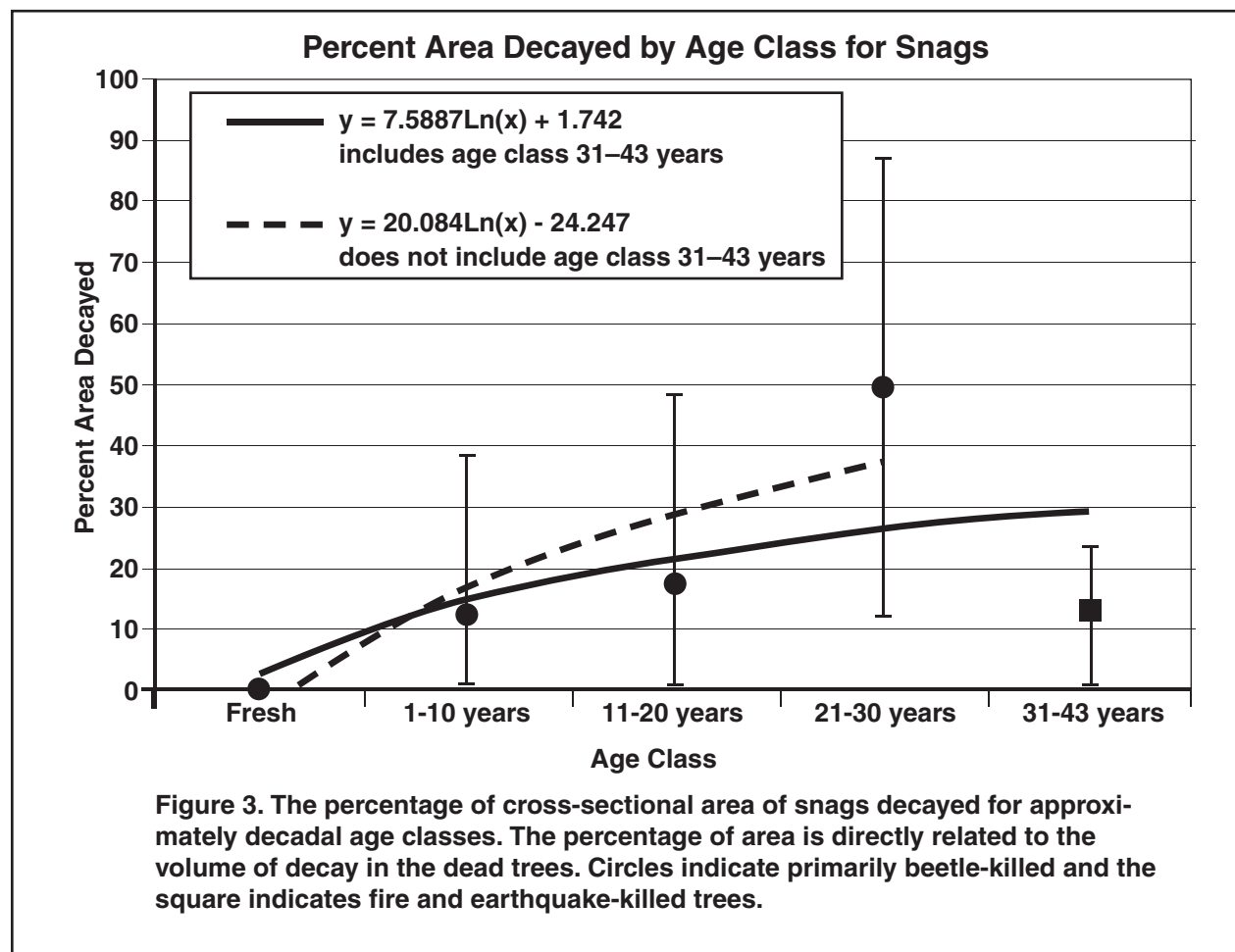
**Table 4. Mean density (g/cm<sup>3</sup>) of combined wood and bark sampled for each position and decay class.**

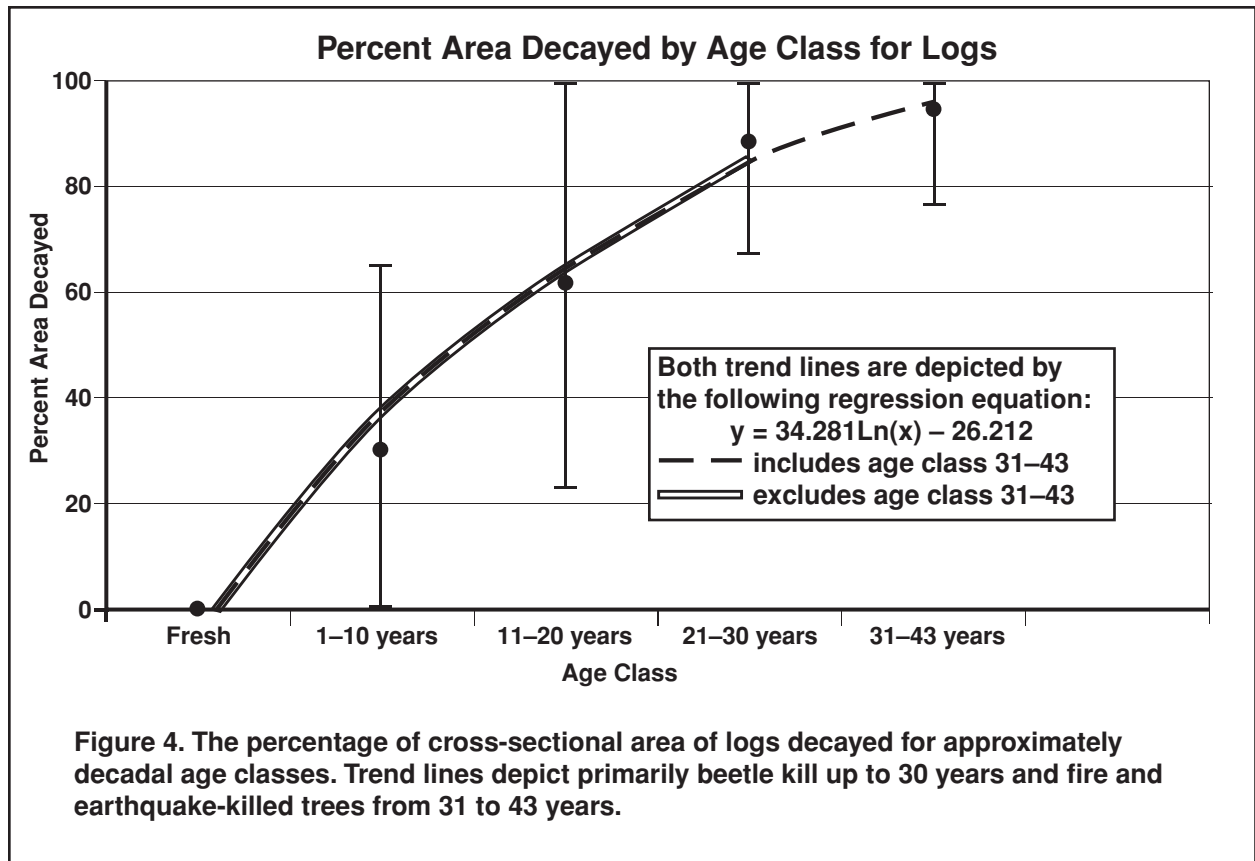
Decay Class	Position					
	Logs			Snags		
	Mean	Std. Error	N	Mean	Std. Error	N
0	0.370	0.005	86	0.370	0.005	86
1	0.353	0.005	130	0.374	0.005	162
2	0.311	0.005	243	0.355	0.005	276
3	0.239	0.004	403	0.411	0.014	37
4	0.162	0.006	112			
5	0.103	0.003	78			

