AN ABSTRACT OF THE DISSERTATION OF

Rebecca S.H. Kennedy for the degree of Doctor of Philosophy in Forest Science presented on June 1, 2005.

Title: Dead Wood Dynamics and Relationships to Biophysical Factors, Forest History, Ownership, and Management Practices in the Coastal Province of Oregon, USA

Abstract approved:

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Thomas A. Spies

Dead wood patterns and dynamics vary with biophysical factors, disturbance history, ownership, and management practices. Through field and modeling studies, I examined the current and potential future amounts of dead wood in two landscapes and region-wide in the Coastal Province of Oregon. The objectives of the first study were to (1) determine whether two landscapes with different recent disturbance histories differ in the amount and characteristics of dead wood; and (2) explore relationships between patterns of dead wood in each landscape to potentially related factors including topography. The objectives of the second study were to (1) describe current regional amounts of dead wood; (2) compare dead wood amounts across ownerships; (3) determine relationships between current dead wood amounts and ownership, current and past vegetation conditions, climate, topography, and soils; and (4) evaluate whether the factors related to dead wood patterns differed according to the scale of analysis. The objectives of the third study were to (1) characterize the projected future change in dead wood amounts in a multi-ownership Province; (2) determine the longevity of present-day dead wood of different types and sizes in relation to amendments from management and stand development; and (3) evaluate differences in management approaches in transitional dynamics and long-term patterns of dead wood.

In the first study, I sampled logs and snags at four topographic positions (streams, lower slopes, middle slopes, upper slopes) in the Tillamook State Forest and the Siuslaw National Forest. These two landscapes experienced catastrophic fire at different points in recent history. I developed statistical models relating various attributes of dead wood abundance to biophysical variables related to climate, topography, historical vegetation, current vegetation, soils, and ecoregion. I found that the type and timing of disturbance was important to dead wood amounts and characteristics, and that potential source and sink areas for dead wood were related to topographic position. In particular, lower slopes had higher amounts of logs, and upper slopes had higher basal areas of potential source wood, in the form of snags and legacy (pre-fire) stumps. Climatic factors were of greater relative importance to overall gradients of dead wood in the landscape in which fire occurred less recently.

In the second study, I analyzed dead wood data from a region-wide systematic grid of field plots according to ownership and biophysical variables at multiple scales of resolution including plots, subwatersheds. Dead wood abundance and types varied greatly among ownerships, with public lands (Forest Service, Bureau of Land Management, State of Oregon) typically having higher amounts of dead wood and more dead wood in the larger size classes than the

private lands (forest industry, non-industrial private). I found that the relative influence of ownership, topography, current and historical vegetation, and climate varied with scale of resolution. Current vegetation was of greater relative importance at finer scales of plots and subwatersheds, whereas climate, topography, and historical vegetation were of greater relative importance at coarser scales of watersheds and subbasins. Ownership was important to overall dead wood gradients at all scales considered.

In the third study, by simulating stand development and dead wood dynamics under various forest management scenarios over a 300-year period, I was able to examine the long-term effects of management on dead wood abundance in the Coastal Province. I estimated potential upper bounds for future dead wood amounts. Dead wood amounts increased over time on average across the Province, mainly because of policies on public lands, especially the federal lands under the Northwest Forest Plan. Forest industry, under the Oregon Forest Practices Act and assuming retention of all snags at harvest and thinning, maintained amounts of dead wood that were similar to present-day levels, but size classes shifted toward the smaller sizes as existing large legacy dead wood decomposed. Non-industrial private lands showed increases from very low present-day amounts of dead wood. Across the Province, legacy logs and snags remained present for over a century of the simulation period, and buffered effects of intensive management to dead wood amounts. Variation across landscapes in starting conditions meant that contrasting management approaches had differential

effects on long-term dead wood dynamics depending on where they were applied. Current amounts of dead wood and live vegetation patterns in the Province resulted from historical fire and logging. Results of this simulation study indicate that recently established policies oriented toward dead wood production and retention, in the absence of fire or other large- or mid-scale disturbances, are likely to result in increases in dead wood amounts that greatly exceed present-day levels. My results suggest that dead wood patterns of abundance will continue to diverge according to land ownership and that management practices that foster dead wood creation are of increasing importance to the long-term abundance of large dead wood as legacy dead wood is lost through decomposition.

Dead Wood Dynamics and Relationships to Biophysical Factors, Forest History, Ownership, and Management Practices in the Coastal Province of Oregon, USA

by
Rebecca S.H. Kennedy

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

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CONTRIBUTION OF AUTHORS

Matthew J. Gregory provided summarized current dead wood and other biophysical data from the systematic grid of plots that were used in regional analyses. Keith A. Olsen and Robert J. Pabst assisted in development and testing of modeling software used in Chapter 3. Dr. Tom Spies collaborated in the development of the conceptual framework for the research project and assisted with writing.

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DEDICATION

This work is dedicated

to my mother,

Suzanne Harriet Hess,

who showed me the world's possibilities,

and

to my daughter,

Lila Nell Kennedy,

that you might see them too.

Dead Wood Dynamics and Relationships to Biophysical Factors, Forest History, Ownership, and Management Practices in the Coastal Province of Oregon, USA

Chapter 1: Introduction

Understanding relationships of complex ecological patterns with multiple underlying mechanisms is crucial to sustaining ecological systems. Spatial pattern has been shown to influence many ecological processes, and the consideration of pattern-process relationships at multiple spatial and temporal scales is important to the advancement of landscape ecological theory and natural resource management (Turner 1989, Wiens 1995, Wiens et al. 2002). Characterizing the relative importance of patterns on processes at different ecologically relevant scales is also important for the accurate description of ecological systems (Wiens 1989). In one example of this approach, we could quantify the amount and direction of influence of each process on a landscape element, the variability inherent to the pattern-process relationships, and how these relationships change with ecologically relevant scale. In landscapes with multiple, interacting processes, it may be questionable whether clear patterns in the landscape element still emerge. Through this approach, we can increase our understanding about the effect of each mechanism, look for spatial and temporal thresholds in the influence of a process, and examine the relative strengths of process-pattern relationships. The study of landscapes, which to-date has relied heavily on descriptions of pattern with some inference about process, would benefit greatly from increased use of this approach.

Dead wood (snags and logs) is important to the ecosystem function and biodiversity of the world's forests (Maser and Trappe 1984, Harmon et al. 1986, Grove 2001, Jonsson and Kruys 2001, Rose et al. 2001, Krankina et al. 2002, Laudenslayer et al. 2002) and is a suitable landscape element for evaluation in the context of multi-scale, multi-process interactions. Dead wood is a fine-grained, persistent landscape element relative to the surrounding forest matrix (Sollins et al. 1987, Oliver and Larson 1990, Spies 1997). Long-term dynamics and spatial patterns of dead wood rely on a suite of processes, such as fire, windthrow, pests and pathogens, competition, and other causes of tree death that add dead wood to ecosystems; and decomposition and transport, that remove dead wood from ecosystems. These processes operate at multiple spatial and temporal scales. The timing of disturbances, historical conditions, and live vegetation also influence the amount, physical characteristics, and origin (legacy or current stand) of dead wood (Swanson et al. 1976, Harmon et al. 1986). In addition, there may be a maximum potential amount of dead wood possible at a given site, based on productivity and other site constraints that may be explained by climatic factors. Variation in processes over time and space, such as shifts in the disturbance regime, may alter the spatial pattern, characteristics, and amount of dead wood. In addition, dead wood amounts and types may also be distributed differentially with respect to topography. There have been conflicting reports on the potential influence of topography, such as elevation and topographic position, to dead wood amounts, and this merits further study in regions of complex topography (Brown and See

1981, Spies et al. 1988, Gale 2000, Clark et al. 2002, Rubino and McCarthy 2003). Field studies and models have developed our understanding of some of the relationships between ecological processes and dead wood. These results still need to be incorporated across spatial scales and across the range of forest conditions and disturbance types of present-day managed forest landscapes and regions.

In this dissertation, I evaluate the relationships of biophysical conditions, ownership, management practices, and forest history to patterns of dead wood. The geographic extent of my research is the Coastal Province of Oregon, a region notable for high forest productivity and large amounts of dead wood relative to other regions (Franklin and Dyrness 1988, Spies et al. 1988). In Chapter 2, I evaluate dead wood patterns in two landscapes in the Coastal Province with different disturbance histories. In each landscape, I explore relationships of snags and logs with current and historical vegetation, climate, and topography. I focus in particular on relationships of topographic position with dead wood. These patterns may provide insights into source-sink dynamics of dead wood in steep mountainous landscapes. This research is important because it shows the significance of history and topography to dead wood patterns, and also because it links aquatic and terrestrial studies of dead wood. This is of interest because these effects are poorly documented and because managers need information on expected patterns to help set management goals and evaluate the impacts of management practices. In Chapter 3, I expand on the field studies of Chapter 2, using a region-wide dataset to describe patterns of dead wood abundance across the Province and by ownership. I relate various sizes and types of logs and snags to biophysical conditions and ownership at multiple scales. I describe domains of scale of ownership, topography, climate, current and historical vegetation to patterns of dead wood, and the relative importance of these factors to dead wood at each scale. This is of interest to landscape ecologists and managers because it shows that current vegetation, historical vegetation, and ownership influences on dead wood patterns transcend scale in this region, whereas climate and topographic influences may have more localized domains of scale. In Chapter 4, I use simulation modeling and regional field plot data to expand on my findings of differences among ownerships in dead wood. In this chapter, I evaluate the effects of current forest policies on future potential amounts and types of dead wood over the next 300 years, given current patterns of vegetation, ownership and forest management. This is of interest to scientists, policymakers, and managers, in that I describe potential dramatic increases in dead wood amounts on Federal lands, increases on State lands, and somewhat stable amounts on private lands, but with shifts in the size and type of dead wood present. This research highlights the importance of the historical context and starting conditions, depicts the relative effects of management, and illustrates that patterns at broad scales can emerge from a complex of long-term, interacting processes at finer scales.

Chapter 2: Dead wood patterns and related factors across two landscapes with different disturbance histories in the Coastal Province of Oregon

Introduction

Dead wood is an important component of forest ecosystems, increasing the structural diversity of forests (Spies and Franklin 1988, Hansen et al. 1991, Sturtevant et al. 1997) providing habitat for sensitive species (Bisson et al. 1986, Jonsson and Kruys 2001, Rose et al. 2001), and contributing to long-term nutrient stores (Harmon et al. 1986, Maser et al. 1988). Understanding dead wood dynamics at the landscape scale is important because some dead wood associated species and processes operate at this scale. Biodiversity may be best maintained by consideration of a variety of scales (Levin 2000, Lindenmayer and Franklin 2002). In addition, in many ecosystems the dominant disturbance type affecting tree death (e.g., fire, windstorm) may occur at scales larger than the individual stand but smaller than the region. Further, forest management regulations and plans are often developed for landscapes and broader scales (U.S. Department of Agriculture Forest Service and U.S. Department of the Interior Bureau of Land Management. 1994a).

Although stand- and regional-level patterns of dead wood amounts and related factors have received some study, patterns at the landscape level remain somewhat cryptic, as landscape-level dead wood patterns have not been the subject of much research (Muller 2003). Stand-level patterns of dead wood amounts have been shown to follow a rough U-shaped pattern over time, increasing immediately after disturbance, decreasing as disturbance-created mortality decomposes, and increasing as the stand grows after disturbance (Harmon et al. 1986, Spies et al. 1988, Sturtevant et al. 1997). At the regional level, dead wood has been shown to vary across habitat types, disturbance types, and climatic gradients (Brown and See 1981, Brown and Schroeder 1999, Krankina et al. 2002, Ohmann and Gregory 2002, Tietje et al. 2002).

We might presume that since landscapes are comprised of stands and occur in a regional context, landscape-level dead wood patterns may be related to a combination of processes occurring at stand and regional levels. However, the numerous processes that occur in natural and managed landscapes may confound the emergence of clear relationships between dead wood patterns and related processes. Disturbance processes such as fire, floods, windthrow, landslides, selective cutting, and clearcutting may affect dead wood patterns through the creation or redistribution of dead wood or the removal of live vegetation. The scale of these disturbance processes on dead wood production and removal varies from the death of an individual tree or movement of a single log, to the death of an entire stand or multiple stands. Patterns of live vegetation, and factors related to live vegetation such as microclimate, soils, site productivity, and the species composition of the live vegetation, may influence the kinds of dead wood produced and dead wood decay rates. Past vegetation may be more closely associated with dead wood amounts than present-day vegetation because of the long decay time of dead wood (Sollins et al. 1987). Topography is probably important to dead wood patterns in landscapes through its influence on productivity, tree species composition, decay rates, and movement of dead wood. However, conflicting relationships between topography and dead wood patterns have been found, from there being no relation to topography, to dead wood amounts increasing from valleys to ridgetops (Gale 2000, Clark et al. 2002), so the relationship of topography to dead wood patterns remains unclear. Climatic variation may affect dead wood production and decay rates, so it is possible that dead wood amounts in landscapes vary with climatic gradients, as they have been shown to do at the regional level (Krankina et al. 2002, Rouvinen et al. 2002).

These patterns and processes with potential relationships to dead wood patterns may overlap in time and space. Because of the long time period of decay of large dead wood, the influence of multiple factors may compound the complexity of effects. The relative strength of relationships among patterns and processes that are potentially related to dead wood patterns at the landscape scale remains unknown. Further, the relative influence of processes related to patterns of dead wood may change over time (Muller 2003).

I assessed patterns of dead wood amounts in two landscapes in the Coastal Province of Oregon, USA, with different disturbance histories. The two landscapes differed in the time since high severity stand-replacing fire which is historically characteristic of the region (Agee 1993), and in the type of post-fire management activities. In each landscape, I evaluated relationships among dead wood attributes and potentially related patterns and processes including topography, live vegetation, climate, historical vegetation, geology, ecoregion, and geographic location. I focused a portion of the study on the potential effects of topography since I presumed that at the landscape scale topography might have a strong effect on dead wood patterns. I was also interested in determining whether some portions of the landscape exhibited patterns of accumulation that might result from source-sink redistribution among topographic positions.

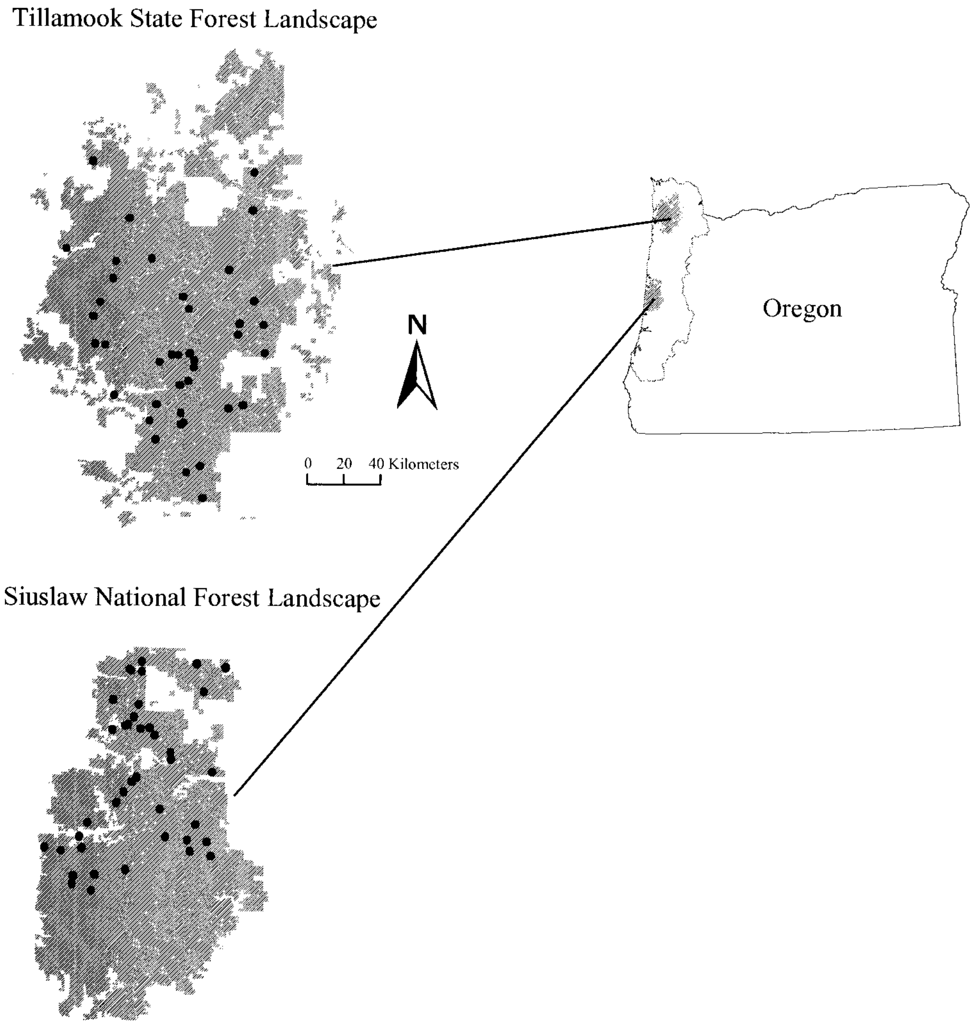
The study had two main objectives: (1) to determine whether two landscapes with different recent disturbance histories differ in the amount and characteristics of dead wood; and (2) to explore relationships between patterns of dead wood in each landscape to potentially related factors, including topography. To address these issues, I sampled dead wood in plots located at different topographic positions throughout the two landscapes. I then developed statistical models relating the amounts and types of dead wood present in these landscapes to a suite of potentially related factors whose characteristics were obtained from a GIS and through field sampling.

Study Area

The Coast Range mountains, where the two landscapes were located in the Coastal Province, are characterized by rugged, steep terrain and a dense network of intermittent and perennial streams. The climate is maritime, with mild wet winters and cool dry summers. Forest vegetation in the extreme western part of the study area near the Pacific Ocean is in the Sitka spruce (*Picea sitchensis* [Bonb.] Carr.) vegetation zone, and the balance lies within the western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) vegetation zone (Franklin and Dyrness 1988). Forest vegetation is dominated by conifers including Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), western hemlock, western redcedar (*Thuja plicata* Donn), and Sitka spruce, with Sitka spruce restricted to near-coastal areas. Hardwood tree species such as red alder (*Alnus rubra* Bong.) and bigleaf maple (*Acer macrophyllum* Pursh) also occur in patches within the coniferous forest matrix.

The major disturbance type in the Coastal Province in recent history is high intensity stand-replacing fire, which occurred at intervals of 200-300 years (Agee 1993, Impara 1997) prior to the advent of fire suppression in the mid-1900s. Other disturbance types related to dead wood recruitment and transport typically occur at finer scales (<1 ha) and higher frequencies (years to decades) and include windthrow related to storm events of the 1950s and 1960s, large flood events of the 1960s and 1990s, periodic landslides and debris flows, and chronic mortality of Douglas-fir and western redcedar from laminated root rot fungus (Ruth and Yoder 1953, Orr 1963, Strome 1986, Spies and Cline 1988).

The first landscape studied, the Tillamook State Forest, is an area of relatively young forest located in the northwestern part of the Coastal Province of



Tillamook State Forest Landscape

Siuslaw National Forest Landscape

Figure. 2.1. Location of two landscapes in the Coastal Province of Oregon, USA. Points indicate locations of sample plots in each landscape.

Oregon (Figure 2.1). The Tillamook State Forest was established after a series of high intensity, stand-replacing fires that occurred between 1929 and 1951. Most of the landscape burned between two and four times during this period (Chen 1997). Prior to the fires, much of the Tillamook landscape consisted of old-growth forest, as determined by stand reconstruction research (Kennedy, unpublished data) and historical accounts (Levesque 1985, Fick and Martin 1992). Salvage logging was widespread after the fires at moderate-to-high levels of removal, as indicated by analysis of historical aerial photo series (Kennedy, unpublished data) and Department of Forestry harvest records (Fick and Martin 1992). To prevent fire spread in the event of a reburn, in addition to salvage efforts, many large felled snags were relocated to locations away from ridgetops, and several miles of roads were established as fire breaks (Fick and Martin 1992). The burned area was planted and aerially seeded after the fires. This resulted in a fairly uniform, even-aged coniferous cover across the landscape. Sampled stands in the Tillamook ranged from approximately 60 to 70 years of age at the time of this study. It was expected that there would be few large snags in the Tillamook because of the high amount of snag felling after the fires, but that the volume per hectare of logs would be high because of the high degree of disturbance and the short time since disturbance relative to the decay rates of large conifer logs (Graham 1981, Harmon et al. 1986, Sollins et al. 1987).

The Siuslaw National Forest, the second landscape studied, is located in the central part of the Coastal Province (Figure 2.1). The fires in the Siuslaw occurred between 1850 and 1880 and were stand-replacing (Impara 1997). Present-day unmanaged stands regenerated naturally after these fires, and are now in the mature or understory reinitiation stage of development (Oliver and Larson 1990, Poage 1994, Impara 1997, Spies 1997). Because some areas of the Siuslaw have been thinned or converted to plantations in recent decades, I sampled only the unmanaged mature and old forest areas in the Siuslaw, which I located using satellite imagery-based vegetation maps, digital orthophotos, and field evaluation. The sampled stands ranged from 120-150 years old, according to analysis of increment cores of dominant site trees that established following disturbance. Results of this study may not apply to those areas of the Siuslaw National Forest landscape that have been converted to plantations or that regenerated after the fires as natural, smaller diameter stands. I expected, based on past stand-level research and models of dead wood amounts following disturbance (Spies et al. 1988), that in the Siuslaw landscape there would be a low level of dead wood.

Methods

I sampled forty plots in each of the two landscapes using a stratified random sampling design. In each landscape, I sampled ten plots at each of four topographic positions: stream (S), lower (L), middle (M), and upper (U) slopes, by establishing transects along the contour of the slope at each position. For streams, the plot ran along the length of the stream. Each plot location was estimated by using a random point generator in a GIS map of the area, and then visually locating the topographic position of interest (i.e., stream, etc.) nearest the point using a streams coverage, an elevation coverage, and digital raster graphics (DRGs) of U.S. Geological Survey standard series topographic maps. I centered stream plots at the center of streams for smaller streams and at the stream's edge for larger streams. I located lower slope plots within the lower one-third of the slope, outside the riparian zone to avoid direct fluvial influences. Middle slope plots were located within the center one-third of the slope. Upper slope plots were located within the upper one-third of the slope and included ridgetop areas. In the Siuslaw, using a remote-sensing-imagery-based land cover map, digital orthophotos, and field observation, I located the plots in areas of unmanaged older forest dominated by large and very large conifer cover.

To measure logs, snags, and legacy stumps (stumps left from the previous stand) at each plot location, I established two slope-corrected transects originating at the same point. The starting location of the transects was located using a Global Positioning System (Garmin 12 XL), and starting locations with respect to topographic position category were later confirmed using this information. A 250 m line transect was sampled for logs. A 10 m by 150 m (1500 m^2) belt transect was sampled for snags and legacy stumps. The log transect was comprised of one, 150 m long transect and four 25 m transects located at 0, 50, 100, and 150 m along the long transect that were at right angles to and were bisected by the longer transect. I measured all logs greater than 1 m in length and greater than 30 cm large end diameter (led). The belt transect was centered on the line transect and ran the length of the 150 m line transect. In the belt transect I measured all snags greater than 30 cm diameter at breast height (dbh). For both snags and logs I noted whether the piece was from the current stand or from a legacy (previous) stand by evaluating the decay class and size in comparison with the age of the dominant trees present in the live stand. To obtain reference information about the pre-disturbance forest in the Tillamook where post-disturbance timber salvage occurred, I also measured legacy stumps greater than 30 cm diameter at breast height. Like snags and logs, stumps were determined to be from the pre-fire stand based on their decay status and size relative to the size of dominant trees in the present-day stand. Where legacy stumps were shorter than breast height (1.3 m), I identified the species, measured the stump height from the base, and estimated the dbh by comparison with field observations of taper-dbh relationships in snags of the same species. The purpose of measuring legacy stumps was three-fold: (1) to develop a more complete estimate of the basal area of the pre-disturbance stand than by snags alone where both snags and stumps were present, (2) to establish a baseline for the evaluation of potential source areas for dead wood, and (3) to provide data for the estimation of the pre-fire density of large old trees in the Tillamook.

I measured several characteristics of logs, snags, stumps, and the forest stand in which the plot was located. For logs, I recorded the species, decay class, legacy status, distance along transect, large end diameter, small end diameter, transect intercept diameter, length, whether the log was cut, presence of char (evidence of fire), whether a root wad was attached, and for stream plots: the source (adjacent to stream ('local') or 'transported' from outside the immediate area), whether the log was in a jam, and if so, the number of pieces in the log jam. For snags, I recorded the species, decay class, legacy status, distance along transect (measured along the central line transect), height, diameter at breast height, and whether bark was present. For legacy stumps, I recorded the species, decay class, distance along transect, height, diameter at breast height, and whether bark was present. I also recorded several characteristics of the live stand, including the two dominant overstory species, the two dominant understory species, the species, dbh, and age of one representative dominant tree, the species and dbh of one representative smaller tree, and the basal area of the stand at 0, 50, 100, and 150 m along the transect.

I calculated several characteristics related to the size and abundance of dead wood. These included the number of logs, log volume (m^3 ha^{-1}), log biomass (Mg ha^{-1}), log carbon (Mg C ha^{-1}), the number of snags (ha^{-1}), snag basal area (m^2 ha^{-1}), snag volume (m^3 ha^{-1}), snag biomass (Mg ha^{-1}) snag carbon (Mg C ha^{-1}), the number of legacy stumps (ha^{-1}), legacy stump basal area (m^2 ha^{-1}), and total dead wood volume (m^3 ha^{-1}). To calculate the volume of logs, I used the Smalian formula,

$$V = ((A_1 + A_2)/2) * L ,$$

where V is the volume of the log in cubic meters (m^3), A_1 is the area of the small end in square meters (m^2), A_2 is the area of the large end in square meters (m^2), and L is the length of the log in meters (m) (Avery and Burkhart 1994). This is the official log scaling rule for the U.S.D.A. Forest Service for cubic-unit-based timber sales (Bell and Dilworth 1988). I summarized the volume per hectare (m^3) each log represented on the plot using the following equation:

$$LOGVOLPH = (3.1416/(2*PLOTLEN)*(LOGVOL/LOGLEN))*10000,$$

where LOGVOLPH is the log volume per hectare, PLOTLEN is the length of the plot transect in meters, LOGVOL is the volume of the log in cubic meters, and LOGLEN is the length of the log in meters. To calculate log biomass estimates, I used the following equation:

$$\mathrm{LOGBIOMKGH} = \mathrm{LOGVOLPH} * 1000 * \mathrm{SPGRAV} * \mathrm{DCR},$$

where LOGBIOMKGH is the biomass of logs in kilograms per hectare, LOGVOLPH is the log volume per hectare, and SPGRAV and DCR are specific gravity and decay reduction factors that vary by tree species (Janet Ohmann, personal communication). To calculate log carbon, I multiplied LOGBIOMKGH by the proportion of wood biomass that is carbon for the type of species (softwood or hardwood). I used the same equations to calculate the biomass and carbon of snags. To calculate the volume of snags, I used the Kozak equation, which is a polynomial equation that incorporates species-specific taper coefficients (Garman et al. 1995), and is based on height-dbh relationships. The Kozak equation is:

$$V = 0.0000785 * \mathrm{dbh}^2 * X,$$

where V is the volume of the snag in cubic meters (m^3), and

$$X = \beta_0 * h_l + (\beta_1 / 2) * (h_l^2 / h) + (\beta_2 / 3) * ((h_l^3) / (h^2)).$$

In calculating X, the betas (β) are the species-specific taper coefficients, h_l is the actual height, and h is the potential full height of the snag. The Kozak equation is considered to be more accurate than the Smalian equation, which may over-or under-estimate log volumes depending the degree of taper of the bole and from where along the bole the log originates (Ministry of Forests of the Province of

British Columbia. 2005). However, I did not know from where along the bole of the tree each field-sampled log had originated. I therefore determined that using the Kozak equation under these circumstances would be questionable for logs. I summarized the results for logs by size for the size classes <50 cm and >50 cm led because distinguishing between small and large logs provides important information to managers of wildlife in western forests (Rose et al. 2001, Laudenslayer et al. 2002). I identified decay classes 1-5 of logs and snags in the field following standard protocols (Maser et al. 1979, Cline et al. 1980) and summarized log and snag amounts accordingly. For parametric statistical tests, the number of logs, log volume, the number of snags, snag volume, snag basal area, and total dead wood volume required the logarithmic transformation to meet assumptions of normality (Ramsey and Shafer 2001).

I obtained information about a suite of factors that would potentially explain observed patterns in dead wood in landscapes. Information was obtained from a GIS and from field sampling. Digital data layers were converted to grids for subsequent analysis in ARC (Environmental Systems Research Institute 1998). Factors related to topography included elevation (m), slope (%), slope position (relativized, from 0 (bottom of drainage) to 100 (ridgetop)), aspect, and topographic position class (stream, lower, middle, or upper slope). Topography-related variables were derived from a 30 m digital elevation model, with the exception of topography class, which was obtained during field sampling and through evaluation of digital raster graphics of U.S. Geological Survey standard series topographic maps. Slope position was calculated using an Arc Macro Language (AML)(Environmental Systems Research Institute 1998), using default parameters for all arguments. Aspect was transformed using the Beers transformation: $ASPTR$=COS(45-ASP)+1 (Beers et al. 1966), so that for the most exposed plots (SW), aspect = 0.0, and for the least exposed plots (NE), aspect = 2.0. I determined whether plot locations were inside or outside 50- and 100-m buffers from streams using ARC (Environmental Systems Research Institute 1998). Climate-related variables were obtained from DAYMET (Thornton et al. 1997, Thornton and Running 1999, Thornton et al. 2000) and included several variables for precipitation, solar radiation, temperature, and humidity. I also obtained data for geologic substrate (Walker and MacLeod 1991) and ecoregions (Woods et al. Unpublished). Information about historical vegetation was obtained from a digital version of the 1936 Forest Survey Type Map (Andrews and Cowlin 1940, Interior Columbia Basin Ecosystem Management Project 2001). I acquired current vegetation data and related factors through field sampling and from remote sensing LANDSAT TM imagery from 1996. Inclusion of remotely sensed variables in the model selection process allowed for the potential that remotely sensed information could be used in addition to or instead of field-based data to explain dead wood patterns. The remote sensing-based variables I considered, tasseled cap wetness, tasseled cap greenness (Kauth and Thomas 1976) have demonstrated relationships with forest vegetation in the Pacific Northwest region (Cohen et al. 2001). Greenness has been associated with total vegetation cover and percent broadleaf cover, and wetness with vegetation structure (stand age and crown diameter). I also considered the Landsat TM band-ratio 5:7, filtered twice in succession using a 3 x 3 pixel window to reduce fine-scale heterogeneity. This has been shown to be a significant variable in the predictive mapping of forest composition and structure (including attributes of dead wood) research (Ohmann and Gregory 2002).

To reduce the set of variables related to environmental and site factors for model development, I examined a correlation matrix for all variables. I retained those variables that were not highly correlated ($|r|<0.8$). If two variables were highly correlated, I selected the one that had the lowest correlation with other variables, and included it. In this way, for each landscape, I developed a final, reduced set of variables to consider in statistical modeling (Table 2.1) with the goal that the selected variables would represent somewhat unique attributes of each landscape. However, I also considered these variables in the context of grouped sets, such as topography, climate, current vegetation, historical vegetation, geology, and location, in assessing general relationships among variables and dead wood patterns. I did this since typically the variables in each set were somewhat related, and because they tended to be characteristic of a scale of pattern or process.

I employed several statistical tests to evaluate relationships among patterns of dead wood and these potential explanatory factors. I used stepwise regression to relate individual dead wood attributes, such as the volume of logs, to

Table 2.1. Mapped explanatory variables considered in stepwise regression models and canonical correspondence analysis (CCA). Landscape = the location for which each variable was considered in statistical modeling: T=Tillamook; S=Siuslaw. In CCA, ecoregion variables were omitted in the Tillamook, and geology variables in the Siuslaw. Please see the text for more details.

Variable code	Definition	Landscape
Topography		
ELEV	Elevation (m), from 30-m digital elevation model (DEM)	TS
ASPTR	Cosine transformation of aspect (degrees) (Beers et al. 1966), 0.0 (southwest) to 2.0 (northeast), from 30-m DEM	TS
SLPPCT	Slope (percent), from 30-m DEM	TS
SLPPOS	Slope position, from 0 (bottom of drainage) to 100 (ridgetop), from 30-m DEM	TS
STREAM	In-stream plot	TS
LOWER	Lower slope plot	TS
MIDDLE	Midslope plot	TS
UPPER	Upper slope plot	TS
STRMBUF50	Within 50 m of streams	TS
STRMBUF100	Within 100 m of streams	TS
Climate		
ANNFROST	Total number of days, annually, where the daily minimum air temperature is less than or equal to 0.0 °C (ln for Tillamook)	TS
ANNSW	Total annual shortwave radiation (MJ m^{-2} day^{-1})	TS
ANNHDD	Total annual heating degree days, the summation of the difference between 18.3 °C and the daily average air temperature, for days when the average air temperature is less than 18.3 °C (°C) (ln)	S
ANNPRE	Mean annual precipitation (ln, mm)	S
AUGMAXT	Mean maximum temperature in August (°C)	TS
CONTPRE	Percentage of mean annual precipitation falling in June - August (percent)	TS
DIFTMP	Difference between August maximum temperature and December minimum temperature (°C)	T
SMRPRE	Mean precipitation from May to September (ln, mm)	S
SMRTP	Moisture stress during the growing season, calculated as SMRTMP/SMRPRE, where SMRTMP is the mean temperature in May-September (°C $(\ln, mm)^{-1}$) (ln)	T
Current Vegetation		
LIVEBA	Basal area of live trees (m^2/ha)	TS
Landsat TM		
WET	Wetness axis from tasseled cap transformation, twice-median-filtered	TS
GRN	Greenness axis from tasseled cap transformation, twice-median-filtered (ln for Siuslaw)	TS
R57	Ratio of band 5 to band 7, twice-median-filtered (ln for Tillamook)	TS
Historical Vegetation		
HVDFOG	Historical vegetation (1936) was Douglas-fir old growth; forest was over 60% Douglas-fir, old-growth greater than 55.9 cm dbh	TS
HVDFLSG	Historical vegetation was Douglas-fir large second growth; forest was over 60% Douglas-fir, second-growth greater than 55.9 cm dbh	TS
HVDFSSG	Historical vegetation was Douglas-fir small second growth; forest was over 60% Douglas-fir, between 15.2 and 50.8 cm dbh	TS
HVAAM	Historical vegetation was hardwood type of alder/ash/maple, a timberland type with alder, ash, and/or maple predominating	TS
HVRC	Historical vegetation was recent cutover	TS
HVNF	Historical vegetation was nonforest land other than agriculture	TS

Table 2.1. contd. Mapped explanatory variables considered in stepwise regression models.

Ecoregion		
UPL	Coastal uplands	TS
VOL	Volcanics	TS
Geology		
VOLC	Volcanic and intrusive rocks	TS
MAFO	Mafic rocks (basalt, basaltic andesite, andesite, gabbro); Miocene and older	TS
SEDR	Sedimentary rocks (siltstones, sandstones, mudstones, conglomerates)	TS
Location		
X	Latitude (m, UTM zone 10)	TS
Y	Longitude (m, UTM zone 10)	TS

environmental and site variables. I used nonparametric statistics including the Wilcoxon rank sum and Kruskal-Wallis tests (Conover 1998) to determine whether there were differences in the observed patterns of dead wood between landscapes, and between topographic positions within landscapes.

In addition, I used canonical correspondence analysis (CCA) (ter Braak 1986) to describe the dominant factors associated with overall gradients of dead wood. CCA is a multivariate approach that allows the user to view the combined relationships between two sets of variables: in this case, a set of dead wood attributes (response variables), and a set of potentially related factors (explanatory variables). Response variables may group along 'axes', which are described by combinations of explanatory variables. The procedure describes the gradients in one set of variables (dead wood) with respect to the second set (explanatory variables). In CCA, I included the following suite of dead wood attributes in the set of response variables: dead wood volume, number of logs, log volume, number of snags, snag basal area, snag volume, and snag+stump basal area. I log-transformed these response variables when necessary to meet the normality assumptions required by the regression component of CCA. I omitted variables related to ecoregion from consideration as a potential explanatory factor in CCA in the Tillamook landscape, and geology from consideration in the CCA in the Siuslaw landscape, because there was inadequate between-plot variation in these factors in their respective landscapes for CCA. I included all other variables from the full set of potential explanatory factors in CCA (Table 2.1). I conducted a preliminary CCA on the full suite of potential explanatory factors to obtain information about how much of the variability in dead wood patterns is explained by these factors. I then conducted individual CCAs on each subset of factors (i.e., inclusion of only the variables in the topography group, etc.), to determine the relative contribution to explained variation in the response variables by each explanatory variable subset. This approach presumes that there is probably some association among variables between explanatory variable subsets. It allows for the description of the strength of relationships of the factors within each subset (i.e., topography) to the variation in the set of response variables (i.e., the suite of dead-wood-related variables).

Results

Amount and characteristics of dead wood

Total dead wood volume was not significantly different between the Tillamook and the Siuslaw landscapes (Table 2.2). However, there were several differences in other characteristics of dead wood between the two landscapes (Table 2.2). The Tillamook had a higher volume of logs and a lower volume of snags than did the Siuslaw. Differences in log volume between the two landscapes resulted mainly from the occurrence of a higher volume of very large logs (>100 cm large end diameter) in the Tillamook (Figure 2.2 a).

Much of the volume and biomass of dead wood in both landscapes was in the form of large pieces (Table 2.3). For example, about 45% of the total volume of dead wood in the Tillamook was of logs and snags greater than 100 cm led or dbh, and almost 70% of this was of large logs. In the Siuslaw, 32% was in pieces sized greater than 100 cm. Snags of all sizes were far more common in the Siuslaw (Figure 2.2 b), with the exception of tall large snags (>50 cm dbh, > 15m height), whose amounts were low and equivalent in the two landscapes (Table 2.3). Most of the snags present in the Tillamook were >50 cm dbh, and most of these were legacy snags (Tables 2.2 and 2.3). The Siuslaw had a large number of >100 cm dbh snags (10 ha^{-1}), and these large-diameter snags were about 60% of the total volume of snags.

Table 2.2. Weighted mean dead wood amounts per hectare, for two landscapes located in the Coastal Province of Oregon. P-values are for comparison between landscapes of medians, from Wilcoxon rank sum tests.