### Salvage Considerations for Beetle-Killed Wood

Related to the pattern of decomposition is the length of time that beetle-killed trees can be salvaged. The degree of decay acceptable will probably depend on the ultimate use. For example, for pulping purposes, the degree of decay does not appear to have a great deal of effect (Wer-

ner et al. 1983, Scott et al. 1996, 2000). In contrast, for structural timbers the amount of decay acceptable is probably minimal if high economic value is desired (Lowell and Willits 1998). Our data indicate that after 30 years for some snags the fraction of decayed volume might be under 30% (Figure 3). In contrast, for logs of a similar age, at least 70% would be decayed (Figure 4). However, for both snags and logs there is a great deal of variability from tree to tree unless undecayed or extremely decayed trees are considered. For example, for logs 10 to 21 years of age, it is possible to have as little as 25% and as much as 100% decayed volume in a tree. For snags of the same age class, it is possible for there to be either no decay or for there to be up to 50% decayed volume. Assuming that less than 25% decay volume would be acceptable, salvage of most trees would need to occur within 10 years. Penetration of decay was very irregular along the stem, in radial pattern and from tree to tree. As a rough guideline, the rate of decay penetration in snags ranged from 0 to 0.25 cm per year over the first 20 to 30 years. The maximum rate is likely to be observed in the first 2 m of height due to bark beetles infesting the lower, larger portions of the bole. For logs the range of decay penetration was 0.25 to 0.50 cm per year over the first 20 to 30 years. In logs, the smallest diameter sections are likely to be fully colonized by decay organisms before the large diameter ones.





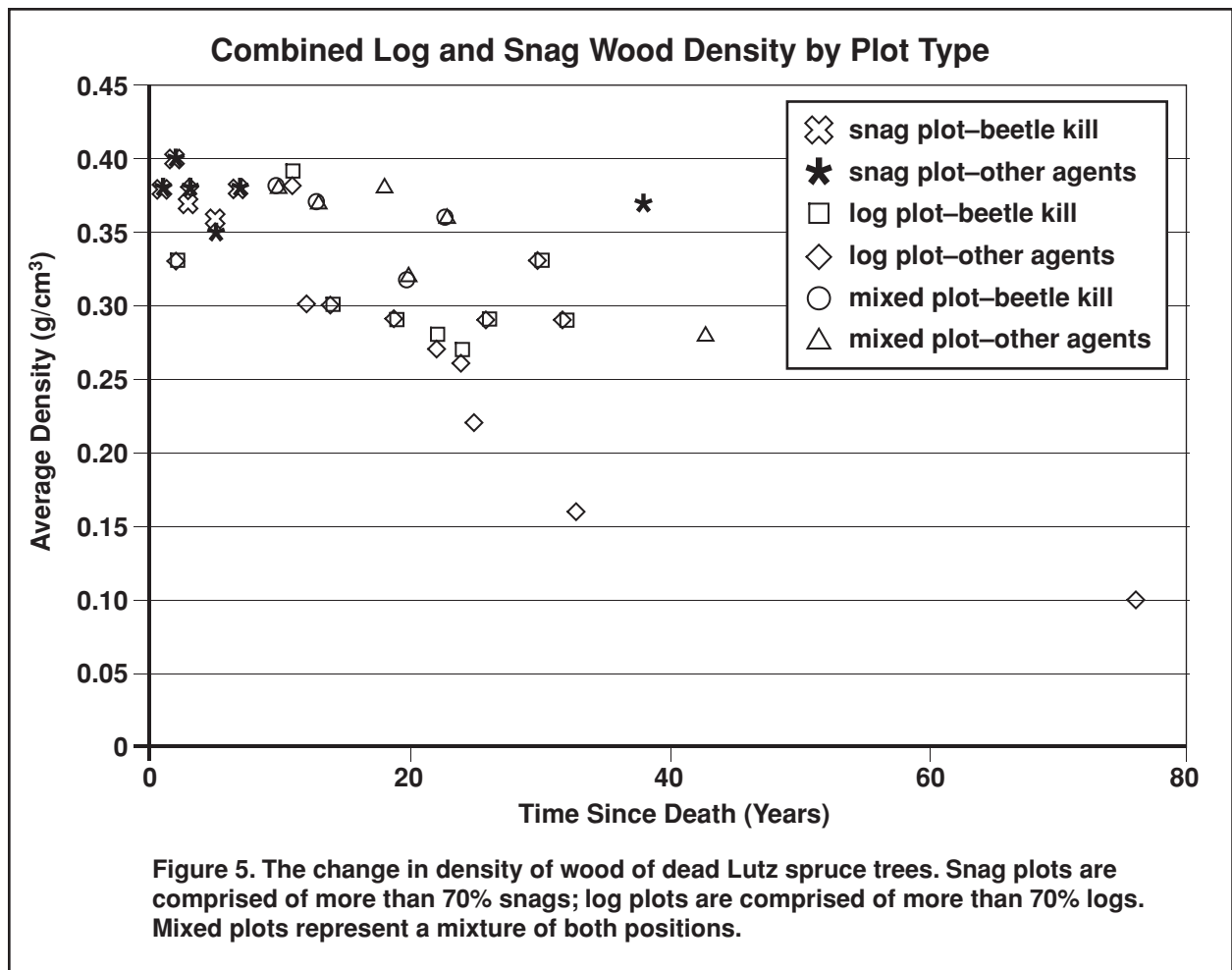
## Decomposition Rates

From the rates calculated, it would appear that snags have very slow decomposition, whereas logs have decomposition rates typical of species of the Pacific Northwest. The long-term decomposition rate was 0.019 per year (or roughly 1.9% per year) for logs and 0.000 per year for snags. This indicates that beetle-killed tree decomposition is minimal (except at the base) until the trees fall to the ground. The average decomposition rate of Lutz spruce snag and log wood combined was 0.015 per year (or roughly 1.5% per year), with the rate being slower in the early years and faster in the later years (Figure 5). This would mean that it might take as long as 200 years for 95% of these beetle-killed trees to disappear.

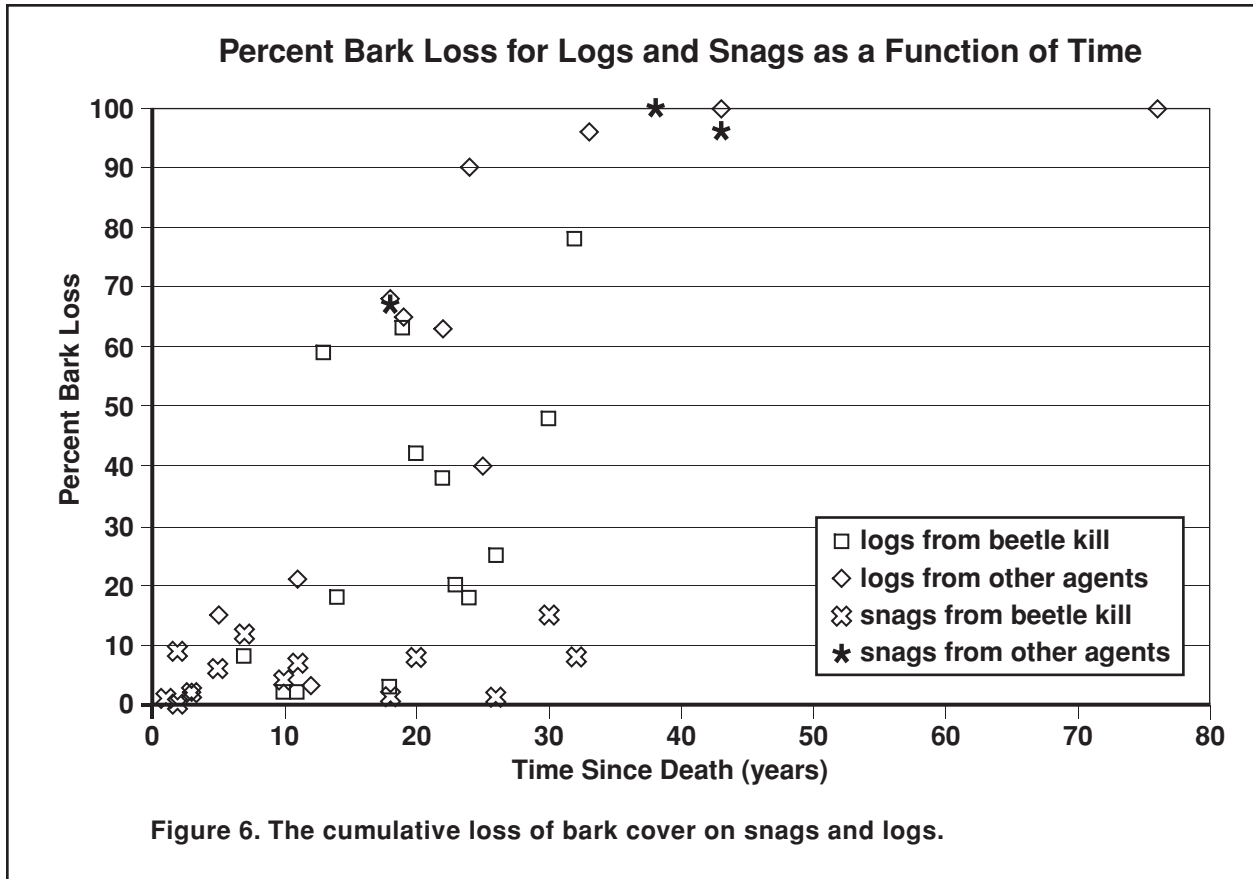
The decomposition rate of Lutz spruce appears to be slower in comparison to other species of spruce. For example, spruce in Europe and Asia have a decomposition rate of 2.6% to 4.8% per year (Yatskov et al. 2003). At Fraser Experimental Forest in Colorado, Englemann spruce (*P. engelmannii*) was estimated to have a decomposition rate of 2.8% per year (Harmon et al. in prep). On the coast of Oregon and Washington Sitka spruce (*P. sitchensis*) decomposition rates of 1.8% and 1%, respectively, were estimated (Harmon et al. in prep, Graham and Cromack 1982). The cause of the decomposition rate difference may be the colder temperatures on the Kenai Peninsula, although temperatures are likely to be equally cold in Russia and Norway. It is more likely that excess moisture of logs on the ground is slowing decomposition as the sites with the slowest decomposition rates are also the wettest. While the Kenai Peninsula does not have

the precipitation of coastal Oregon and Washington, it is colder and this may make it effectively just as wet.

Relative to conifer species within the Pacific Northwest region, Lutz spruce appears to decompose only slightly slower. Douglas-fir, perhaps the most studied species to date, has a decomposition rate constant of 0.01 to 0.05 per year (Sollins et al. 1987, Edmonds and Eglitis 1989). The higher value may be an anomaly as the log length in this study was 1 m, a length subject to substantial end rot. More typical values for this species would be 0.015-0.02 per year (Harmon and Chen 1991). Lodgepole pine, had a decomposition rate constant of 0.027 per year on a much drier site with 28 cm (11 inches) of annual precipitation in Central Oregon (Busse 1994).