	Tillamook State Forest $n=40$			Siuslaw National Forest $n=40$			
Dead wood variable	Mean	s.e.	Median	Mean	s.e.	Median	p-value
Total dead wood							
Dead wood volume (m^3)	275.7	31.9	218.7	282.6	32.1	251.4	n.s.
Legacy dead wood volume (m^3)	265.3	31.6	190.2	192.7	25.6	124.8	0.02
Non-legacy dead wood volume (m^3)	10.4	3.0	0.0	90.0	14.2	70.0	<0.0001
Dead wood biomass (Mg)	73.0	9.2	54.6	73.9	8.5	61.0	n.s.
Legacy dead wood biomass (Mg)	69.7	9.1	53.8	45.4	6.3	30.0	0.009
Non-legacy dead wood biomass (Mg)	3.4	1.0	0.0	28.5	4.6	20.4	<0.0001
Dead wood carbon (Mg)	38.0	4.8	28.3	38.4	4.4	31.8	n.s.
Legacy dead wood carbon (Mg)	36.3	4.7	28.0	23.6	3.3	15.7	0.009
Non-legacy dead wood carbon (Mg)	1.7	0.5	0.0	14.8	2.4	10.6	<0.0001
Logs							
Number of logs	168.6	18.4	154.8	163.4	20.7	117.6	n.s.
Number of legacy logs	159.1	18.5	125.2	89.9	11.5	70.6	0.0007
Number of non-legacy logs	9.5	2.8	0.0	73.6	13.3	40.3	<0.0001
Log volume (m^3)	226.7	27.6	190.2	176.1	23.2	130.2	0.04
Legacy log volume (m^3)	216.8	27.9	160.0	109.3	16.8	69.4	0.0003
Non-legacy log volume (m^3)	9.8	2.9	0.0	66.8	11.3	42.8	<0.0001
Log biomass (Mg)	60.4	8.1	51.0	46.6	6.6	36.1	0.07
Legacy log biomass (Mg)	57.2	8.2	40.7	26.3	4.4	16.2	0.0003
Non-legacy log biomass (Mg)	3.2	0.9	0.0	20.3	3.5	11.4	<0.0001
Log carbon (Mg)	31.5	4.2	26.6	24.2	3.4	18.8	0.07
Legacy log carbon (Mg)	29.8	4.3	21.2	13.7	2.3	8.5	0.0004
Non-legacy log carbon (Mg)	1.6	0.5	0.0	10.5	1.8	6.0	<0.0001
Snags							
Number of snags	11.9	2.1	6.7	47.8	5.8	40.0	<0.0001
Number of legacy snags	11.0	2.0	6.7	32.2	4.8	20.0	0.002
Number of non-legacy snags	0.9	0.5	0.0	15.6	3.1	6.7	<0.0001
Snag volume (m^3)	49.0	15.8	6.4	106.6	15.1	95.1	0.0006
Legacy snag volume (m^3)	48.5	15.8	6.4	83.4	14.4	46.4	0.01
Non-legacy snag volume (m^3)	0.5	0.3	0.0	23.2	5.7	5.4	<0.0001
Snag biomass (Mg)	12.6	4.6	1.2	27.3	3.8	24.3	0.0003
Legacy snag biomass (Mg)	12.5	4.6	1.2	19.1	3.4	9.1	0.01
Non-legacy snag biomass (Mg)	0.2	0.1	0.0	4.3	1.1	0.6	<0.0001
Snag carbon (Mg)	6.6	2.4	0.6	14.2	2.0	12.7	0.0003
Legacy snag carbon (Mg)	6.5	2.4	0.6	10.0	1.8	4.7	0.01
Non-legacy snag carbon (Mg)	0.1	0.1	0.0	4.3	1.1	0.6	<0.0001
Snag basal area (m^2)	8.8	2.1	3.3	25.9	3.6	21.2	0.0005
Legacy snag basal area (m^2)	8.6	2.1	3.3	21.8	3.5	14.6	0.005
Non-legacy snag basal area (m^2)	0.2	0.1	0.0	4.1	0.9	1.3	<0.0001
Number of legacy stumps	49.8	5.5	33.3	17.4	6.3	6.7	<0.0001
Legacy stump basal area (m^2)	49.5	4.2	49.8	10.9	4.3	2.0	<0.0001
Legacy snag + stump basal area (m^2)	58.1	5.1	59.2	32.7	4.7	26.5	0.0004

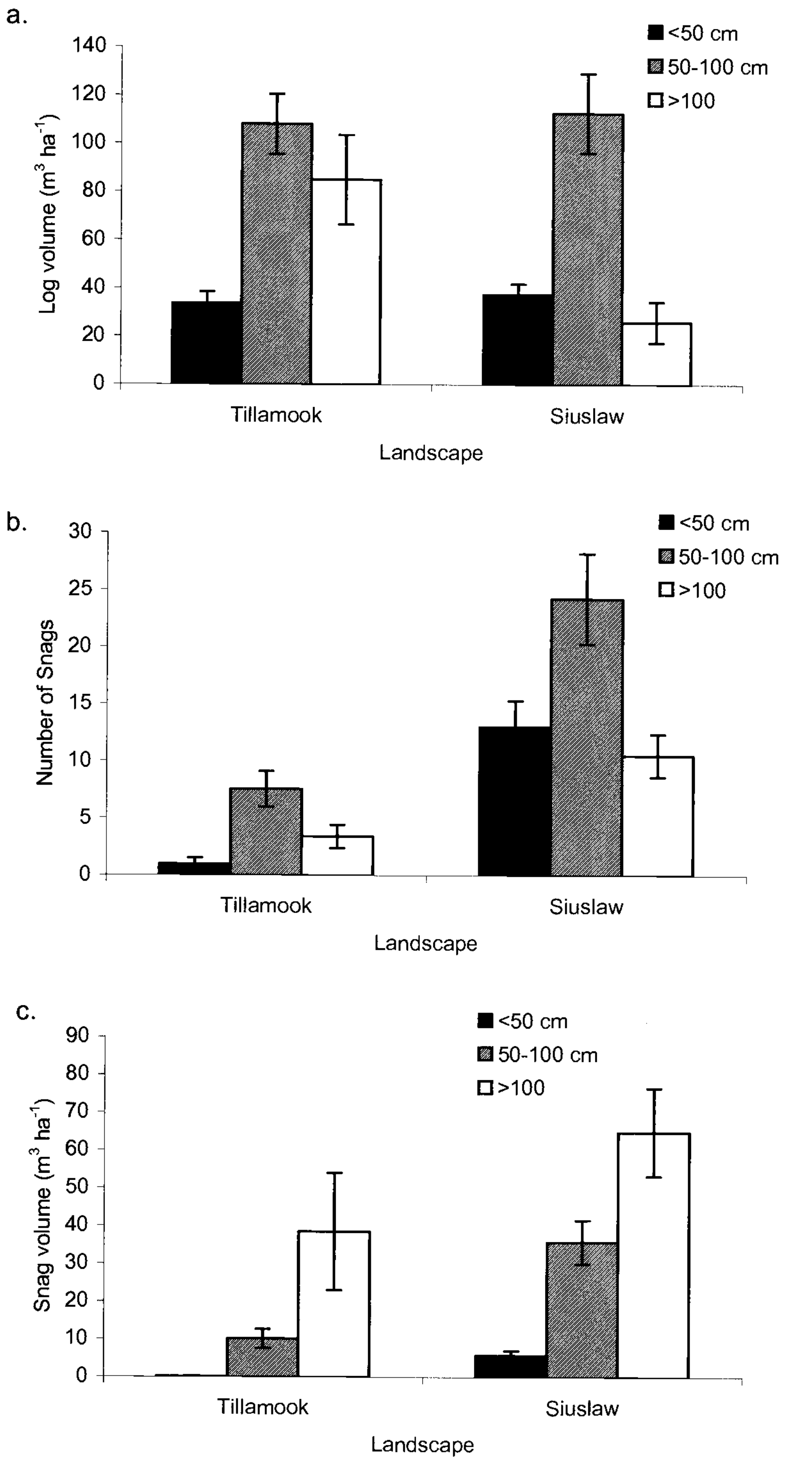


Figure 2.2. Mean amount of: (a) log volume, (b) number of snags, and (c) snag volume per hectare by size class and landscape in the Coastal Province of Oregon.

Table 2.3. Weighted mean and median dead wood amounts, by size and landscape in the Coastal Province of Oregon. Sizes are for large end diameter (logs), diameter at breast height (snags), and height at least 15 m where noted (snags). Standard errors are for means.

	Tillamook			Siuslaw		
Characteristic	Mean	s.e.	Median	Mean	s.e.	Median
Total Dead Wood Volume, m^3 ha^{-1}						
<50 cm	33.90	4.78	21.34	43.27	4.79	42.49
50-100 cm	118.26	12.5	109.84	148.54	19.68	112.24
≥50 cm	241.75	32.27	192.77	239.37	29.09	223.24
≥100 cm	123.49	24.09	55.58	90.83	14.46	67.11
Total Dead Wood Biomass, Mg ha^{-1}						
<50 cm	8.33	1.17	5.34	11.54	1.31	10.36
50-100 cm	29.97	3.41	27.90	39.10	5.44	30.49
≥50 cm	64.72	9.27	42.92	62.31	7.60	54.41
≥100 cm	34.74	7.05	15.49	23.22	3.82	17.63
Log Volume, m^3 ha^{-1}						
<50 cm	33.69	4.78	21.34	37.46	4.39	34.19
50-100 cm	108.03	12.47	96.13	112.66	16.49	75.40
≥50 cm	192.96	27.67	174.63	138.63	20.28	102.52
≥100 cm	84.93	18.60	47.44	25.98	8.51	0
Log Biomass, Mg ha^{-1}						
<50 cm	8.29	1.18	5.34	9.74	1.17	8.64
50-100 cm	27.70	3.44	24.65	29.76	4.58	22.01
≥50 cm	52.12	8.09	39.29	36.81	5.70	27.77
≥100 cm	24.43	5.54	11.46	7.05	2.38	0
Snags, # ha^{-1}						
<50 cm	0.98	0.54	0	12.99	2.32	13.33
50-100 cm	7.53	1.56	0	24.26	3.98	20.00
≥50 cm	10.94	2.04	6.67	34.76	5.07	26.67
≥50 cm, 15 m ht.	0.31	0.23	0	0.80	0.35	0
≥100 cm	3.40	1.02	0	10.50	1.87	6.67
Snag Volume, m^3 ha^{-1}						
<50 cm	0.21	0.15	0	5.81	1.23	1.97
50-100 cm	10.22	2.56	0	35.88	5.77	23.78
≥50 cm	48.79	15.79	6.38	100.74	14.99	82.11
≥50 cm, 15 m ht.	13.06	9.43	0	8.88	4.37	0
≥100 cm	38.56	15.53	0	64.86	11.67	34.99
Snag Biomass, Mg ha^{-1}						
<50 cm	0.04	0.03	0	1.80	0.40	0.42
50-100 cm	2.28	0.61	0	9.34	1.53	4.39
≥50 cm	12.59	4.59	1.18	25.50	3.72	23.48
≥50 cm, 15 m ht.	4.27	3.08	0	2.89	1.36	0
≥100 cm	10.32	4.55	0	16.16	3.01	7.66
Snag Basal Area, m^2 ha^{-1}						
<50 cm	0.13	0.07	0	1.49	0.27	1.25
50-100 cm	2.91	0.62	0	11.17	1.94	8.89
≥50 cm	8.69	2.08	3.27	24.40	3.58	19.27
≥50 cm, 15 m ht.	0.82	0.59	0	0.77	0.39	0
≥100 cm	5.77	1.96	0	13.23	2.34	9.40

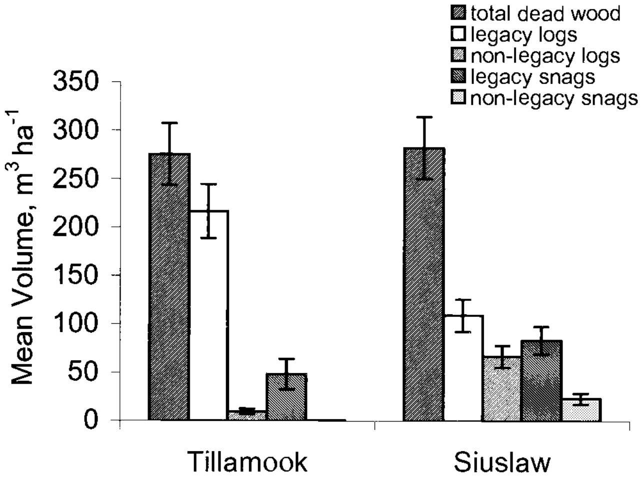


Figure 2.3. The relative contribution of legacy and non-legacy snags and logs to total dead wood volume, by landscape in the Coastal Province of Oregon. Standard error bars are shown.

The relative contribution of legacy and non-legacy dead wood to the total volume of dead wood differed dramatically between the two landscapes (Figure 2.3; Table 2.2). Median volume of legacy logs was greater in the Tillamook, whereas median volumes of non-legacy logs and non-legacy snags were greater in the Siuslaw (Table 2.2). These differences offset each other so that total dead wood volume did not differ between the two landscapes. The Siuslaw had a higher volume of legacy snags (Table 2.2). The Tillamook had a higher basal area of legacy snags plus stumps than the Siuslaw. Patterns for amounts of biomass and carbon were similar to those of volume in both landscapes (Table 2.2).

Most dead wood in both landscapes was of decay classes 3 and 4 (Figure 2.4). The Tillamook had higher mean volume and mass of decay class 3 logs and snags than the Siuslaw (logs $p<0.0001$; snags $p=0.01$ (paired t-tests)). The Siuslaw

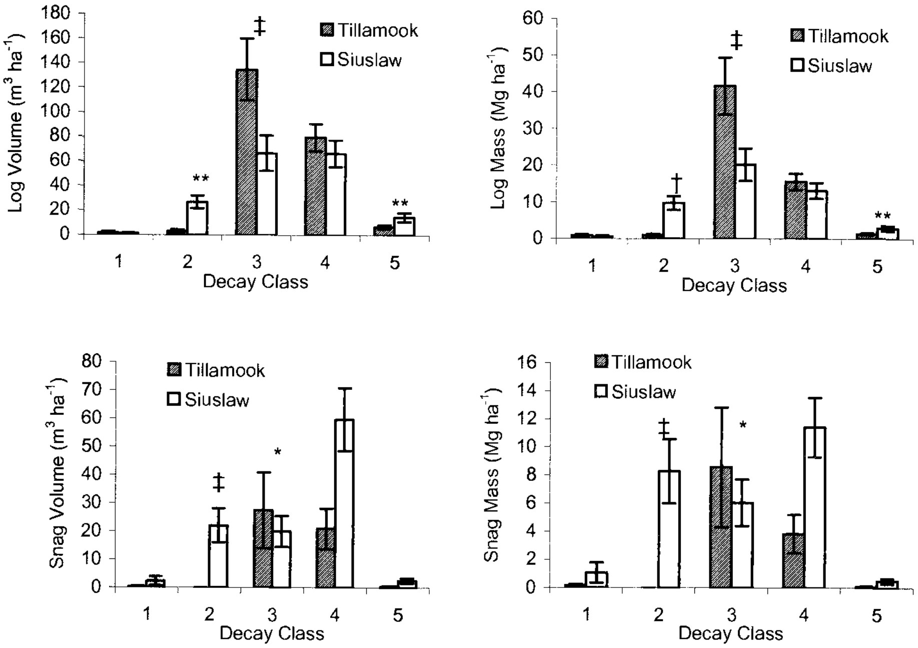


Figure 2.4. Mean volume and mass of logs and snags by decay class and landscape in the Coastal Province of Oregon. Letters above bar pairs in each decay class denote significant difference of means (paired t-test) between landscapes for decay classes at the significance levels of * = $p<0.05$; ** =$p<0.01$; † =: $p<0.001$; ‡ = $p<0.0001$.

had higher volume and mass of decay class 2 and 5 logs and decay class 2 snags than the Tillamook (Figure 2.4). Measured amounts of decay class 5 logs and snags were very low.

Factors related to dead wood abundance

Tillamook State Forest

In the Tillamook State Forest, the models with the highest R^2 values were for non-legacy dead wood (Table 2.4). Topography was the most important independent variable in these models, with highest non-legacy dead wood and log volumes at lower elevations, and higher non-legacy dead wood biomass and numbers of logs at lower slope positions (Table 2.4). For non-legacy logs, climate-related factors were also important, with higher volumes in areas with more annual frost. The historical hardwood vegetation type and riparian locations were positively associated with non-legacy snag volume and basal area. Numbers and basal areas of legacy snags and legacy stumps were greater at higher elevations (Table 2.4).

Siuslaw National Forest

In the Siuslaw National Forest, the models with the highest R^2 values were related to snags (Table 2.4). Current vegetation, historical vegetation, and distance to streams were the most important independent variables in these models. Total numbers of snags, and the number, volume, and basal area of non-legacy snags were positively associated with live tree basal area. The volume, number, and basal areas of legacy and total snags were negatively associated with areas of hardwoods (higher greenness). Snags tended to be found outside stream areas: nearly all models describing snag characteristics indicated a negative relationship of snag abundance with stream topographic positions or presence in the 50 m stream buffer. For example, legacy snag and stump basal area was higher outside of stream plots.

Table 2.4. Regression models of selected dead wood variables on explanatory factors in the Tillamook State Forest and the Siuslaw National Forest in the Coastal Province of Oregon. Explanatory variables were selected using the stepwise regression procedure with $p<0.05$ required to enter and stay. For some dead wood variables no models were produced because no explanatory variables met the criteria to enter and stay, even when these thresholds were raised to $p<0.2$. [a]Biomass model for this class of dead wood had the same variables and direction and magnitude of parameter estimates as this model so is not reported. See Table 1 for explanatory variable names.

Dead Wood Variable	Variable Name	Partial R^2	Regression equation	Model R^2
Tillamook State Forest				
Total Dead Wood				
Dead wood volume (m^3) (ln) [a]	STREAM	0.17	5.27 + 0.80(STREAM)	0.17
Legacy dead wood volume (m^3) (ln) [a]	STREAM	0.14	5.23 + 0.73(STREAM)	0.14
Non-legacy dead wood volume (m^3) (ln)	ELEV	0.20	-11.36 - 0.01(ELEV) + 4.32(ANNFROST) - 0.05(GRN)	0.50
	ANNFROST	0.20		
	GRN	0.09		
Non-legacy dead wood biomass (Mg) (ln)	SLPPOS	0.25	1.35 + 2.31(UPL) - 0.01(SLPPOS)	0.35
	UPL	0.09		
Logs				
Number of logs	STREAM	0.20	30.96 + 201.31(STREAM) – 123.88 (HVDFOG) + 0.35(ELEV)	0.43
	ELEV	0.17		
	HVDFOG	0.06		
Number of legacy logs	LOWER	0.20	232.59 – 143.87(LOWER)	0.20
Number of non-legacy logs (ln)	SLPPOS	0.25	-282.73 -0.02(SLPPOS) + 6.57(MED2R57) + 0.00005(YUTM)	0.45
	YUTM	0.09		
	MED2R57	0.11		
Log volume (m^3) (ln) [a]	STREAM	0.12	4.79 + 0.71(STREAM) + 0.38(ASPTR)	0.22
	ASPTR	0.10		
Legacy log volume (m^3) (ln) [a]	ASPTR	0.11	4.81 + 0.46(ASPTR)	0.11
Non-legacy log volume (m^3) (ln)	ELEV	0.20	-11.30 – 0.01(ELEV) + 4.28(ANNFROST) - 0.05(GRN)	0.50
	ANNFROST	0.20		
	GRN	0.10		
Non-legacy log biomass (Mg) (ln)	SLPPOS	0.25	1.31 + 2.34(UPL) - 0.01(SLPPOS)	0.35
	UPL	0.10		

Table 2.4 contd. Regression models of selected dead wood variables on explanatory factors in the Tillamook State Forest and the Siuslaw National Forest.