Bark fragmentation appears to occur immediately following beetle-kill in some trees and by 40 years all bark seems to have been lost from both snags and logs (Figure 6). This would suggest a bark loss rate of 8% per year. Early losses in bark are most likely associated with woodpecker activity.



While we were not able to estimate an exact rate of snag fall from our data, the mixture of snags versus logs in stands of various ages indicates that most snags fall to the ground within 40 years, suggesting an average fall rate of 8% per year. This is higher than 4% per year indicated by Holsten et al. (1995) however, the results of the latter study are dominated by the earliest phases of decomposition when few snags fall. It is likely that all snags in this environment stand for up to a decade, and then begin falling at an annual rate of 10% per year once the base decays to the point that it can not support the weight of the upper crown.

Most of the sampled trees were killed by bark beetles less than 3 decades ago. Thus, to extend the chronosequence beyond 30 years, we also sampled trees that were cut in right-of-ways, fire-killed, and trees that died from salt water inundation during the 1964 earthquake. While it is likely that the cause of death influences both the decomposition rate and deterioration patterns, this is not clearly proven with the current data set.

Data indicate, however, that there are decomposition rate differences between logs (fallen trees) and snags (trees that died standing). For trees that are on the ground immediately following death, such as cut or windthrown trees, decomposition progresses rapidly. Those that die standing appear to have a lag period of 10 to 40 years before decay accelerates.



Lag period differences for snags killed by various agents are difficult to judge with the data we have. However, we can speculate on what may cause those differences. While beetle-killed, fire-killed, and trees killed in the aftermath of the 1964 Earthquake may all be exposed to full sunlight following tree death, beetle-killed trees in areas with partial canopy mortality may have a slower drying process. Also in beetle-killed stands, the presence of understory plants may ameliorate high temperatures at these sites.

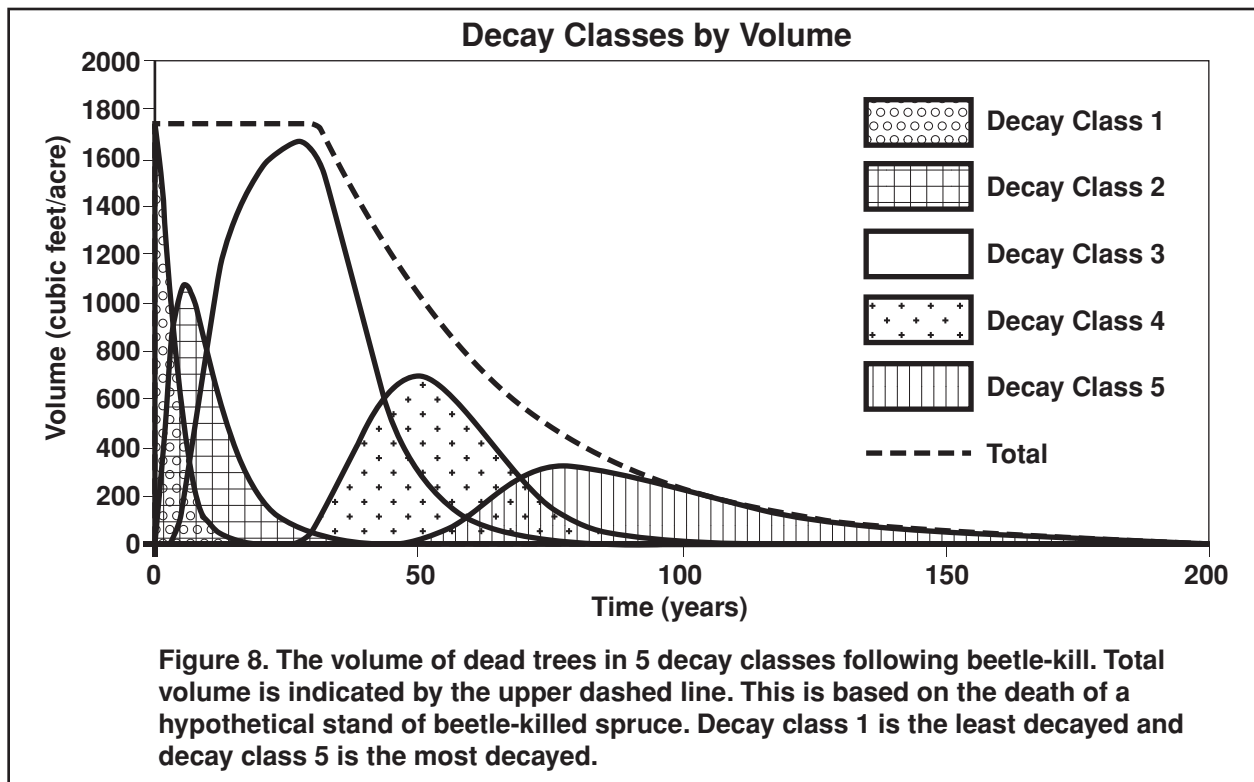
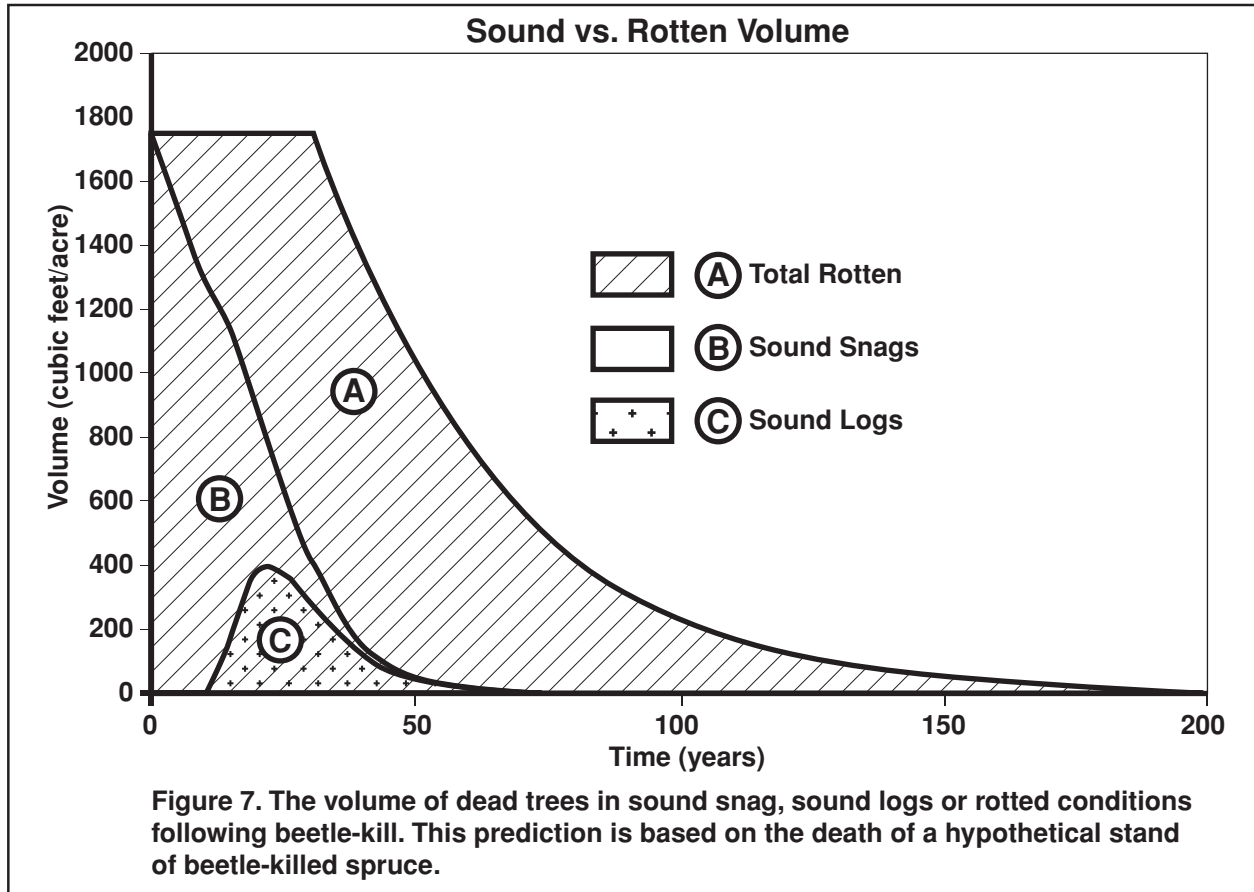
Since the interaction between moisture and temperature drives the decomposition process, it is therefore likely that fire-killed trees and trees killed as a result of the 1964 Earthquake dry out faster and thus decompose slower than beetle-killed trees (Figure 3). In the case of trees killed as a result of the 1964 Earthquake, decomposition may be further slowed due to continual inundation by salt water in low lying areas.

Decay fungi that invade logs and snags may be fairly similar regardless of mortality agent, except in the case of trees killed by salt water inundation in the 1964 Earthquake. The presence of salt likely changes the wood habitat and may exclude some fungi from invading this material. Further investigation is warranted to test the fungal communities of logs and snags from various mortality agents.

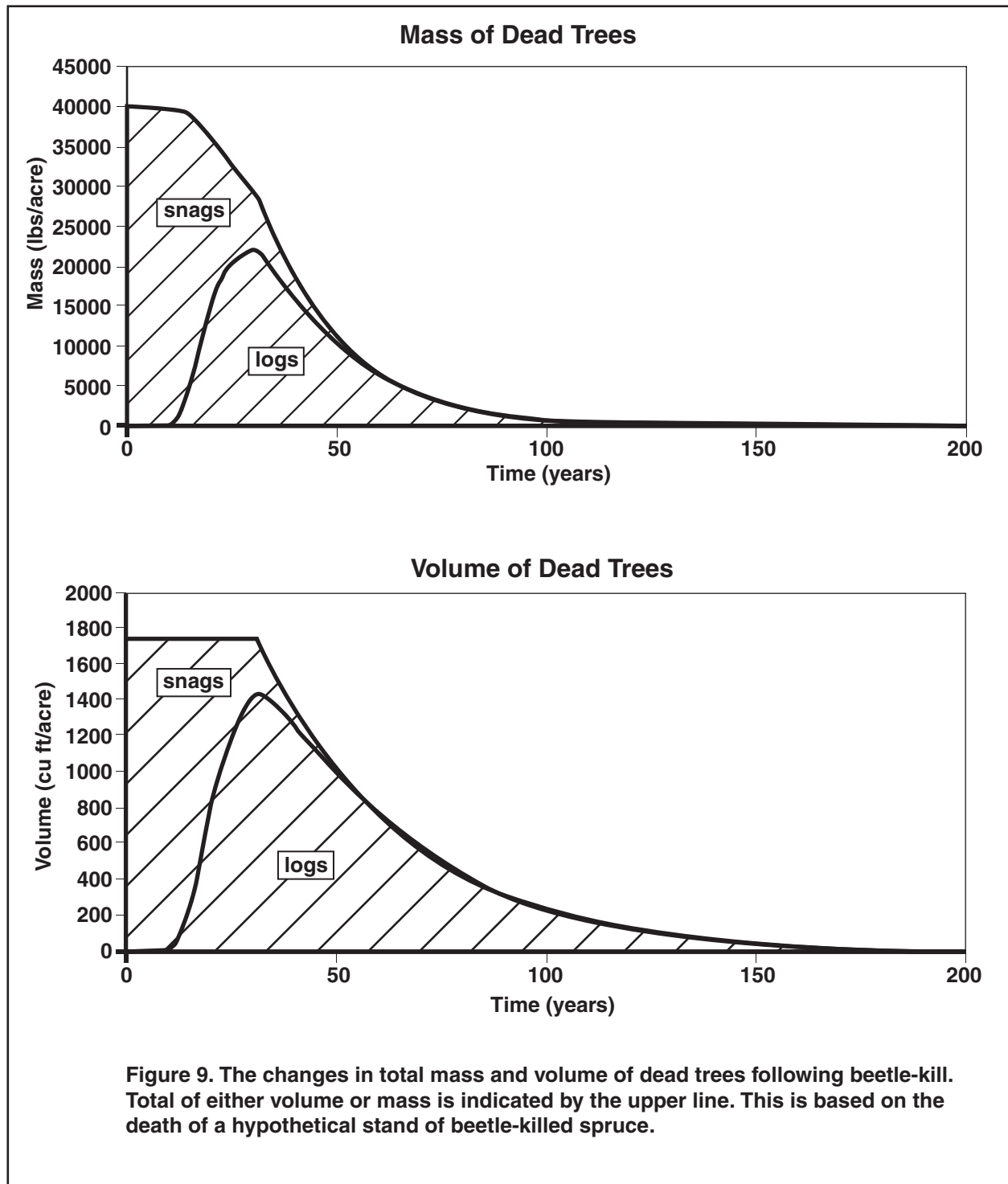
## **WHAT HAPPENS FOLLOWING BEETLE-KILL? A HYPOTHETICAL STAND**