Dead Wood Variable	Variable Name	Partial R^2	Regression equation	Model R^2
Tillamook State Forest				
Snags				
Number of legacy snags	STREAM	0.10	11.33 - 8.67(STREAM)	0.10
Number of non-legacy snags (ln)	STRMBUF50	0.17	-1.48(STREAM) + 2.04(HVAAM) + 2.04(STRMBUF50)	0.40
	HVAAM	0.15		
	STREAM	0.09		
Non-legacy snag volume (m^3) (ln) [a]	HVAAM	0.28	2.09(HVAAM) + 0.48(STRMBUF50)	0.42
	STRMBUF50	0.14		
Non-legacy snag basal area (m^2) (ln)	STRMBUF50	0.15	-0.95(STREAM) + 0.86(HVAAM) + 1.21(STRMBUF50)	0.43
	STREAM	0.15		
	HVAAM	0.13		
Number of legacy stumps	ELEV	0.34	-35.11 + 1.77(LIVEBA) + 0.07(ELEV)	0.51
	LIVEBA	0.17		
Legacy stump basal area (m^2)	SLPPOS	0.37	27.96 + 0.51(SLPPOS)	0.37
Legacy snag + stump basal area (m^2)	SLPPOS	0.27	36.25 + 0.49(SLPPOS)	0.27
Siuslaw National Forest				
Total Dead Wood				
Dead wood volume (m^3)	GRN	0.12	639.42 - 121.79(GRN)	0.12
Legacy dead wood volume (m^3) [a]	HVAAM	0.13	172.11 + 176.26(HVAAM)	0.13
Non-legacy dead wood volume (m^3) [a]	SMRPRE	0.24	-5073.25 - 4.38(ANNFROST) + 925.43(SMRPRE)	0.33
	ANNFROST	0.09		
Dead wood biomass (Mg)	SMRPRE	0.14	-2247.90 + 405.55(SMRPRE)	0.14
Logs				
Number of logs (ln)	GRN	0.10	6.33 – 0.53(GRN)	0.10
Number of non-legacy logs	SMRPRE	0.18	-4769.35 - 4.82(ANNFROST) + 873.25(SMRPRE)	0.30
	ANNFROST	0.11		
Log volume (m^3) (ln)	GRN	0.11	6.53 – 0.59(GRN)	0.11
Non-legacy log volume (m^3)	SMRPRE	0.22	-4068.61 - 3.64(ANNFROST) + 742.68(SMRPRE)	0.31
	ANNFROST	0.10		
Log biomass (Mg) (ln)	ANNSW	0.16	34.78 - 0.20(ANNSW)	0.16
Non-legacy log biomass (Mg)	SMRPRE	0.21	-1412.24 - 20.57 (UPL) - 1.55(ANNFROST) + 259.38(SMRPRE)	0.40
	ANNFROST	0.11		
	UPL	0.08		
Snags				
Number of snags	LIVEBA	0.30	82.44 + 0.74(LIVEBA) - 26.41(STRMBUF50) - 20.37(GRN)	0.49
	STRMBUF50	0.10		
	GRN	0.09		
Number of legacy snags	STREAM	0.20	75.18 - 27.99(STREAM) - 14.20(GRN)	0.29
	GRN	0.09		
Number of non-legacy snags	LIVEBA	0.27	-743.06 + 0.50(LIVEBA) - 7.18(ASPTR) + 96.43(ANNPRE)	0.45
	ANNPRE	0.11		
	ASPTR	0.07		

Table 2.4 contd. Regression models of selected dead wood variables on explanatory factors in the Tillamook State Forest and the Siuslaw National Forest.

Siuslaw National Forest				
Snags (contd.)				
Snag volume (m^3)	STREAM	0.20	232.97 - 97.16(STREAM) + 103.58(UPL) - 46.35(GRN)	0.44
	UPL	0.14		
	GRN	0.10		
Legacy snag volume (m^3)	HVAAM	0.18	183.50 + 82.33(UPL) + 75.58(HVAAM) - 69.87(STRMBUF50) - 39.28(GRN)	0.48
	STRMBUF50	0.12		
	UPL	0.09		
	GRN	0.09		
Non-legacy snag volume (m^3) (ln) [a]	LIVEBA	0.25	-0.10 + 0.05(LIVEBA) + 2.34(HVDFSSG)	0.37
	HVDFSSG	0.13		
Snag biomass (Mg)	STREAM	0.20	123.66 - 26.98(STREAM) + 27.59(UPL) - 8.55(AUGMAXT) + 3.41(R57)	0.56
	AUGMAXT	0.17		
	UPL	0.14		
	R57	0.05		
Legacy snag biomass (Mg)	HVAAM	0.26	-840.19 - 14.22(STREAM) + 22.61(UPL) + 22.30(HVAAM) + 87.50(ANNHDD) + 2.97(R57)	0.56
	STREAM	0.09		
	UPL	0.09		
	ANNHDD	0.07		
	R57	0.06		
Snag basal area (m^2)	STREAM	0.21	63.70 – 20.75(STREAM) – 12.89(GRN)	0.35
	GRN	0.14		
Legacy snag basal area (m^2)	STREAM	0.18	55.56 – 17.56(STREAM) – 11.47(GRN)	0.30
	GRN	0.13		
Non-legacy snag basal area (m^2) (ln)	LIVEBA	0.24	-0.12 + 0.03(LIVEBA) + 1.51(HVDFSSG)	0.40
	HVDFSSG	0.15		
Number of legacy stumps (ln)	ANNSW	0.24	8.38 – 1.01(STREAM) + 0.26(ANNSW) – 8.14(SMRPRE)	0.40
	SMRPRE	0.08		
	STREAM	0.07		
Legacy stump basal area (m^2) (ln)	ANNSW	0.25	45.54 + 1.07(SEDR) – 10.02(ANNPRE) + 0.20(ANNSW) + 0.14(WET)	0.54
	ANNPRE	0.14		
	WET	0.07		
	SEDR	0.09		
Legacy snag + stump basal area (m^2) (ln)	STREAM	0.46	325.01 – 2.27(STREAM) – 2.98(MAFO) – 0.00006(Y) – 0.50(AUGMAXT)	0.66
	Y	0.09		
	MAFO	0.06		
	AUGMAXT	0.05		

Legacy snag volume and biomass were positively associated with historical hardwoods, whereas non-legacy snag volume and basal areas were positively associated with the occurrence of historical small second-growth Douglas-fir. Climate was also of some importance: total snag biomass and legacy snag and stump basal area were lower in areas with lower August maximum temperatures, and the number of non-legacy snags was higher where annual precipitation was higher. The abundance, volume, and biomass of non-legacy logs and the total volume of non-legacy dead wood were positively associated with sites with higher summer precipitation and more frost-free days per year (Table 2.4).

Relative contribution of factors to explained variation in overall patterns of dead wood

In both landscapes, overall gradients in dead wood were most strongly associated with topography, climate, and current vegetation, in that order (Table 2.5). In the Tillamook, the full model explained 63% of the total explained variation, and in the Siuslaw, 79%. In the Siuslaw, climate and location were somewhat more important than in the Tillamook. In the Tillamook, snag variables grouped with higher slope positions and high elevation streams, and log volume and number grouped with lower slope positions. In the Siuslaw, log volume and number and dead wood volume variables grouped near stream plots and in areas with higher August maximum temperatures, and snag variables grouped away from stream plots in areas with more summer rains.

Table 2.5. Relative contribution to explained variation (Axes 1 and 2) by subsets of factors associated with dead wood gradients in the Tillamook State Forest and the Siuslaw National Forest in the Coastal Province of Oregon, from canonical correspondence analysis (CCA). Dead wood variables included in CCA were: number of logs, log volume, number of snags, snag volume, snag basal area, legacy snag and stump basal area, and dead wood volume. See Table 1 for variable membership in subsets.

Subset of explanatory variable	Percentage of total inertia	
	Tillamook	Siuslaw
Climate	16.6	25.2
Topography	39.2	38.0
Current Vegetation	13.9	17.1
Historical Vegetation	2.8	7.2
Location	5.3	16.7
Geology	2.2	--
Ecoregion	--	5.4

Topography

Because topography was important in many regression models describing dead wood patterns, I further explored relationships between dead wood and topography. In both landscapes, I found relatively little difference in dead wood amounts according to topography except with respect to streams (Figure 2.5; Table 2.6). In the Tillamook, stream areas had higher median log volumes than all other topographic positions (Figure 2.5 a). In the Siuslaw, stream locations had lower snag basal areas than other locations (Figure 2.5 b). The frequency distributions for landscape mean log volume, snag basal area, and legacy source wood basal area

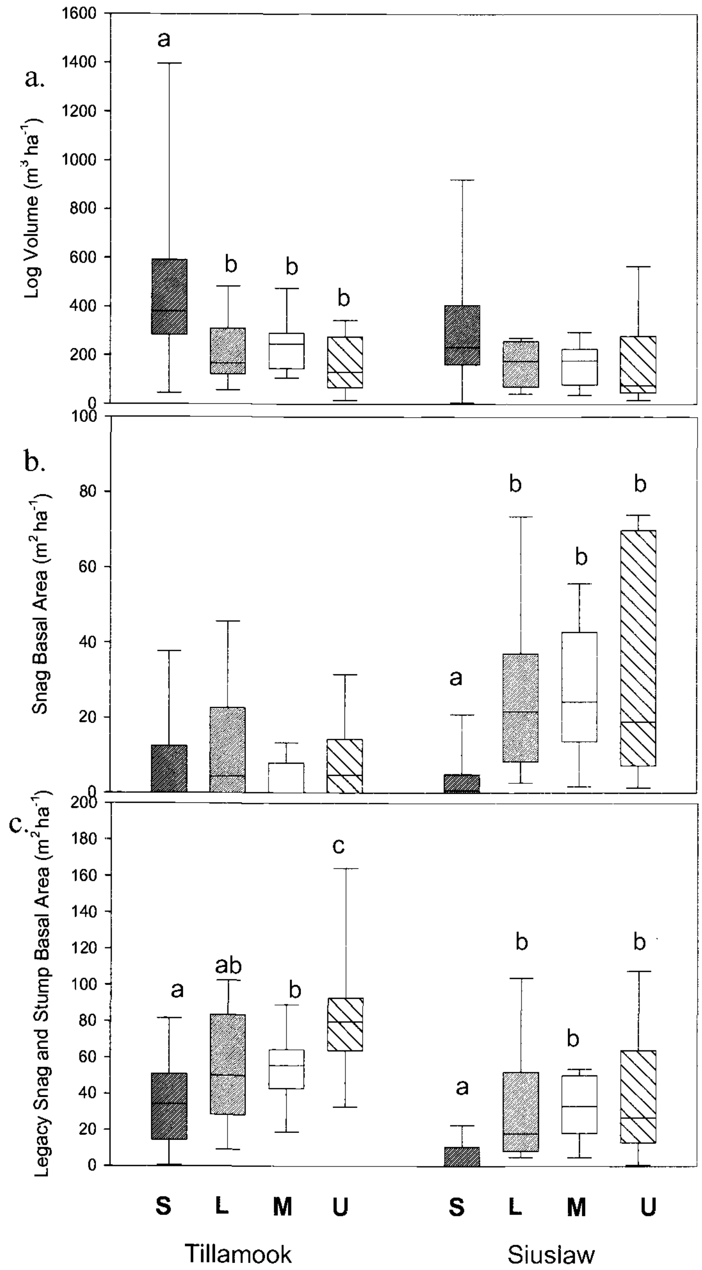


Figure 2.5. Distribution of log volume, snag basal area, and legacy snag and stump basal area, by topographic position and landscape in the Coastal Province of Oregon. Lower and upper boundaries of boxes represent the 25th and 75th percentiles, lower and upper whiskers the 10th and 90th percentiles, and mid-line the median. S=Stream, L=Lower slope, M=Midslope, U=Upper slope. Different letters above bars indicate differences among topographic positions within each landscape ($p<0.05$ from Kruskal-Wallis tests followed by paired Wilcoxon rank sum tests).

were positively skewed (Figure 2.6). Steam and lower slope plots had some of the highest log volumes, while upper slope positions had a high proportion of the lowest values. Upper slope positions had some of the highest values for snag basal area (Figure 2.6). In the Tillamook, most non-legacy logs and snags occurred near streams and at lower topographic positions (Table 2.6). By contrast, in the Siuslaw, non-legacy logs and snags occurred in all topographic positions. Amounts

Table 2.6. Mean values per hectare of dead wood variables by topographic position in two landscapes in the Coastal Province of Oregon. Standard errors for means are shown. Ten plots per topographic position were sampled in each landscape.

	Streams		Lower		Middle		Upper	
Variable	Mean	s.e.	Mean	s.e.	Mean	s.e.	Mean	s.e.
Tillamook								
Total Dead Wood								
Dead wood volume (m^3)	528.5	130.0	282.9	63.4	255.6	35.9	202.8	46.1
Dead wood biomass (Mg)	150.3	39.7	73.3	17.8	69.0	9.8	52.6	12.4
Dead wood carbon (Mg)	78.2	20.7	38.2	9.3	36.0	5.1	27.4	6.4
Legacy dead wood volume (m^3)	495.1	134.1	268.7	62.3	251.5	37.5	200.9	46.3
Non-legacy dead wood volume (m^3)	33.5	13.3	14.3	5.8	4.1	3.6	1.9	1.9
Logs								
Number of logs	320.3	53.2	114.6	14.7	200.8	36.6	202.0	46.8
Number of legacy logs	287.3	55.5	101.3	14.6	198.9	36.4	199.0	46.7
Number of non-legacy logs	33.1	14.2	13.3	4.7	1.8	1.5	3.0	3.0
Log volume (m^3)	503.9	132.3	207.3	42.2	242.3	35.5	162.1	36.5
Legacy log volume (m^3)	472.0	135.6	194.0	44.1	238.2	36.9	160.3	36.6
Non-legacy log volume (m3)	31.9	13.2	13.4	5.5	4.1	3.6	1.9	1.9
Snags								
Number of snags	6.7	3.6	14.7	4.6	6.0	3.1	14.7	4.6
Number of legacy snags	2.7	1.5	13.3	4.2	6.0	3.1	14.7	4.6
Number of non-legacy snags	4.0	3.3	1.3	0.9	0.0	0.0	0.0	0.0
Snag basal area (m^2)	7.5	4.2	12.1	5.2	3.2	1.6	8.6	3.5
Legacy snag basal area (m^2)	6.9	4.1	11.8	5.2	3.2	1.6	8.6	3.5
Non-legacy snag basal area (m2)	0.6	0.5	0.4	0.3	0.0	0.0	0.0	0.0
Snag volume (m^3)	24.6	14.9	75.6	43.5	13.3	7.7	40.7	19.9
Legacy snag volume (m^3)	23.1	14.7	74.7	43.5	13.3	7.7	40.7	19.9
Non-legacy snag volume (m3)	1.5	1.1	0.9	0.7	0.0	0.0	0.0	0.0
Legacy snag + stump basal area (m^2)	34.7	8.1	52.6	9.8	53.8	7.0	83.3	11.6

Table 2.6 contd. Mean values per hectare of dead wood variables by topographic position in two landscapes in the Coastal Province of Oregon.

	Streams		Lower		Middle		Upper	
Variable	Mean	s.e.	Mean	s.e.	Mean	s.e.	Mean	s.e.
Siuslaw								
Total Dead Wood								
Dead wood volume (m^3)	323.0	96.4	270.7	38.8	282.7	52.5	291.7	98.0
Dead wood biomass (Mg)	96.1	28.7	69.9	9.9	70.9	13.0	77.7	25.8
Dead wood carbon (Mg)	49.8	14.9	36.3	5.2	36.9	6.7	40.4	13.4
Legacy dead wood volume (m^3)	227.2	80.6	165.2	33.5	236.2	52.7	183.2	65.5
Non-legacy dead wood volume (m^3)	95.8	27.1	105.5	27.0	46.5	14.7	108.5	38.6
Logs								
Number of logs	256.7	75.8	151.9	27.8	160.3	21.8	162.6	61.5
Number of legacy logs	145.4	50.0	63.8	9.4	121.6	20.6	85.3	26.7
Number of non-legacy logs	111.3	35.3	88.1	24.7	38.7	10.8	77.3	36.8
Log volume (m^3)	307.4	88.1	166.2	28.9	164.0	27.1	172.8	67.3
Legacy log volume (m^3)	213.7	73.5	85.8	17.9	127.3	26.5	102.9	41.9
Non-legacy log volume (m3)	93.7	26.0	80.4	21.8	36.7	11.2	69.8	30.1
Snags								
Number of snags	8.0	3.4	45.3	8.8	46.0	7.2	62.7	17.7
Number of legacy snags	4.0	2.3	26.0	7.7	38.7	7.0	42.0	14.0
Number of non-legacy snags	4.0	2.0	19.3	7.4	7.3	1.9	20.7	7.1
Snag basal area (m^2)	3.8	2.2	25.2	7.0	27.7	5.7	30.4	9.4
Legacy snag basal area (m^2)	3.1	2.0	20.3	7.3	25.7	5.6	24.7	8.4
Non-legacy snag basal area (m2)	0.7	0.4	4.9	1.9	1.9	0.8	5.7	2.5
Snag volume (m^3)	15.6	10.4	104.5	26.7	118.7	34.7	118.9	34.2
Legacy snag volume (m^3)	13.5	9.6	79.4	28.6	108.9	34.3	80.3	26.6
Non-legacy snag volume (m3)	2.1	1.3	25.1	10.0	9.8	4.5	38.6	17.5
Legacy snag + stump basal area (m^2)	5.0	2.8	32.4	11.0	32.6	5.4	39.9	11.0

of non-legacy logs were highest in stream and lower slope positions, while amounts of non-legacy snags were higher at upper and lower slope positions (Table 2.6).