We can use our data to envision what would happen to a stand of trees killed by bark beetles on the Kenai Peninsula. We assumed that the initial stand of trees containing 1746 cubic feet of spruce wood per acre that was entirely killed by beetles in a few years (van Hees and Larson 1991). Given our estimated rates of snag fall, volume loss, and progression of decay, the stand would initially be dominated by sound snag wood (Figure 7). Within 10 years these snags would begin to fall and create primarily sound logs, although rotten logs would also be present. There would be far less volume in sound logs than sound snags, however, and within 40 years most of the beetle-killed trees would be decayed and unsalvageable for most uses. After this point we would anticipate that the volume of beetle-killed trees would steadily decline and by 150 years would probably not be detectable.

We would also expect to see a progression in the decay classes that are present following beetle-kill (Figure 8). Interestingly, the volume of decay class 2 is likely to be the least abundant following the beetle-kill, because it stays within that decay class relatively little time compared to decay class 3 (i.e., 15 versus 30 years) and while decay classes 4 and 5 last longer than decay class 3, they are undergoing significant fragmentation. The process of fragmentation would begin during decay class 3 and continue until the logs are completely incorporated into the organic soil layer.



Changes in the mass of dead trees would probably be similar to that of volume, with the exception that the lag before loss began would be about 15 years for mass and 30 years for volume (Figure 9). Mass is probably the parameter most related to fire control and hazard. The most dangerous stage in terms of fire is probably in the first decade following beetle-kill, not because of the presence of snags, but because of the positive response of flammable grasses in areas

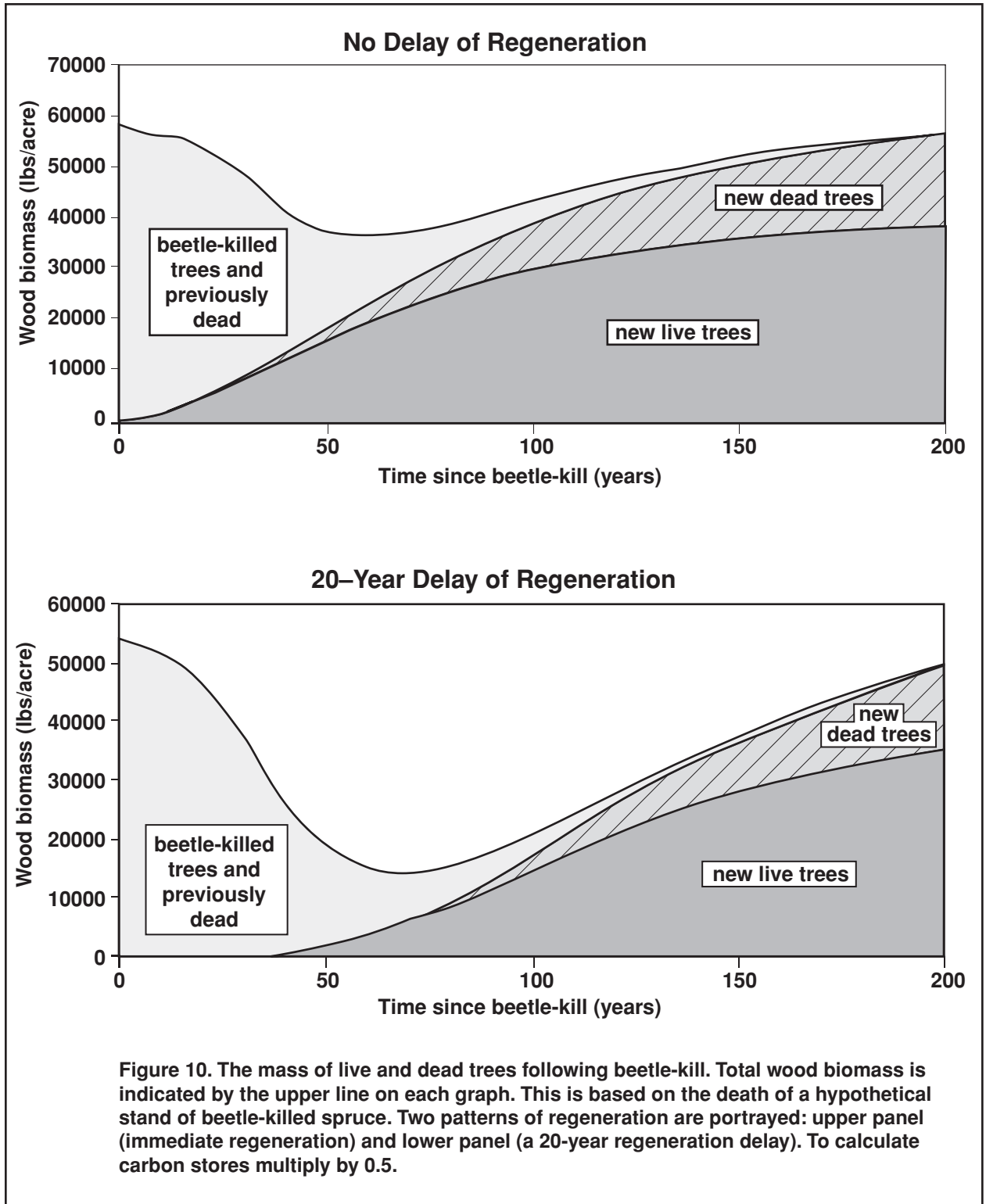


of canopy openings (Schulz 1995). By 20 to 40 years, much of the mass of dead trees would be in the form of logs, most likely becoming the most difficult stage in terms of fire control. Here the logs would be decayed enough to sustain fire and arranged in a manner that would probably allow them to burn independently of fine fuels, but would be solid enough to be difficult to cut and remove. There would be little motivation to remove these logs as they would be of little economic value. As the stand ages, not only would the mass of material decrease, but the ability of this wood to hold water should increase. This material would still pose a fire hazard because once it dries, it would be capable of smoldering for a long period, thus making fire mop-up difficult. Based on our data it would probably take at least 75 years for coarse woody fuel loadings to approximate those found in forests undisturbed by bark beetle.