Topographic positions differed in their potential to produce dead wood in both sampled landscapes, as evidenced by the basal area of legacy snags and stumps. Higher basal areas of legacy snags and stumps were found in upper slope areas than on lower slopes (Figure 2.5), suggesting that these areas could produce

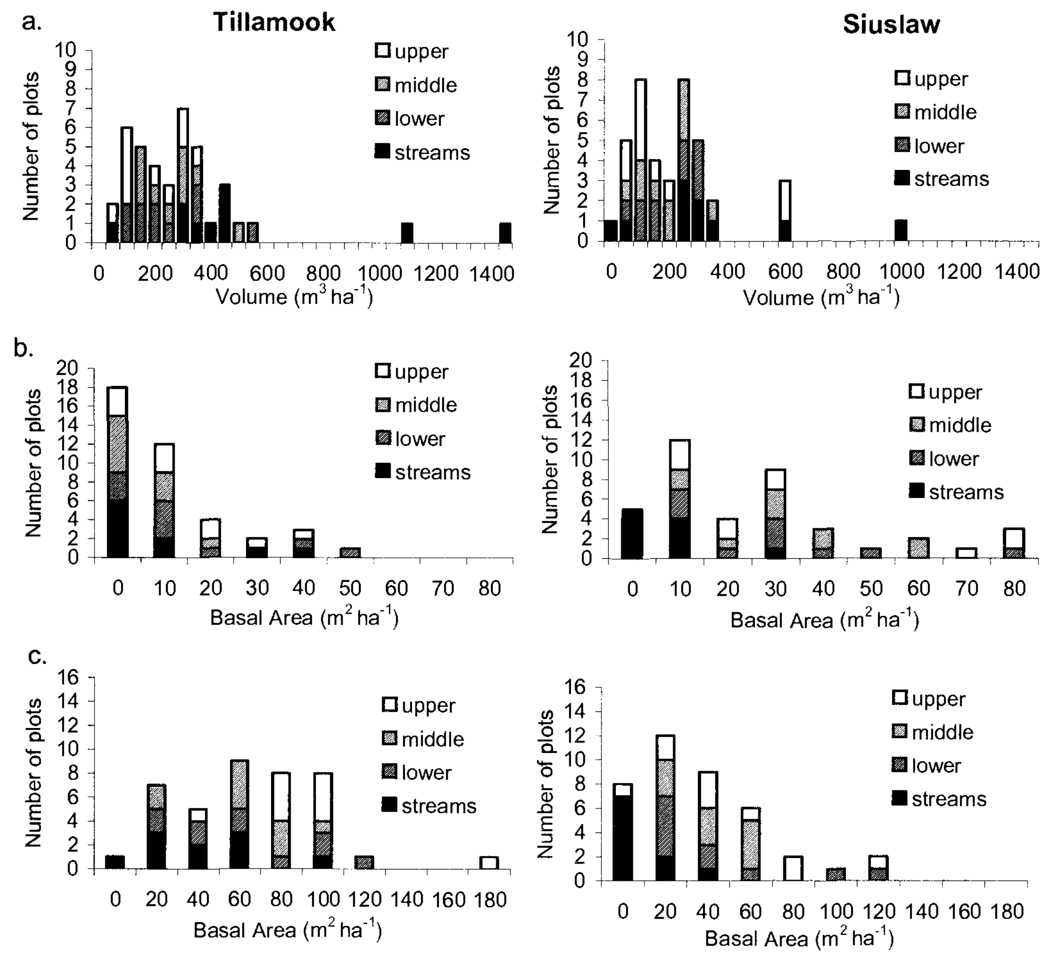


Figure 2.6. Frequency distribution of mean (a) log volume, (b) snag basal area, and (c) legacy snag and stump basal area, per hectare, by topographic position and landscape in the Coastal Province of Oregon.

more legacy dead wood than lower topographic positions. Higher total dead wood amounts occurred in lower slope areas, suggesting that upper slopes might be source areas, and lower slopes sink areas, for dead wood. This pattern was very pronounced in the Tillamook, where disturbance is relatively recent. It was moderately evident in the Siuslaw, where stream plots had significantly lower amounts of legacy snags and stumps; log volume was not significantly higher in stream plots but some of the highest volumes occurred there (Figure 2.5).

Discussion

Disturbance effects

Disturbance history affected the type (size, origin) of dead wood present more than it did the total amount of dead wood in the two landscapes. In the Tillamook, with relatively recent catastrophic fire and post-fire salvage, there were overall dead wood volumes that were similar to those of the Siuslaw, which had burned several decades earlier and had not undergone salvage. Most of the volume of dead wood in the recently burned and salvaged landscape was in the form of legacy logs, whereas the landscape that burned longer ago had a more even distribution of volume among legacy logs, non-legacy logs, and legacy snags.

The observation of higher volumes of logs in the Tillamook than the Siuslaw is generally consistent with stand-level research on differences in dead wood amounts with respect to time since disturbance (Spies et al. 1988). I expected that most of the dead wood in both landscapes would be in the form of logs. This is because snags in Douglas-fir forests have a tendency to deteriorate and/or fall within a few decades after disturbance (Cline et al. 1980). In both landscapes I did observe that most of the dead wood was in the form of logs. I expected that with greater time for decay, the landscape that burned earlier would have lower log mass and volume. Log volume in the Tillamook, where fires last occurred 60-70 years ago, was indeed greater than that of the Siuslaw, which last experienced fire 120-150 years ago. However, the amounts in the Tillamook would probably have been even higher were it not for the extensive salvage that took place there. It is estimated that approximately 7.5 billion board feet (roughly equivalent to 1.5 billion ft^3 or 42.5 million m^3) of timber were removed from the Tillamook between the years 1934-1955 (Oregon Department of Forestry. 1997). There was additional salvage of high value slow-decaying species, such as western redcedar, continuing nearly to the present day (Fick and Martin 1992). On a per hectare basis in the Tillamook State Forest area, the estimated amount salvaged represents approximately a decrease of 295 m^3 ha^{-1} of dead wood volume from pre-removal levels in the burned area. Based on the results of simulation modeling of dead wood dynamics in the Coast Range (Kennedy, unpublished data), about 60% of the volume of large dead wood in the Tillamook might be expected to remain after 60 years. Thus, without salvage, after 60 years of decay, post-fire dead wood volumes in the Tillamook might be expected to be more on the order of 450 m^3 ha^{-1} rather than 300 m^3 ha^{-1}. In old-growth forests affected by catastrophic fire, salvage activities may depress volumes of dead wood significantly. This may result in dead wood volumes that more closely resemble a forest at greater time since disturbance. This might be more pronounced if the catastrophic disturbance event and subsequent salvage have occurred fairly recently, relative to the time required for the loss of dead wood from the system through decay processes.

The finding that log volume varied by topographic position in the Tillamook State Forest was probably related in part to the locations where salvage logging was conducted after the fires. "Snag free" roads were established along ridgelines throughout the Tillamook to serve as fire breaks, and felled snags were pulled away from these zones (Levesque 1985). Thereby, salvage undoubtedly affected both log and snag amounts and their distribution in the Tillamook. Despite the salvage, the Tillamook still had higher amounts of logs than did the Siuslaw. The similarity of distributions of log volumes in the two landscapes suggests that salvage logging did not strongly alter the spatial and topographic patterns of dead wood, but instead lowered the overall amount of dead wood present.

The effects of salvage on the current number of large snags in the Tillamook were great. The legacy snag and stump basal area in the Tillamook, was mainly comprised of legacy stumps (Table 2.2). This confirms reports that most large snags in the Tillamook were felled during salvage operations (Levesque 1985, Fick and Martin 1992). The presence of cut ends on most of the logs I sampled further confirms reports of the extensive felling of snags. Because of salvage, I found few large old snags remaining at present day in the Tillamook. This in turn influenced the relative abundance of logs versus snags in the Tillamook, shifting the proportion toward logs.

Differences between the two landscapes in the proportion of logs and snags that were legacy and non-legacy dead wood are attributable to differences in the timing and type of disturbance. The Siuslaw's higher frequency of snags derived from post-fire stands can be expected, given that the trees that are dying now in the Siuslaw are older and more massive than those of the Tillamook. The Siuslaw's higher amount of legacy snags is understandable given the snag felling in the Tillamook. The Tillamook's higher volume of legacy logs is not surprising given the shorter time for decay there. The fact that most dead wood volume and biomass in both landscapes was of decay classes 3 and 4 is not surprising given the geometrically increasing residence time of large dead wood in decay classes in Pacific Northwest forests (Harmon et al. 1986, Sollins et al. 1987).

At the stand level, a U-shaped curve has been used as a model to describe temporal patterns of dead wood amounts for a 450-year-old conifer forest in western Oregon or Washington (Spies et al. 1988). This model includes a pulse of dead wood following disturbance, followed by lower than pre-disturbance levels, as remnant carryover and fire mortality-created dead wood decays and new wood is produced by the developing stand. There is then a gradual increase in dead wood after about 200 years based mainly on input from the new stand to pre-disturbance levels, as the stand age approaches 500 years once more (Spies et al. 1988). My results are generally consistent with this model, with some differences. Amounts of legacy wood in the Siuslaw appear to be higher than predicted by the stand-level model (Spies et al. 1988), which showed legacy dead wood levels close to near-zero amounts at 100 years since the first of a series of fires. The higher amounts in the mature forests of the Siuslaw may result from higher decay rates or higher survivorship in the model as compared to the actual situation in the Siuslaw. It is likely that variability in surviving trees and/or decay among the stands that comprise landscapes may lead to a longer time of presence of legacy wood, when dead wood is evaluated at the landscape level.

Topographic effects

Few other studies of temperate landscapes have evaluated dead wood patterns in relation to topographic position (but cf. (Rubino and McCarthy 2003), although the importance of better understanding the relationships between topography and the spatial distribution of dead wood has been noted (Harmon et al. 1986, May and Gresswell 2003). Spies et al. (1988) evaluated the biomass of dead wood in forest stands of Oregon and Washington on dry, moderate, and moist sites, which tended to be located at higher, middle, and lower elevations, respectively. They found that dead wood mass tended to be greatest on moist sites, intermediate on moderate sites, and lowest on dry sites. For stands in the Coast Range, Spies et al. (1988) found that topographic position and aspect explained 63% of the variation in dead wood biomass, but was less important in Cascade Range models (Spies et al. 1988). In another study, in a mixed-oak forest landscape in Ohio, total down wood density (pieces ha^{-1}) was found to be positively correlated with increasing slope position and negatively correlated with percent slope; likewise, the volume of decay class 4 (moderately-highly-decayed) logs was positively correlated with increasing slope position. The volume of decay class 5 (highly-decayed) logs was negatively correlated with aspect (Rubino and McCarthy 2003).

Studies of dead wood in tropical forests have found conflicting relationships between topography and dead wood patterns. A study comparing dead wood amounts on flat, old alluvial terraces, flat ridgetops, and steep slopes in a tropical rain forest landscape in Costa Rica found no significant differences in volume, biomass, or number of pieces of standing or down wood along this topographic gradient, perhaps due to high inter-site variability in tree mortality or high inter-annual variability in dead wood inputs and temperature over the three-year study period (Clark et al. 2002). On the other hand, in a study of four tropical rain forests in Borneo and Ecuador, the number and basal area of snags increased with increasing slope position from valleys to ridges, with the volume of snags four times higher on ridge tops (54 m^3 ha^{-1}) compared with valley and midslope positions (both 13 m^3 ha^{-1}) (Gale 2000). However, in this study of tropical forests, log volume did not vary with slope position (Gale 2000).

According to the results of the present study, topography, and in particular slope position, was strongly associated with log and snag amounts at the landscape scale. This is probably in part because larger trees tended to be found more often at upper slope positions. Riparian forests in these landscapes are often dominated by red alder (*Alnus rubra*) (Hibbs et al. 1994), a disturbance-related species that does not attain great size relative to longer-lived conifers such as Douglas-fir (*Pseudotsuga menziesii*) and western redcedar (*Thuja plicata*) (Burns and Honkala 1990). In the Coast Range of Oregon, conifer basal area has been found to increase with increasing distance from streams (Pabst and Spies 1999). The fact that decay rates of wood in streams may be lower than those on terrestrial sites (Harmon et al. 1986) might also have contributed slightly to the higher log volumes observed for stream plots than those observed elsewhere.

In this study, slope position was also strongly associated with the locations of what was considered to be potential source areas for dead wood (legacy snags and stumps) and sink areas for dead wood (logs). I am aware of no prior landscape study that has estimated the landscape distribution of upslope and riparian dead wood, or that has evaluated patterns to see if they were consistent with source-sink processes related to topography. A few studies of debris flows and dead wood in streams have tracked the recruitment mechanisms for dead wood, with one study indicating that slope instability and windthrow are the two main delivery mechanisms in second- and third-order channels when wood is delivered from local hillslopes and riparian areas (May and Gresswell 2003). The present study documents the overall landscape distribution for dead wood including streams and non-stream areas at differing locations within a basin. The findings of this study also indicate that mid- to upper slopes may be source areas for dead wood, as there were higher basal areas of legacy snags and stumps there, and streams may be sink areas, with higher volumes of logs there. In the present study, streams in the Tillamook landscape contained approximately 2 to 3 times the volume of logs of the other slope positions, and streams in the Siuslaw landscape contained approximately 2 times the volume of logs of the other slope positions. Streams and the areas within 12.5 m of them comprised only about 6% of the landscape area, but provided approximately 15% of total log volume in the Tillamook, and 11% of total dead wood volume in the Siuslaw.

The potential function of upper and mid-slopes as source areas for dead wood is probably related to the characteristics of riparian vs upslope forests, and to gravity. The lower basal areas of live trees near streams (Pabst and Spies 1999) means that these areas have less material for the potential contribution to the dead wood pool. The lower snag basal areas found at stream topographic positions in both landscapes in this study may be attributed in part to this feature of riparian forests. It may also be attributed to the propensity for trees to fall when they die along lower order streams. In fact, slope instability was the leading recruitment process of wood delivered to second-order stream channels in an old-growth stream basin in the Oregon Coast Range (May and Gresswell 2003). In general, the streams measured in this study probably also received dead wood as a result of landslides, floods, windthrow, and debris flows that killed trees or transported already dead wood (Bisson et al. 1986, Fetherston et al. 1995). These processes probably occurred in both stream and non-stream topographic positions, with delivery directed downslope to streams.

Relationships with climate

Patterns of climate may be of moderate importance in explaining patterns of dead wood in landscapes. Relative to the regional level, in a landscape that typically is fairly homogeneous as to general habitat type (i.e. westside conifer-hardwood forest), climatic differences may be less of a determinant of vegetation and consequent dead wood patterns. At the regional level, differences in climatic regimes such as temperature and precipitation presumably lead to wide variability in the habitat types present (i.e., juniper woodland and westside conifer forest both occur in the forested habitats of Oregon and Washington (Ohmann and Waddell 2002)). It is therefore not surprising that at the landscape level, differences in dead wood patterns are strongly associated with patterns of topography, which tended to have high variation across the two landscapes studied. However, I expected climate to have some importance, for at least three reasons: first, variations in climate do occur across landscapes, including those evaluated in this study; second, patterns of live vegetation (which may be related to the kinds of dead wood produced) may vary according to climatic gradients (Ohmann and Spies 1998, Ohmann and Gregory 2002) even within landscapes (Franklin and Dyrness 1988); and third, dead wood decay processes may vary according to differences in climatic conditions, including moisture and temperature (Harmon et al. 1986). My results do indicate that climatic factors were strongly associated with some of the dead wood patterns in both landscapes.

The results of this study indicated that climate was of modest relevance to dead wood patterns in the Tillamook and relatively greater significance in the Siuslaw. This may be because the landscapes have differences in the patterns of climate variables evaluated, and/or because the landscapes are of different ages and climate is of increasing relevance to processes and patterns related to dead wood production and decay as the time since catastrophic disturbance increases. Climate is thought to be an underlying driver of regional differences in habitat (Ohmann 2000) and dead wood patterns across habitat types (Ohmann and Waddell 2002). It may be that in forested landscapes, habitat differences based on physical environment and ecosystem processes, driven by climate, are of increasing relevance to dead wood patterns with increasing time since catastrophic disturbance. This is probably in part because the dead wood produced via the disturbance event declines in amount as time since disturbance increases as it decays, is mobilized by floods or landslides, or is transported from the landscape (Maser et al. 1988). New contributions to the dead wood pool are produced by the developing forests, which vary in the potential to produce dead wood according to habitat type. Thus, over time since disturbance, potentially more subtle processes and patterns such as climate and related gradients of productivity and vegetation type may be of relatively greater relevance to landscape patterns of dead wood.

Conclusion

The total volume of dead wood was similar among the two landscapes studied, but the allocation among types (sizes, origin) of dead wood differed. Overall similarity of dead wood volume was probably the result of post-fire salvage in the Tillamook. However, in the Tillamook, high amounts of legacy wood remained even after salvage, probably because the pre-fire forests were primarily old-growth and contained many very large trees. The relative amount of legacy and non-legacy wood, and snag and log amounts differed between the two landscapes, reflecting differences in the timing and types of disturbance. Climate-related patterns and processes may be of increasing relevance to dead wood patterns in landscapes as time since catastrophic disturbance increases. In these landscapes, topography is strongly related to landscape-level dead wood patterns, and streams contain disproportionately high amounts of dead wood in relation to their area in the landscape. Upper and mid-slope positions may be source areas for dead wood, and stream areas sinks. At the landscape level, legacy wood may be present for multiple centuries, both resulting from the slow decay of large pieces, and through the averaging of stand-level variability in the timing and amount of dead wood production following large disturbance events.

Chapter 3: Patterns of dead wood abundance and relationships with biophysical and ownership characteristics according to scale in the forests of the Coastal Province of Oregon, USA

Introduction

Dead wood has important influences on long-term productivity and biodiversity in forest ecosystems (Harmon et al. 1986, Spies et al. 1988, Franklin 1990, Harcombe et al. 1990, Tyrrell and Crow 1994, Cohen et al. 1996, Jonsson and Kruys 2001, Barrett 2002, Lindenmayer and Franklin 2002, MacNally et al. 2002, Mellen et al. 2003). Understanding patterns and processes related to the abundance of dead wood is facilitated by examining multiple spatial and temporal scales, since related factors may differ by scale. This is of interest to scientists and managers concerned with forest attributes such as the potential contribution of particular forest landscapes to regional biodiversity or the spatial distribution of fuels in watersheds. Determining the relevant scales of patterns and processes related to dead wood abundance may also be of assistance to the attainment of management goals such as increasing the efficiency of forest management (National Forest System Land and Resource Planning Rules, Federal Register 36 CFR Part 219, RIN 0596-AB86), reducing fire risk (Healthy Forests Restoration Act of 2003, HR 1904), and maintaining the sustainability of ecological systems (U.S. Department of Agriculture Forest Service and U.S. Department of the Interior Bureau of Land Management. 1994a).

The amount and types of dead wood in a region reflects a variety of related processes. In fire-prone regions such as the Pacific Northwestern U.S.A. (Agee 1993), infrequent large fire events may create large amounts of dead wood in the form of snags and logs, whereas persistent, recurring, low-severity fires may reduce the amount of dead wood (Skinner 2002). Harvest frequency and intensity, combined with dead wood treatment, also may control the amounts and types of dead wood found in managed forests (Ferguson and Elkie 2003). Landslides and floods may contribute to the production, migration, and repositioning of dead wood, especially in near-stream areas or areas of steep slopes (Maser et al. 1988, May and Gresswell 2003). Topography may be related to dead wood patterns, as some topographic positions may be source or sink areas for movement of dead wood. Site productivity, which is related to soils and climatic factors, influences the potential of an area to produce large trees which may eventually become large dead wood. Microclimate conditions influence the decay rates of dead wood (Harmon et al. 1986). Thus, multiple factors are involved in determining the amount and types of dead wood that occur and the variability of dead wood across landscapes and regions. The importance of these factors may differ with scale.

Landowner behavior may have a strong influence on the distribution of dead wood. In the Coastal Province of Oregon, USA, forest management activities vary according to ownership type. The federal lands are managed largely to promote late successional and old-growth forest conditions and old-growth associated biodiversity, protect threatened and endangered species, and to promote aquatic health (U.S. Department of Agriculture Forest Service and U.S. Department of the Interior Bureau of Land Management. 1994b). The State of Oregon lands are managed to promote healthy forests, protect indigenous species, protect threatened and endangered species, and produce timber (Oregon Department of Forestry. 2001a, b). Private lands are managed with a focus on commodity production, and also aim to protect the environment, fish and wildlife (Oregon Department of Forestry 2001). These differences in goals among ownership groups affect the type and timing of harvest and the treatment of dead wood.

It is important to understand the relative importance of biophysical factors and forest management to dead wood patterns at multiple scales for several reasons. First, landscapes such as those in the Oregon Coastal Province are increasingly managed for long-term and broad scale goals such as large patches of older forest (U.S. Department of Agriculture Forest Service and U.S. Department of the Interior Bureau of Land Management. 1994b). Second, species and ecological processes often cross ownership lines, and a better understanding of potential differences in dead wood patterns by ownership can help in habitat assessment. Third, present-day patterns of dead wood may not reflect current management practices due to the longevity of large pieces of dead wood relative to the advent and duration of forest plans, so any adverse effects of management on long-term dead wood abundance may be masked if present-day conditions alone are evaluated. Fourth, since the apparent influence of factors may depend on scale, the efficacy of forest management to achieve goals related to dead wood retention or production may be limited without an understanding of the controls on patterns of dead wood.

I studied the current patterns of dead wood and related patterns and processes in the Coastal Province of Oregon at multiple spatial scales, as defined by different levels of spatial resolution from plots to subbasins. The study had four main objectives: (1) to describe current regional amounts of several characteristics of dead wood; (2) to compare dead wood amounts across ownerships; (3) to determine the relationships between current dead wood amounts and ownership, current and past vegetation conditions, climate, topography, and soils; and (4) to evaluate whether the factors related to dead wood patterns differed according to the scale of analysis.

I had several working hypotheses. I presumed that climate, with its influences on site productivity, might be the most strongly related factor at the regional scale (Ohmann and Gregory 2002). Further, I was interested to determine whether ownership effects were more pronounced than those of climate at the regional scale. Since forest management linked to ownership has been shown to have a strong effect on the patterns of live vegetation in the region (Ohmann et al. accepted), I presumed that similar relationships might hold for the patterns of dead wood. I found in a study of two landscapes (Kennedy and Spies in prep.) that topography, in particular distance to streams and slope position, was very important to dead wood amounts at the landscape scale. Therefore, I hypothesized that topography might also be important at large sub-regional scales. Since decay rates of large dead wood may be long relative to cycles of forest management in this region (Sollins 1982), patterns of recent historical vegetation, which may reflect historical disturbance patterns such as large fire events, incidence of grazing, and prior harvest (Moe 1993), might also explain current patterns of dead wood abundance.

Methods

The study area

The study was carried out in the Coastal Province of Oregon, an area of almost 30,000 km^2, in the Pacific Northwest region of the United States (Figure 3.1). The Coast Range mountains run north-south through the Province, are steep and rugged, and contain a dense network of intermittent and perennial streams. Elevations range from sea level to 1247 m. The climate of the Coastal Province is maritime, with warm, dry summers and cool, wet winters; the high levels of precipitation (2500-3000 mm/yr) in the area occur primarily as winter rains, or as snows at higher elevations. Growing-season moisture stress increases with increasing distance to the coast as temperature increases and precipitation decreases. Soils in the region are derived mainly from marine sandstones and basaltic volcanics (Franklin and Dyrness 1988).

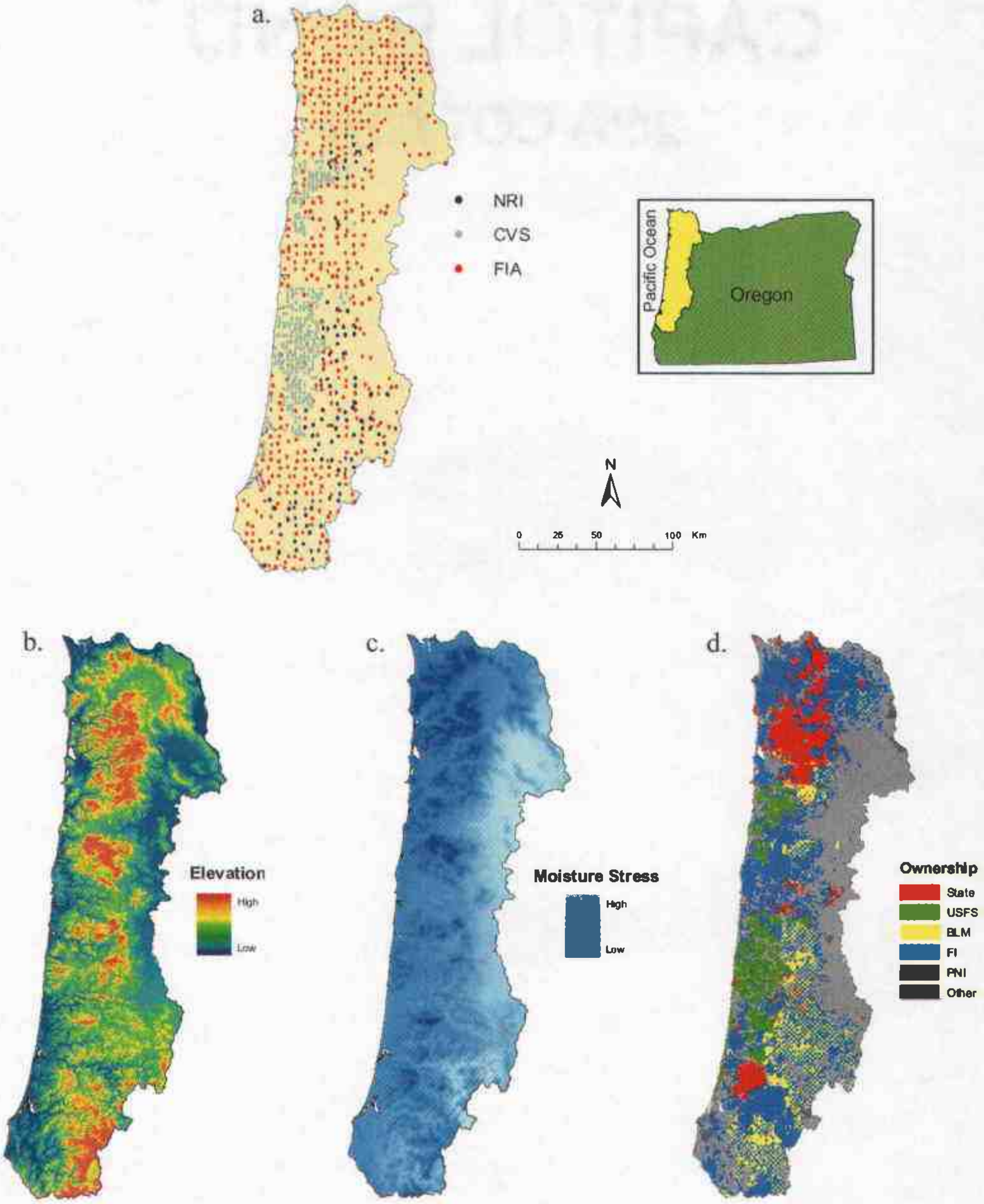


Figure 3.1. Location of plots and selected independent variables used to model dead wood amounts in the Coastal Province of Oregon. (a) Plot locations; (b) Elevation; (c) Moisture stress index; (d) Ownership class. See Table 1 for a list and description of all independent variables. See text for description of plot types.

The Coastal Province is a region of highly productive coniferous forests, occurring in the western hemlock (*Tsuga heterophylla*) and Sitka spruce (*Picea sitchensis*) vegetation zones (Franklin and Dyrness 1988). The dominant tree species include Douglas-fir (*Pseudotsuga menziesii*), western hemlock, western redcedar (*Thuja plicata*), and Sitka spruce, the latter prevalent in areas near the coast. Hardwood trees, especially red alder (*Alnus rubra*) and bigleaf maple (*Acer macrophyllum*), occur in patches in the coniferous matrix, often near streams or on recently disturbed sites (Franklin and Dyrness 1988, Kennedy and Spies 2005).

Vegetation occurs primarily in forested patches that are typically up to 150 years in age on public lands and 60 years in age on private lands. Land ownership of the forested areas is mainly public (Forest Service, Bureau of Land Management, State) or is owned by forest industry, and is not strongly differentiated by topography; non-industrial private land ownership tends to occur in the inland and coastal valleys. Bureau of Land Management holdings tend to be interspersed with forest industry lands in a checkerboard pattern, whereas Forest Service, forest industry, and State lands tend to occur in larger blocks (Figure 3.1). Changes in land ownership have occurred primarily within and not between the three major ownership types (Federal, forest industry, non-industrial private) in the past several decades (Azuma et al. 2002).

Historically, disturbance in the Coastal Province was dominated by large fires. Fire suppression became common by the mid 1900s, but prior to this time, high severity stand-replacing fires had a mean return interval of about 200 to 300 years (Agee 1993, Impara 1997). Fires have occurred in several areas in the past two centuries, primarily on lands currently owned by the State of Oregon (Tillamook and Clatsop State Forests, multiple fires between 1929-1951, Elliott State Forest, fire in 1868), and the Forest Service (Siuslaw National Forest, multiple fires between 1850s-1880s). In addition, historical, frequent burning of lands at the forest margins was conducted by native Americans to facilitate hunting (Hays 1976). Large windstorms, such as the Columbus Day storm of 1962, have also killed large numbers of trees across multiple ownerships. Euro-American settlement and subsequent timber harvest focused on the selective removal of the larger trees, and forestlands were cleared for grazing and farming in the late part of the 1800s and early- to mid- part of the 1900s (Moe 1993). In the early 1900s, railroad-based logging also removed large amounts of timber from portions of the Coastal Province (Palmer 1982). In the past 50 years, many of the forests have been intensively managed for timber production. In the early 1990s, large portions of the federal lands in the Coastal Province were designated as reserve areas to provide habitat for the northern spotted owl (*Strix occidentalis*) and the marbled murrelet (*Brachyramphus marmoratus*).

Data sources

I obtained dead and live vegetation data collected on field plots established for regional forest inventories: Current Vegetation Survey (CVS) (Siuslaw

National Forest, n=317, measured 1993-1996), Forest Inventory and Analysis (FIA) (nonfederal lands, n=497, measured 1997), Natural Resources Inventory (NRI) (Bureau of Land Management, n=116, measured 1997) (Figure 3.1). The total number of plots was 930. All plots were located on a systematic grid of 5.5 km spacing excepting CVS plots (2.75 km spacing), were of about 1 ha in area, and were located on forested lands. Data from the three sources were combined into a consistent format and summary variables calculated for various live vegetation (Table 3.1) and dead wood (Table 3.2) attributes, on a units per hectare basis for uniform land cover condition classes in each plot. Because plot sampling densities were non-uniform across component datasets, I calculated weighted mean values for any area-based measures of plot data. The minimum piece sizes considered were 12.5 cm diameter at breast height (dbh) and 2m tall for snags, and 12.5 cm large-end diameter led and 1m in length for logs, because this was the minimum uniform size across the three datasets. Summary statistics were calculated for each plot for the number of snags of various sizes, volume of snags (m^3 ha^{-1}) of various sizes, snag biomass (Mg ha^{-1}), snag carbon (Mg C ha^{-1}), number of legacy snags, volume of legacy snags, and percent of all snags that are legacy. Summary statistics for logs included the volume of logs for various sizes of logs, log biomass, log carbon, volume of legacy logs, and percent of all logs that are legacy. Legacy dead wood was defined as that which was produced by a previous forest stand, as determined by comparison of diameters and decay classes with characteristics of the present-day stand.

Potential explanatory variables (Table 3.1; Figure 3.1) were identified based on hypothesized relationships with dead wood and mapped data availability. Some of the variables have been shown to be associated with patterns of live vegetation in the region (Ohmann and Spies 1998). Live vegetation data were obtained from plot surveys, as described above. To obtain mean (for continuous variables) or maximum (for categorical variables) plot values for each mapped explanatory variable, plot locations were superimposed on 30-m-resolution GIS grids of each variable. Climate variables were obtained from Daymet (Thornton et al. 1997) rasters at 1 km resolution which were based on 18 years of weather station data. Topography-related variables were derived from a digital elevation model having 30 m resolution, excepting potential relative radiation (Pierce et al. in press) and topographic position index. Land ownership data originated from a GIS coverage that was based on a variety of data sources including fire protection district maps and county assessor plats and was considered current for 1990-1996. Geologic types were obtained from a digitized geologic map of Oregon (Walker and MacLeod 1991). Ecoregions originated from a digitized map of Pacific Northwest Ecoregions (Woods et al. Unpublished). Historical vegetation information was obtained for 1936 from a digitized forest vegetation map with a minimum mapping unit of about 16 ha, that was developed by the Pacific Northwest Research Station from surveys conducted between 1933 and 1936 (Andrews and Cowlin 1940, Interior Columbia Basin Ecosystem Management Project 2001). I acquired historical vegetation data for 1900 from the Bureau of

Table 3.1. Mapped explanatory variables used in statistical analysis. * = Variables (n=32) included in 'complete' plot-level canonical correspondence analysis (CCA). † = Variables (n=12) that were included in plot-to-subbasin level CCAs. These 12 variables were also used in regression modeling of dead wood volume by scale.

Variable class and code	Definition
Climate	
ANNGDD*†	Total annual growing degree days
ANNSW	Total annual shortwave radiation (MJ m^{-2} day^{-1})
ANNVP	Total annual vapor pressure deficit
AUGMAXT	Mean maximum temperature in August (°C)
CONTPRE*	Percentage of mean annual precipitation falling in June - August (%)
DECMINT	Mean December minimum temperature (usually the coldest month) (°C)
DIFTMP	Difference between August maximum temperature and December minimum temperature (°C)
SMRPRE*	Mean precipitation from May to September (mm)
SMRTP*†	Moisture stress during the growing season, calculated as SMRTMP/SMRPRE, where SMRTMP is the mean temperature in May-September (°C $(mm)^{-1}$)
FOG	Percent of the hours (tenths of percent) in July with cloud ceiling of marine stratus <91 m and visibility <1.6 km.
Topography	
DEM*	Elevation (m), from 30-m digital elevation model (DEM)
ASPTR	Cosine transformation of aspect (degrees) (Beers et al. 1966), 0.0 (southwest) to 2.0 (northeast), from 30-m DEM
SLPPCT*†	Slope (percent), from 30-m DEM
TPI300	Topographic position index, 300-m radius window used to calculate
PRR*	Potential relative radiation
RIVBUF50	Within 50 m of streams
RIVBUF100*†	Within 100 m of streams
Land Ownership	
PUBLIC*	Public ownership, including USFS, BLM, and State
PRIVATE	Private ownership, including private industrial and non-industrial private
USFS*†	USDA Forest Service ownership
BLM	USDI Bureau of Land Management ownership
STATE*	State of Oregon ownership
FI*	Forest Industry
NIP†	Non-industrial private ownership
Current Vegetation	
BAAALL	Total basal area of all trees (m2/ha)
BAA1	Total basal area of all trees in size class 0-25 cm dbh
BAA2*	Total basal area of all trees in size class 25-50 cm dbh
BAA3*	Total basal area of all trees in size class 50-75 cm dbh
BAA4*†	Total basal area of all trees in size class 75-100 cm dbh
BAA5	Total basal area of all trees in size class 100+ cm dbh
BAH1	Total basal area of all hardwood trees in size class 0-25 cm dbh (ln)
BAH2*	Total basal area of all hardwood trees in size class 25-50 cm dbh (ln)
BAH3	Total basal area of all hardwood trees in size class 50-75 cm dbh (ln)
BAH4	Total basal area of all hardwood trees in size class 75-100 cm dbh (ln)
BAH5	Total basal area of all hardwood trees in size class 100+ cm dbh (ln)
BACPROP	Proportion of total plot basal area that is conifer
BAHPROP	Proportion of total plot basal area that is hardwood (ln)

Table 3.1 contd. Mapped explanatory variables used in statistical analysis.

Current Vegetation	
BAC1*	Conifer basal area in size class 0-25 cm dbh (ln)
BAC5*	Conifer basal area in size class 100+ cm dbh (ln)
BAHALL	Total basal area of all hardwood trees (ln)
QMDADOM1*	QMD (cm) of all live trees that are dominant or codominant
QMDAALL†	QMD (cm) of all live trees
TPHCON	Number of conifer trees (ha^{-1}) (ln)
TPHHDW	Number of hardwood trees (ha^{-1}) (ln)
TPHALL	Number of all trees (ha^{-1}) (ln)
IVVS	Importance value of very small trees, calculated as (100*BAVS/BAAALL) + (100*TPHVS/TPHALL), where BAVS = basal area of trees 2.54 - 12.4 cm dbh. (ln)
IV100	Importance value of trees >100 cm dbh, calculated as (100*BA100/BAAALL) + (100*TPH100/TPHALL), where BA100 = basal area of trees >100 cm dbh. (ln)
DDI*	Diameter diversity index. An indicator of the structural diversity of a forest stand, based on tree densities in different DBH classes. Calculation procedures are described in Spies and Pabst (2000)
AGEDOM	Age of dominant/codominant trees (ln)
CANCOV	Canopy cover (percent) for all trees
TPHREML	Remnant live tree density (TPH) (ln)
VPHREML	Remnant volume of live trees > 2.5 cm dbh (VPH) (ln)
REMPCTL*	Remnant live tree percent [(VPHREML / Volume of live trees >2.5 cm dbh) * 100] (ln)
LBIOMASS*	Biomass of live trees (Mg ha-1)
DIST*	Age since disturbance, from Cohen et al. 1998.
Historical Vegetation	
1936	
CONSS	Conifer, seedling-sapling, over 60% conifer, <6 in. dbh.
CONS	Conifer, small second growth, over 50% conifer, 6-20 in. dbh.
CONLG*	Conifer, large, over 50% conifer, >24 in. dbh.
CONOG*†	Douglas-fir, old-growth, >22 in. dbh.
SUBALP*	Subalpine.
HDWD	Alder/ash/maple or oak/madrone predominate.
CUTOVER	Logged area.
BURN	Deforested burned area, not cutover.
NONFOR*	Nonforest land: nonforest, agriculture, and water.
1900	
0	No data (n=7)
1*†	Nonforest land
2	Woodland
3	0-5000 MBF/Ac
4	5000-10000 MBF/Ac
5	10000-25,000 MBF/Ac
6	25,000-50,000 MBF/Ac
7	50,000+ MBF/Ac
8	Barren
9*	Burned
10	Cut timber not restocking
11	Cut timber restocking

Table 3.1 contd. Mapped explanatory variables used in statistical analysis.

Ecoregion	
CLOW*	Coastal lowlands
CUPL	Coastal uplands
VOL*†	Volcanics
WILH	Willapa Hills
MIDCS†	Mid-coastal sedimentary
SOCM	Southern Oregon coastal mountains
PVBA	Portland/Vancouver basin
WILGF	Willamette and tributaries gallery forest
PRTE	Prairie terraces
VALF	Valley foothills
UMCA	Umpqua Cascades
UMIN	Umpqua interior foothills
INSI	Inland Siskiyous
Geology	
DEPO*	Depositional: dune sand, alluvial, glacial, glaciofluvial, loess, landslide and debris flow, playa, lacustrine, fluvial
MAFO	Igneous: Mafic rocks (basalt, basaltic andesite, andesite, gabbro); Miocene and older
SEDR	Sedimentary: siltstones, sandstones, mudstones, conglomerates
TUFO	Sedimentary: tuffaceous rocks and tuffs, pumicites, silicic flows, Miocene and older
VOLC	Igneous: volcanic and intrusive rocks
Location	
XCOORD	Latitude (m, UTM zone 10), fuzzed to within 1000 m with random azimuth
YCOORD	Longitude (m, UTM zone 10), fuzzed to within 1000 m with random azimuth

Land Management from a digitized Oregon map of timber resources surveyed by township between 1898 and 1902. All potential explanatory variables were obtained from data sources also in use in other research in the region (Ohmann and Gregory 2002, Spies et al. 2003, Kennedy et al. 2004, Burnett et al. accepted, Johnson et al. accepted, Ohmann et al. accepted, Spies et al. accepted).

Data analysis

I conducted statistical analyses at four levels of spatial resolution across the Coastal Province region. From the finest to coarsest grain size, these levels of resolution are: individual plots (n=930), subwatersheds (6th code hydrologic units (HUs), n=345), watersheds (5th code HUs, n=84), and subbasins (4th code HUs; n=18). The hydrologic units-level analyses were conducted by summarizing plot-level data for each hydrologic unit, as follows: for continuous variables, I calculated mean values per hydrologic unit; for categorical variables, I calculated the percent of the hydrologic unit in each class. Subwatersheds were nested within watersheds, and watersheds within subbasins. Subwatersheds had a maximum size of about 225 km^2, watersheds 1265 km^2, and subbasins 3260 km^2. I used hydrologic units because they provided a means of linking plot data to riparian and in-stream processes, which have been strongly associated with dead wood patterns (Bisson et al. 1986, Maser et al. 1988, Fetherston et al. 1995, May and Gresswell 2003).