## **Carbon Storage**

Currently there is a great deal of interest in understanding how the carbon stored by forests is influenced by disturbances (Randerson et al. 2002, Alden 2001). Our data, when combined with data on stand growth, can provide some general indication of the expected trends. Assuming again that the stand initially contained 1746 cubic feet of spruce wood per acre and was entirely killed by beetles in a few years, we can evaluate several possible scenarios: 1) if stands regenerate rapidly after the disturbance and 2) if there is a 20-year delay in regenerating the stand.

We assumed that after the stand regenerated, it took 150 years to reach the pre-beetle-kill live volume. Given that the new stand also has trees that are dying we assumed that 0.5% of these trees died each year to form new dead wood. In addition to the trees killed by the bark beetles there would be a pool of dead wood that existed prior to the disturbance and we assumed this material decomposed similarly to logs. The total wood carbon stores over time would therefore be the sum of all these pools. This simple model indicates that beetle-killed stands would lose carbon to the atmosphere for 60 to 70 years depending upon the rate they regenerate (Figure 10). Although the timing of the stands to go from a carbon source to a sink is very similar, the amount of carbon lost is increased by a factor of two if regeneration is delayed for 20 years. While harvesting some of the carbon and converting it to forest products would store some of the beetle-killed carbon, losses during manufacturing of lumber or pulp (these can be close to 50% of the harvested material) are likely to be very similar to those experienced by the quickly regenerating stand without timber salvage (20,000 versus 21,520 lbs of biomass per acre; to convert to carbon multiply by 0.5; Harmon et al. 1996). Conversely, salvage harvest on sites prone to regeneration failure might halve the amount of carbon released to the atmosphere during the first 70 years as the slow regenerating stand loses 39,571 lbs per acre of biomass during this time.



## Future Studies

This study provides the first long-term estimates of tree decomposition for the Kenai Peninsula. Despite the value of these estimates and the types of analyses they help to support, additional information would improve our understanding of not only the rate beetle-killed trees decompose, but also how long these trees will persist, what form they will take, and what ecological function they will provide.

The method used to estimate decomposition rates indicates general trends but cannot replace the information gained from a well-designed time series study. However, by resampling the trees in 5–10 years, more precise estimates can be obtained using decomposition vector analysis that would reveal more about how the position and decay class would influence decomposition (Harmon et al. 2000).

We saw evidence that snags decomposed more slowly than logs. This hypothesis can be further tested if snags, felled during this study, are compared in the future to snags that remain standing. It is very likely that decomposition rates are not constant during decomposition and we saw some evidence to support that view in our data. Future resampling will confirm if this pattern holds. The rates nutrients are taken up (immobilized) or released (mineralized) by dead trees can also best be examined by resampling trees. There is likely to be considerable variation from tree to tree that will make detection of temporal trends difficult. But this variation can be assessed through log resampling.

There are also other kinds of data that could help with understanding the implications of the decomposition and nutrient cycling data. For example, the transition from standing snags to fallen logs has a great influence on the decomposition rate. Better estimates of the temporal patterns and rates of snag fall are therefore critical to predicting decomposition rates. To put decomposition rates in context, inventories of dead wood in beetle and non-beetle-killed stands are needed. This would allow the examination of actual versus hypothetical patterns of dead tree biomass accumulation after beetle attack. Measurements of live tree establishment, growth and mortality rates would allow better prediction of the temporal trends in dead wood following beetle-kill and to predict with more confidence the time beetle-killed stands are likely to remain a source of carbon to the atmosphere.

It is also essential that we understand how the function of dead trees change as they decompose. Fuel characteristics, such as ability to retain moisture, drying rates, ability to sustain smoldering fire, and arrangement, all change as beetle-killed trees progress from standing to fallen to part of the organic soil. Likewise dead trees also serve ecological functions such as wildlife habitat. How the quantity and quality of these dead trees influence these ecological functions will need to be balanced against the management hazards, such as fire danger, that they present.

## CONCLUSIONS

We presented preliminary estimates of the decomposition rates of primarily beetle-killed Lutz spruce trees on the Kenai Peninsula. Snags created by the beetle-kill have very low rates of decomposition except at their bases. Once these snags fall down, their decomposition rate increases and significant volume loss begins to occur. Based on the overall rate of decomposition estimated (1.5% per year), it would take close to 200 years for beetle-killed trees to disappear. Given the rates that decay penetrates dead trees, salvage would have to occur within a decade to yield a high percentage of sound wood. Beetle-killed trees are likely to influence fire behavior and present a hazard for over 75 years, but the nature of the hazard is likely to change significantly over this time. Based on a very simple model of forest regrowth, and assuming that beetles kill an entire stand of spruce trees, it is likely that this disturbance will cause forests to lose carbon to the atmosphere for 60 to 70 years. The rate forests are regenerated would have a very large impact on the amount of carbon released during this time, and even a 20-year lag in tree establishment could double carbon lost to the atmosphere.