I calculated weighted mean and median values for each plot for each dead wood variable, and for each ownership type. To test for differences between ownership groups, I performed two-sided Wilcoxon rank-sum tests on the medians, because dead wood data are commonly skewed and therefore tests of difference between means would not meet normality assumptions (Ohmann and Waddell 2002). However, reporting of means for dead wood amounts is commonplace (Spies and Cline 1988, Ohmann and Waddell 2002), so I report mean values as well to increase ease of comparison among locales. After omitting highly correlated potential explanatory variables ($|r|>0.8$) and transforming skewed variables, to evaluate relationships between dead wood variables and potential explanatory factors, I developed a stepwise multiple linear regression model for each dead wood variable, with the requirements that (1) the model p-value must remain at less than 0.05 for each potential explanatory variable to enter and stay in the model, and (2) partial R^2 values for each retained variable must exceed 0.01 (Appendix A). Univariate statistical analysis were carried out using SAS (SAS Institute Inc. 2004).

To evaluate the influence of biophysical factors and forest management on dead wood patterns at multiple scales, I developed stepwise multiple linear regression models for total dead wood volume, at the plot, 4th, 5th, and 6th code hydrologic unit (HU) levels. I considered 12 explanatory variables (Table 3.1) that were the same as variables selected for multivariate analysis I also conducted (described below). The rules used for variable inclusion in the reduced models were the same as those used in the plot-level stepwise models, with the additional caveat that each explanatory variable must have a partial R^2 value of at least 0.05 to remain in the model. In addition, I addressed potential spatial autocorrelation concerns using permutation testing. Because each HU occupies a location in space with relation to its neighbors, it might be expected that neighboring HUs would have values that are more alike than those at greater distance. Permutation testing of the partial regression coefficients in the reduced linear model (Anderson and Legendre 1999) has been shown to be a robust method when there may be spatial autocorrelation among sample units in linear modeling (Legendre 1993). It is a non-parametric method of hypothesis testing that does not require the multiple linear regression assumptions of random sampling and independent error terms (Manly 1991). Therefore, I conducted a randomization test based on permutations of the reduced models for each HU to test the contribution of each variable to the final regression model. I based each significance test on 999 permutations, and retained only variables with $p<0.05$ in the final models. I conducted permutation tests using S-Plus (Insightful 2002).

I also conducted a series of analyses to describe the multivariate relationships of various dead wood attributes to a suite of potentially related factors at multiple scales. To do this, I used the multivariate statistical method of Canonical Correspondence Analysis (CCA) (ter Braak 1986). Canonical correspondence analysis allows the user to evaluate the relative strength of relationships among a set of response variables (here, a set of dead wood variables), and a set of explanatory variables (here, a set of potential explanatory factors related to climate, topography, ownership, etc.). To evaluate the relative strength of relationships among different variables and patterns of dead wood, I calculated the degree of contribution of sets of explanatory variables to the explained variation in the set of dead wood variables. For each CCA model, I included all explanatory variables that were significant ($p<0.05$). I tested for significance using a Monte Carlo permutation test on the reduced model using 999 permutations (H_0: no relationship between matrices). To determine the percentage of total inertia contributed by each subset of explanatory variables, I conducted subset-CCAs on the members of each subset. In this way, there was no confounding correlation among variables from different subsets. I reported the relative contribution to explained variation by subsets of variables summarized for Axes 1 and 2 of these CCAs. The results of these separate subset CCAs are reported. All multivariate analyses were conducted using the software PC-ORD (McCune and Mefford 1999).

I conducted two canonical correspondence analyses at the plot level and one at each hydrologic unit level of spatial resolution (subwatershed, watershed, subbasin), for a total of 5 CCAs. I selected 17 dead wood summary variables that I considered to span the range of dead wood attributes measured (Table 3.2) for inclusion in the set of dead wood variables. For the two plot-level CCAs, I included all plots that had some form of dead wood present (n=903). The two plot-level CCAs differed in the number of explanatory variables included. Stepwise multiple linear regression, upon which the CCAs were based, is sensitive to the number of explanatory variables considered in relation to the number of sample units. Therefore, to compare dead wood relationships to the same explanatory variables among scales from plots to subbasins, I needed to dramatically reduce the explanatory variable set for one of the plot-level CCAs, since there were only 18 subbasins. For the first plot-level CCA, the 'complete' plot-level CCA, my goal was to maximize the explained variation in the model, so I wanted to retain a higher number of potential explanatory variables.

For the complete plot-level CCA, then, I used all those explanatory variables that were present in at least one of the stepwise multiple linear regression models of the individual dead wood variables. Although CCA is considered to be robust to multicollinearity (Palmer 1993), to address potential multicollinearity problems in CCA as indicated by PC-ORD, I dropped four explanatory variables that had very low partial R^2 values. This resulted in the inclusion of 32 explanatory variables in this CCA (Table 3.1).

For the second plot-level CCA, my goal was to explore the relative importance of potential explanatory factors at multiple scales, from plots to subbasins. Therefore, I reduced the set of explanatory variables for the remaining four CCAs to a uniform set of only a few variables so that I could compare results among scales using the same explanatory variables. I wished to retain variables that were of some value in describing dead wood gradients at each scale; however, my primary interest in using CCA here was to determine the relative contribution of each type of explanatory variable (i.e. topography, climate, etc.) to multi-variable dead wood patterns at each scale. To develop the reduced explanatory variable set, I first built an up-to-6-variable stepwise multiple linear regression model for each single dead wood variable at each scale, following the approach described above for individual plots. Then I followed an iterative approach to variable reduction, as follows. I evaluated the variables that appeared in a range of univariate models and scales, with relatively high R^2 values for at least one univariate model at each scale. I omitted variables that were highly correlated ($|r|>0.8$) with any other candidate variable at a given scale. I retained two variables from each of 6 subsets of factors (climate, topography, current vegetation, ownership, historical vegetation, ecoregion/geology) so my results would span the set of potential explanatory variables. I compared the resulting candidate variables across the range of spatial scales. This procedure resulted in the inclusion of 12 explanatory variables that were used in these four CCAs (Table 3.1). Eight 6th code hydrologic units that contained forested plots were lacking any dead wood and thus were not included in the 6th code CCA.

Results

Regional patterns

Much of the dead wood present in the Coastal Province was in the form of logs: about 85% of the biomass and 70% of the volume of dead wood occurred as logs (Table 3.2). Very large logs (> 100 cm led) comprised about 65% of total log volume, and very large snags (> 100 cm dbh) comprised about half of total snag volume. The volumes of moderate-sized logs and snags (25-50 dbh or led) were about the same as the volume of large logs and snags (75-100 cm dbh or led), indicating there were probably fewer larger-sized pieces. Legacy snags and logs were each about 20% of the total volume of snags and logs present. About 70% of the total dead wood volume in the Province occurred in pieces exceeding 50 cm dbh or led (Table 3.2).

Table 3.2. Weighted mean amount per ha and standard error of various attributes of dead wood in the Coastal Province of Oregon and apportioned by public and private ownership classes. Note: Snags were at least 2m in height and logs were at least 1 m in length unless otherwise indicated. Dbh is diameter at breast height. Led is large-end diameter. Asterisks indicate dead wood attributes that were included in canonical correspondence analysis, and abbreviations following are codes used in CCA biplots.

	Coastal Province (n=930)		All Public (n=511)		All Private (n=419)	
Variable	Mean	*s.e.*	Mean	*s.e.*	Mean	*s.e.*
Total dead wood volume >12.5 cm dbh or led	186.5	*6.4*	249.6	*10.4*	140.2	*7.0*
Total dead wood volume >50.0 cm dbh or led	132.8	*5.8*	188.9	*9.8*	91.7	*6.0*
Snags						
Number of snags >12.5 cm dbh* (STPH12)	34.1	*2.0*	43.8	*2.7*	26.9	*3.0*
Number of snags >50 cm dbh* (STPH50)	4.7	*0.3*	7.9	*0.5*	2.3	*0.2*
Number of snags >50 cm dbh and >15m tall	0.6	*0.1*	1.2	*0.1*	0.2	*0.1*
Volume of snags >12.5 cm dbh (m^3)	26.3	*1.7*	44.3	*3.0*	13.0	*1.5*
Volume of snags >50 cm dbh (m^3)	19.6	*1.6*	35.5	*2.9*	8.0	*1.3*
Volume of snags 12.5-25.0 cm dbh (m3)* (SVPH1)	2.6	*0.2*	3.2	*0.3*	2.2	*0.3*
Volume of snags 25.0-50.0 cm dbh (m3)* (SVPH2)	4.0	*0.3*	5.7	*0.5*	2.8	*0.4*
Volume of snags 50.0-75.0 cm dbh (m3)* (SVPH3)	3.0	*0.3*	5.4	*0.5*	1.2	*0.2*
Volume of snags 75.0-100.0 cm dbh (m3)* (SVPH4)	4.2	*0.4*	7.3	*0.7*	2.0	*0.4*
Volume of snags >100.0 cm dbh (m3)* (SVPH5)	12.4	*1.3*	22.8	*2.4*	4.8	*1.0*
Snag biomass (Mg)	7.4	*0.5*	12.5	*0.9*	3.7	*0.5*
Snag carbon (Mg C)	3.9	*0.3*	6.5	*0.5*	1.9	*0.2*
Number of remnant snags >12.5cm dbh* (TPHREMS)	1.4	*0.1*	1.9	*0.2*	1.0	*0.1*
Volume of remnant snags >12.5 cm dbh (m^3)* (VPHREMS)	7.1	*0.8*	10.0	*1.3*	5.1	*1.0*
% of all snags >12.5 cm dbh that are remnants* (REMPCTS)	19.9	*1.4*	22.0	*2.2*	18.3	*1.8*
Logs						
Volume of logs >12.5 cm led (m^3)	160.2	*5.7*	205.2	*9.2*	127.2	*6.5*
Volume of logs >25 cm led (m^3)	149.0	*5.6*	194.8	*9.1*	115.3	*6.3*
Volume of logs >50 cm led (m^3)	113.2	*5.1*	153.4	*8.5*	83.7	*5.6*
Volume of logs 12.5-25.0 cm led (m3)* (DVPH1)	11.3	*0.4*	10.4	*0.6*	11.8	*0.5*
Volume of logs 25.0-50.0 cm led (m3)* (DVPH2)	35.8	*1.1*	41.4	*1.7*	31.6	*1.4*
Volume of logs 50.0-75.0 cm led (m3)* (DVPH3)	40.1	*1.7*	49.1	*2.7*	33.5	*2.2*
Volume of logs 75.0-100.0 cm led (m3)* (DVPH4)	34.2	*2.1*	50.3	*3.8*	22.4	*2.0*
Volume of logs >100.0 cm led (m3)* (DVPH5)	38.9	*3.2*	54.0	*5.5*	27.8	*3.3*
Log biomass (Mg)	44.2	*1.6*	54.4	*2.4*	36.8	*1.9*
Log carbon (Mg C)	23.0	*0.8*	28.3	*1.3*	19.1	*1.0*
Volume of remnant logs >12.5cm led (m^3)* (VPHREMD)	55.2	*3.3*	63.4	*5.0*	49.2	*4.3*
Percent of all logs >12.5 cm led that are remnant logs* (REMPCTD)	21.9	*1.0*	20.2	*1.3*	23.1	*1.4*

The strongest snag regression models were for the volume of snags ($R^2 = 0.52$), the number of large snags ($R^2 = 0.47$), and the volume of large snags

(R^2=0.46) (Appendix A). Higher volume and number of snags were associated most strongly with higher live tree biomass and the basal area of very large conifers (Figure 3.2 a and b). The log regression models with the highest R^2 values were for the volume of logs ($R^2 = 0.30$) (Appendix A) and the volume and percent of legacy logs ($R^2 = 0.30$ and 0.31). Higher volume of logs was most strongly associated with higher summer moisture stress (Figure 3.2 c). Higher volumes and relative abundance of legacy logs were most strongly associated with higher quadratic mean diameter of dominant trees. Ownership variables were also present in several snag and log regression models with low partial R^2s. Climate was also present in several snag regression models, with more or larger snags associated with less summer moisture stress and higher precipitation (Appendix A). Historical vegetation variables occurred in several log models, with higher log biomass and volumes associated with historical conifer old-growth (1936), or burned (1936), and lower log biomass and volumes associated with historically (1900) non-forested areas.

Relationships with ownership

Snag amounts differed according to ownership (Table 3.3). The volume of snags was much higher on public than private lands (mean 44.3 vs. 13.0 m^3 ha^{-1})

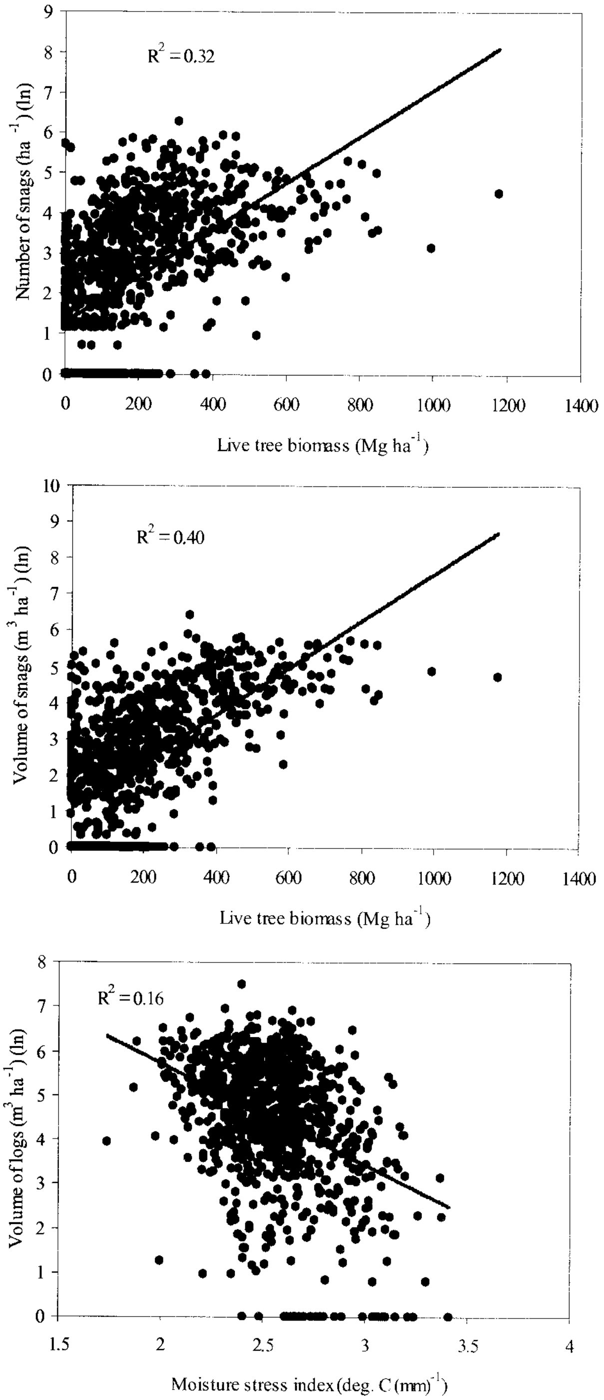


Figure 3.2. Relationships of selected dead wood characteristics to independent variables with high explanatory power as determined by stepwise multiple linear regression, in the Coastal Province of Oregon. R^2 values are from simple linear regression.

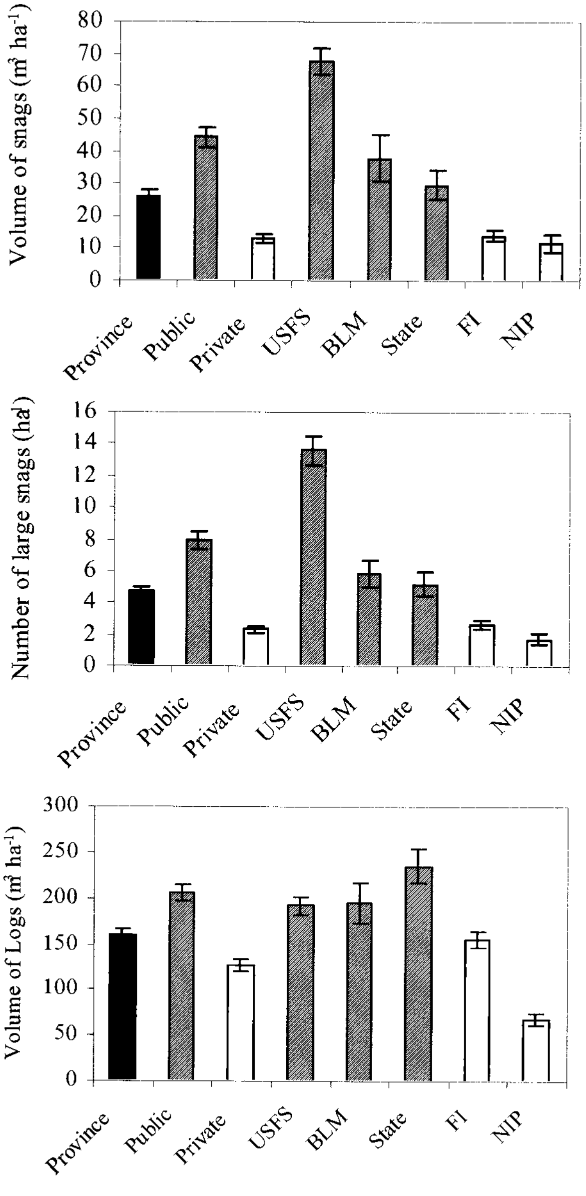


Figure 3.3. Relationship of selected dead wood characteristics to ownership in the Coastal Province of Oregon, as determined by stepwise multiple linear regression.

(Figure 3.3 a), as was the number of large snags (mean 7.9 vs. 2.3 snags ha^{-1}) (Figure 3.3 b). Among public owners (USFS, BLM, and State), the USFS had about twice the mean amounts of the other public ownerships for these two snag

Table 3.3. Median amount per hectare of dead wood characteristics, for the entire Coastal Province (CP) and by ownership group. Only plots occurring on the 5.5 km spacing grid were used so plot densities were the same among data subsets. P-values indicate difference in dead wood amount between public and private ownerships, from two-sided Wilcoxon rank-sum tests. For the five ownership classes, different superscript letters indicate significant difference (p<0.05) between classes in dead wood amount, from two-sided Wilcoxon rank-sum tests. Note: Snags were at least 2m in height and logs were at least 1 m in length unless otherwise indicated. Dbh is diameter at breast height. Led is large-end diameter. CP is Coastal Province. FI is forest industry. NIP is non-industrial private.