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## REFERENCES CITED

- ACRC Alaska Climate Research Center, Geophysical Institute, University of Alaska, Fairbanks.  
<http://Fclimate.gi.alaska.edu>
- Alden, J. N. ed. 2001. Reforestation needs and opportunities for carbon sequestration in Alaska. Agricultural and Forestry Experiment Station, University of Alaska-Fairbanks, Miscellaneous Publication 2001-2. 67 p.
- Busse, M.D. 1994. Downed bole-wood decomposition in lodgepole pine forests of central Oregon. Soil Science Society of America Journal 58:221-227. Franklin, J.F., H.H. Shugart, and M.E. Harmon. 1987. Tree death as an ecological process. Bioscience 37:550-556.
- Edmonds, R. L. and A. Eglitis. 1989. The role of the Douglas-fir beetle and wood borers in the decomposition of and nutrient release from Douglas-fir logs. Canadian Journal of Forest Research. 19:853-859.
- Graham, R. L. 1982. Biomass dynamics of dead Douglas-fir and western hemlock boles in mid-elevation forests of the Cascade Range. PhD Thesis Oregon State University, Corvallis, OR.
- Graham, R. L., and K. Cromack. 1982. Mass, nutrient content, and decay rate of dead boles in rain forests of Olympic National Park. Canadian Journal of Forest Research 12:511-521.
- Grier, C.C. 1978. *Tsuga heterophylla* – *Picea sitchensis* ecosystem of coastal Oregon: decomposition and nutrient balances of fallen logs. Canadian Journal of Forest Research 8:198-206.
- Harmon, M. E., B. Fasth, and J. M. Sexton. In prep. Bole decomposition rates of seventeen tree species in western U.S.A. Report to the Rocky Mountain Research Station.
- Harmon, M. E. 2001. Moving towards a new paradigm for dead wood management. Ecological Bulletins (Sweden) 49:269-278.
- Harmon, M.E., O. Krankina, and J. Sexton. 2000. Decomposition vectors: a new approach to estimating woody detritus decomposition dynamics. Canadian Journal of Forest Research 30:76-84.
- Harmon, M. E., K. J. Nadelhoffer, and J. M. Blair. 1999. Measuring decomposition, nutrient turnover, and stores in plant litter. pp 202-240 In Robertson, G. P., C. S. Bledsoe, D. C. Coleman, and P. Sollins editors, Standard Soil Methods for Long Term Ecological Research, Oxford University Press, New York.
- Harmon, M. E., J. M. Harmon, W. K. Ferrell, and D. Brooks. 1996. Modeling carbon stores in Oregon and Washington forest products: 1900-1992. Climatic Change 33:521-550.
- Harmon, M. E. and J. Sexton. 1996. Guidelines for measurements of woody detritus in forest ecosystems. LTER Network Office Publication Number 20.
- Harmon, M. E. 1992. Long-term experiments on log decomposition at the H. J. Andrews Experimental Forest. USDA Forest Service General Technical Report PNW-GTR-280. 28 p.
- Harmon, M.E. and H. Chen. 1991. Coarse woody debris dynamics in two old-growth ecosystems: Comparing a deciduous forest in China and a conifer forest in Oregon. Bioscience 41:604-610.
- Harmon, M. E., K. Cromack Jr. and B. G. Smith. 1987. Coarse woody debris in mixed-conifer forests, Sequoia National Park, California. Canadian Journal of Forest Research 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. Lienkamper, K. Cromack Jr., and K. W. Cummins. 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research 15:133-302.
- Holsten, E.H., R.A. Werner, and R.L. Develice. 1995. Effects of a spruce beetle (Coleoptera: Scolytidae) outbreak and fire on Lutz spruce in Alaska. Environmental Entomologist. 24:1539-1547.

- Holsten, E.H. 1984. Factors of susceptibility in spruce beetle attack on white spruce in Alaska. *Journal of the Entomological Society of British Columbia* 81:39-45.
- Lowell, E. C. and S. A. Willits. 1998. Lumber recovery from beetle-killed spruce trees, Kenai Peninsula, Alaska. *Western Journal of Applied Forestry* 13:54-59.
- Means, J. E., K. Cromack Jr. and P. C. MacMillan 1985. Comparison of decomposition models using wood density of Douglas-fir logs. *Canadian Journal of Forest Research* 15:1092-1098.
- Ross, D. W., G. E. Daterman, J. L. Boughton, and T. M. Quigley. 2001. Forest health restoration in South-central Alaska: a problem analysis. Gen. Tech. Rep. PNW-GTR-523. Portland, OR: U.S.D.A., Forest Service, Pacific Northwest Research Station. 38 p.
- Schulz, B. 1995. Changes over time in fuel-loading associated with spruce beetle impacted stands of the Kenai Peninsula, Alaska. Tech. Rep. R10-TP-53. Anchorage, AK: U.S.D.A., Forest Service, Alaska Region. 17 p.
- Scott, G. M., D. W. Bormett, N. R. Sutherland, S. Abubakr, and E. Lowell. 2000. Beetle-killed spruce utilization in the Kenai peninsula. *TAPPI Journal* 83:1-7.
- Scott, G. M., D. W. Bormett, N. R. Sutherland, S. Abubakr, and E. Lowell. 1996. Pulpability of beetle-killed spruce. USDA Forest Service Forest Products Laboratory Research Paper FPL-RP-557. 8 p.
- Sollins, P., S. P. Cline, T. Verhoeven, D. Sachs, and G. Spycher. 1987. Patterns of log decay in old-growth Douglas-fir forests. *Canadian Journal of forest Research* 17:1585-1595.
- Sollins, P. 1982. Input and decay of coarse woody debris in coniferous stands in western Oregon and Washington. *Canadian Journal of Forest Research* 12:18-28.
- Triska, F. J., and K. Cromack, Jr. 1980. The roles of wood debris in forests and streams. In *Forests: Fresh perspectives from Ecosystem Analysis*. Proceedings 40th Biology Colloquium (1979) (R. H. Waring, ed), pp.171-190. Oregon State University Press, Corvallis.
- Randerson, J. T., F. S. Chapin, III, J. Harden, J. C. Neff, and M. E. Harmon. 2002. Net Ecosystem Production: A Comprehensive Measure of Net Carbon Accumulation by Ecosystems. *Ecological Applications* 12:937-947.
- Van Hees, W. W. S. 1992. An analytical method to assess spruce beetle impacts on white spruce resources, Kenai Peninsula, Alaska. USDA Forest Service Pacific Northwest Resrearch Station Research Paper PNW-RP-446. 15 p.
- Van Hees, W. W. S., and F. R. Larson. 1991. Timberland resources of the Kenai Penisula, Alaska, 1987. USDA Forest Service Pacific Northwest Research Station Resource Bulletin PNW-RB-180. 56 p.
- Werner, R.A., E. E. Elert, and E. H. Holsten. 1983. Evaluation of beetle-killed white spruce for pulp and paper. *Canadian Journal of Forest Research* 13:246-250.
- Werner, R.A., E. H. Holsten. 1983. Mortality of white spruce during a spruce beetle outbreak on the Kenai Peninsula in Alaska. *Canadian Journal of Forest Research* 13:96-101.
- Yatskov, M., O. N. Krankina, M. E. Harmon. 2003. A chronosequence of wood decomposition in the boreal forests of Russia. *Canadian Journal of Forest Research* 33: 1211-1226.

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