Variable	**CP**	**Public**	**Private**		**USFS**	**BLM**	**State**	**FI**	**NIP**
n	694	282	412	*p-value*	81	117	84	271	141
Total dead wood volume >12.5 cm	121.1	192.1	92.6	<0.001	204.0 ^{a}	136.6 ^{ab}	233.4 ^{a}	128.8 ^{b}	45.5 ^{c}
Total dead wood volume >50.0 cm	63.9	116.6	43.4	<0.001	118.6 ^{a}	80.1 ^{ab}	169.0 ^{a}	67.9 ^{b}	12.6 ^{c}
Snags									
Number of snags >12.5 cm dbh	8.2	22.7	0	<0.001	32.3 ^{a}	20.8 ^{b}	18.0 ^{b}	2.2 ^{c}	0 ^{c}
Number of snags >50 cm dbh	0	2.7	0	<0.001	9.9 ^{a}	2.6 ^{b}	2.2 ^{b}	0 ^{c}	0 ^{c}
Number of snags >50 cm dbh and >15m t	0	0	0	<0.001	0 ^{a}	0 ^{b}	0 ^{c}	0 ^{d}	0 ^{cd}
Volume of snags >12.5 cm dbh (m3)	7.3	16.4	0	<0.001	40.9 ^{a}	11.8 ^{b}	13.2 ^{b}	2.6 ^{c}	0 ^{cd}
Volume of snags >50 cm dbh (m3)	0	8.2	0	<0.001	31.6 ^{a}	6.7 ^{bc}	2.8 ^{c}	0 ^{d}	0 ^{c}
Volume of snags 12.5-25.0 cm dbh (m3)	0	0	0	<0.001	0.5 ^{a}	0.7 ^{a}	0 ^{ab}	0 ^{b}	0 ^{c}
Volume of snags 25.0-50.0 cm dbh (m3)	0	1.0	0	<0.001	3.5 ^{a}	0 ^{b}	0 ^{b}	0 ^{c}	0 ^{c}
Volume of snags 50.0-75.0 cm dbh (m3)	0	0	0	<0.001	3.8 ^{a}	0 ^{b}	0 ^{b}	0 ^{c}	0 ^{c}
Volume of snags 75.0-100.0 cm dbh (m3)	0	0	0	<0.001	0.0 ^{a}	0 ^{b}	0 ^{c}	0 ^{c}	0 ^{c}
Volume of snags >100.0 cm dbh (m3)	0	0	0	<0.001	16.2 ^{a}	0 ^{b}	0 ^{b}	0 ^{c}	0 ^{c}
Snag biomass (Mg)	1.9	5.2	0	<0.001	10.4 ^{a}	4.6 ^{b}	4.5 ^{b}	0.5 ^{c}	0 ^{c}
Snag carbon (Mg C)	1.0	2.7	0	<0.001	5.4 ^{a}	2.4 ^{b}	2.3 ^{b}	0.3 ^{c}	0 ^{c}
Number of remnant snags	0	0	0	0.03	0 ^{abc}	0 ^{ab}	0 ^{a}	0 ^{b}	0 ^{c}
Volume of legacy snags >12.5 cm dbh (m3)	0	0	0	0.03	0 ^{abc}	0 ^{ab}	0 ^{a}	0 ^{b}	0 ^{c}
Percent of all >12.5 cm dbh snags that are legacy snags	0	0	0	n.s.	0 ^{ab}	0 ^{ab}	0 ^{a}	0 ^{ab}	0 ^{b}
Logs									
Volume of logs >12.5 cm led (m3)	103.8	149.4	78.1	<0.001	135.3 ^{ac}	115.2 ^{ac}	201.5 ^{b}	114.5 ^{c}	33.7 ^{d}
Volume of logs >25 cm led (m3)	91.6	138.3	66.7	<0.001	125.5 ^{ac}	100.2 ^{ac}	188.3 ^{b}	101.9 ^{c}	25.1 ^{d}
Volume of logs >50 cm led (m3)	53.1	96.7	37.2	<0.001	63.9 ^{ac}	62.0 ^{ac}	146.7 ^{b}	65.2 ^{c}	9.9 ^{d}
Volume of logs 12.5-25.0 cm led (m3)	8.1	7.3	8.7	0.04	11.6 ^{ac}	6.2 ^{bd}	7.1 ^{bd}	10.5 ^{bc}	5.8 ^{d}
Volume of logs 25.0-50.0 cm led (m3)	25.7	32.4	23.8	0.001	27.1 ^{a}	27.1 ^{a}	34.8 ^{a}	29.1 ^{a}	11.6 ^{b}
Volume of logs 50.0-75.0 cm led (m3)	20.1	26.2	17.2	0.02	26.2 ^{a}	0 ^{a}	39.4 ^{b}	24.7 ^{a}	0 ^{c}
Volume of logs 75.0-100.0 cm led (m3)	0	0	0	0.001	0 ^{ac}	0 ^{ac}	33.0 ^{b}	0 ^{c}	0 ^{d}
Volume of logs >100.0 cm led (m3)	0	0	0	n.s.	0 ^{a}	0 ^{ac}	42.2 ^{b}	0 ^{c}	0 ^{a}
Log biomass (Mg)	28.1	39.0	24.3	<0.001	33.4 ^{a}	30.4 ^{a}	59.3 ^{b}	34.6 ^{a}	10.2 ^{c}
Log carbon (Mg C)	14.5	20.3	12.4	<0.001	17.3 ^{a}	15.8 ^{a}	30.9 ^{b}	17.9 ^{a}	5.2 ^{c}
Volume of legacy logs >12.5cm led (m3)	0	0	0	n.s.	0 ^{a}	0 ^{b}	79.0 ^{c}	22.1 ^{d}	0 ^{a}
Legacy logs as % of all >12.5 cm led logs	0	0	0	n.s.	0 ^{ad}	0 ^{bd}	33.8 ^{c}	20.5 ^{c}	0 ^{d}

metrics (Figures 3.3 a and b; Appendix B). Both federal ownerships had higher snag amounts than either private ownership group (forest industry and non-industrial private) for all the snag metrics considered (Appendix B). The State was similar to private ownerships for some snag metrics, such as the volume of 75-100 cm dbh snags (Table 3.3). In general, the number and volume of small snags per hectare on private ownerships was about 50-70% of that of public ownerships, whereas the number and volume of large snags was only about 20-30% (Table 3.2).

Public ownerships had higher log volumes than did private ownerships for nearly all sizes of logs (Figure 3.3 c, Table 3.3, Appendix B). The exception to this was very small logs (12.5 to 25.0 cm led), which occurred at slightly higher volumes on private lands (Table 3.2). In general, volume of small logs on private lands was about 60-80% that of public lands, whereas volume of large logs was about 45-70%. Log volumes for all sizes of logs were much lower on non-industrial private than on forest industry lands (Table 3.3, Appendix B). Neither legacy log nor snag amounts as a proportion of the total present differed significantly between the generalized public-private ownership groups (Table 3.3).

Spatial distribution of dead wood volume

Across the province, the total volume of dead wood varied at fairly fine scales; variability among subwatersheds was high and apparently clustered (Figure

3.4). At watershed or subbasin scales, the variation decreased, and only extreme differences were evident. For example, total dead wood volume in the interior forested watersheds and subbasins of the Coastal Province tended to be consistently low relative to the more coastal watersheds and subbasins, regardless of scale (Figures 3.4 b, c).

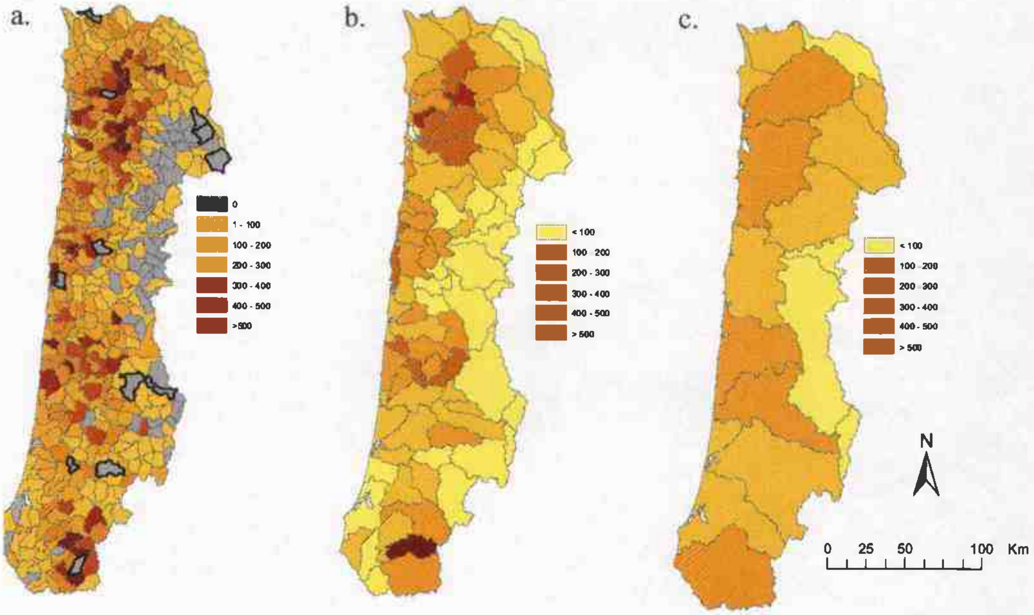


Figure 3.4. Total dead wood volume (m^3 ha^{-1}) in the Coastal Province of Oregon, summarized by (a) subwatershed, (b) watershed, (c) subbasin. Twelve subwatersheds, outlined in black, contained plots but no dead wood. Thirty subwatersheds, shaded gray, were non-forested and therefore were not sampled. Two watersheds located in the central interior contained only 2 plots and thus were primarily non-forested.

Univariate analysis of total dead wood volume

The factors most strongly associated with variation in the total volume of dead wood differed by scale (Table 3.4). At plot, subwatershed, and watershed levels, total dead wood volume was most strongly related to climate, with less dead wood volume where growing season moisture stress was greater. At the plot level, current vegetation (basal area of large trees) was of moderate positive association with variation in total dead wood volume (Table 3.4). In addition, at the watershed level, topography was moderately related to total dead wood volume, with dead wood volumes increasing with % slope, whereas current vegetation (basal area of large trees) was modestly, but significantly positively related. At the subwatershed level, current and historical vegetation (basal area of large trees and 1936 conifer old growth) were both of moderate positive association, after climate. Total dead wood volume was most strongly associated with ownership and topography at the subbasin level. The total volume of dead wood was most predictable at the subbasin scale, which had the highest model R^2.

Table 3.4. Stepwise regression models of total dead wood volume and explanatory variables at four spatial scales. Variable transformations used to meet normality assumptions are in parentheses. Partial R^2 value required for variable inclusion in the reduced model was 0.05. P-values are derived from a randomization test based on permutations under the reduced model.

Model	Variable	Coefficient	*F*	*p-value*	Partial R^2	Cumulative R^2
Plot dead wood volume (sqrt)	SMRTP	-10.09	157.11	<0.001	0.14	0.14
	BAA4 (ln)	1.71	99.66	<0.001	0.08	0.23
Sub-watershed dead wood volume (sqrt) (6th code HU)	SMRTP	-12.50	162.56	<0.001	0.32	0.32
	BAA4(ln)	1.77	46.31	<0.001	0.08	0.40
	CONOG	4.70	44.55	<0.001	0.07	0.47
Watershed dead wood volume (5th code HU)	SMRTP	-233.50	46.34	<0.001	0.36	0.36
	SLPPCT	3.18	22.05	<0.001	0.14	0.50
	BAA4 (ln)	41.40	10.35	<0.001	0.06	0.56
Subbasin dead wood volume (4th code HU)	NIP	-292.32	22.37	0.028	0.58	0.58
	RIVBUF100	218.59	5.90	<0.001	0.12	0.70

Multivariate relationships of dead wood with biophysical factors and ownership

The complete plot-level CCA, which included the full suite of 32 explanatory variables, explained 21% of the cumulative variation in dead wood gradients. The complete plot-level CCA showed that multivariate gradients of dead wood were most strongly associated with current vegetation, which had a relative contribution of 18% to explained variation (Table 3.5). Ownership explained about half as much variation as current vegetation, whereas historical vegetation explained about half that of ownership. Climate, topography, and ecoregion/geology were minor contributants to the explained variation of dead wood gradients (Table 3.5).

Table 3.5. Relative contribution to explained variation (Axes 1 and 2) in dead wood gradients by subsets of associated variables in the Coastal Province of Oregon, from canonical correspondence analysis (CCA), at the individual plot level (n=903), for the model containing 32 explanatory variables. See Table 1 for membership of explanatory variables in subsets. See Table 2 for list of dead wood variables included in CCA.

Subset of explanatory variable (number of variables)	Percentage of total inertia
Climate (4)	3.0
Topography (4)	1.3
Current vegetation (11)	18.0
Ownership (4)	9.0
Historical vegetation (6)	4.8
Ecoregion and geology (3)	0.8

At the plot level, the reduced explanatory variable set (12 variables), explained 17% of the cumulative variation in dead wood gradients. The current vegetation subset contributed about 14% to total explained variation (Table 3.6). However, the relative contribution of historical vegetation to total explained variation was lower than it was in the complete plot-level CCA, at only 9% of that explained by current vegetation, compared to 27% of that explained by current vegetation in the complete plot-level CCA (Table 3.5). The proportional contribution of the other subsets remained about the same relative to current vegetation. For example, ownership still explained about half as much of the explained variation as current vegetation (about 8% of explained variation). Even with the decline in explanatory power of the reduced historical vegetation subset, the rank order of subsets in explaining dead wood gradients remained consistent between the reduced (n=12) and complete (n=32) explanatory variable sets (Tables 3.5 and 3.4, respectively).

Differences in multivariate relationships with scale

Different dead wood attributes tended to be associated with different explanatory variables in the CCAs at each scale (Figure 3.5). Some relationships were consistent across scales. For example, the amount of snags of various sizes tended to be positively associated with variables related to the size of current vegetation and Forest Service ownership at the plot, subwatershed, and watershed levels. At the subbasin level, patterns for snags were not as clear, with small snags positively associated with non-industrial private ownership, and larger snags associated with variables related to climate. At the watershed level, legacy snags tended to be weakly positively associated with non-industrial private ownership. At the subwatershed level, legacy snags tended to be located on moderate slopes and in areas that were historically forested.

Volumes of logs of all sizes and origins (legacy and present stand) tended to be weakly to strongly positively associated with the 1936 presence of conifer old growth at the plot level (Figure 3.5). At the subwatershed level, the volume of larger logs and legacy logs tended to be greater in areas that were historically forested and where slopes were moderate. At the watershed level, higher volumes of larger logs were also weakly positively associated with moderate slopes, and inversely related to non-industrial private ownership. The volume of very large logs and legacy logs was strongly positively associated with location within 100 m of streams, and with historically forested conditions (Figure 3.5).

The relative strength of relationships of gradients of dead wood to climate, topography, current vegetation, ownership, historical vegetation, and ecoregion differed across scales of resolution (Table 3.6). At the level of subwatersheds, current vegetation emerged as the most important factor. Ownership provided a moderate contribution to the explained variation. The rank order and magnitude of influence of variable sets at the subwatershed level was similar to those found at the plot level (Table 3.6). However, topography (steeper slopes) became important

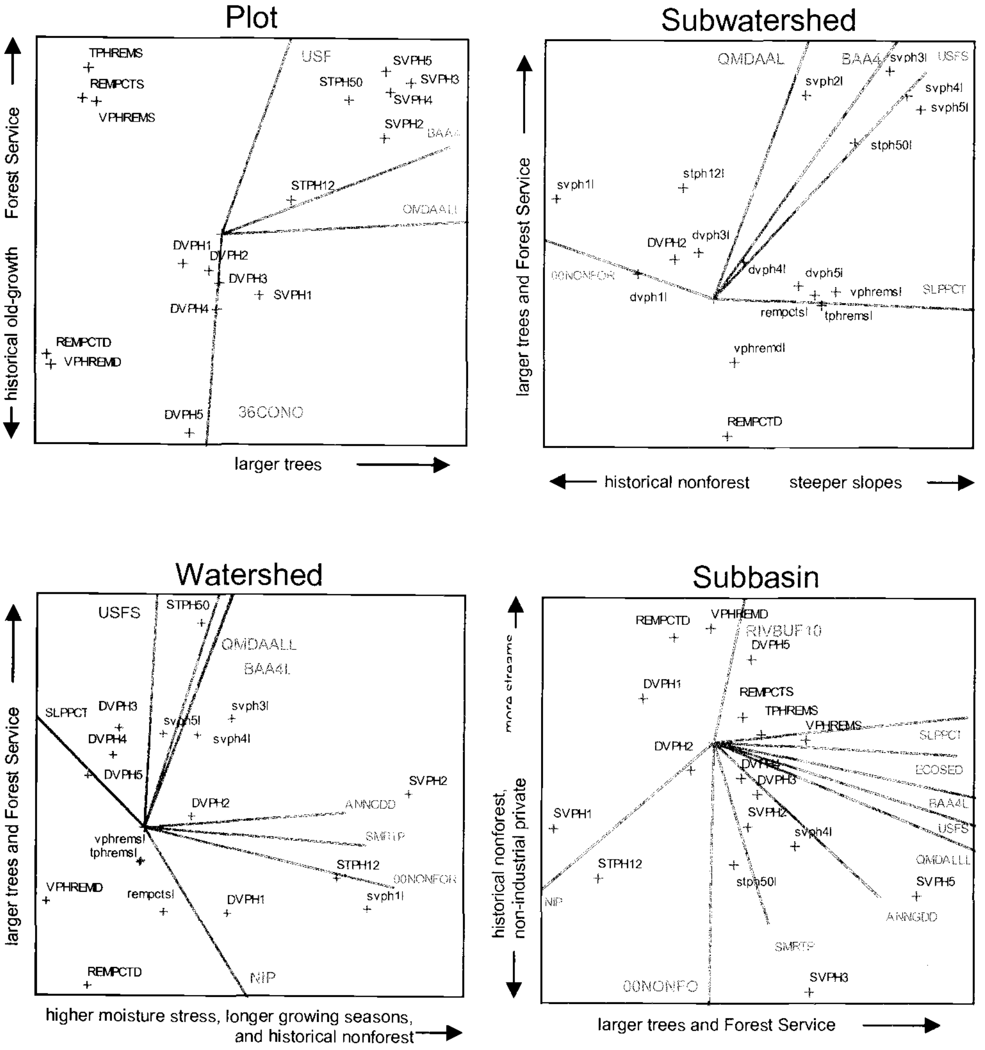


Fig 3.5. Biplots from Canonical Correspondence Analyses of dead wood attributes conducted with 12 potential explanatory variables at four levels of resolution: plot, subwatershed, watershed, and subbasin. Vectors (lines) show important explanatory variables. Length of line shows magnitude of contribution to explained variation in dead wood variables in that CCA. Cross locations indicate relationship of each dead wood variable to the explanatory variables. Dead wood variable codes (cross labels) are in Table 2. The list of explanatory variables considered in the four CCAs is in Table 5. An ‘L’ following a variable name indicates the logarithmic transformation was applied.

Table 3.6. Relative contribution to explained variation (Axes 1 and 2) in dead woo gradients by subsets of factors in the Coastal Province of Oregon, from canonical correspondence analysis (CCA), at subbasin, watershed, sub-watershed, and individual plot levels of analysis. Seventeen dead wood variables were included in the CCAs, as noted in Table 2. Twelve explanatory variables (listed below) were considered. Percentage of total inertia is from a CCA on each subset, and thus correlations among variables between subsets may result in totals of greater than 100%. Percentages should be compared among subsets at each scale and not among scales. Subbasin (4th code HUs) n=18. Watershed (5th code HUs) n=84. Sub-watershed (6th code HUs) n=337. Plots n=903.

	Percentage of total inertia Scale of Model			
Subset of explanatory variable	Plot n=903	Subwatershed n=337	Watershed n=84	Subbasin n=18
Climate (ANNGDD, SMRTP)	2.0	2.4	12.2	15.4
Topography (RIVBF100, SLPPCT)	1.0	1.8	11.0	32.9
Current Veg. (QMDAALL, BAA4)	14.3	11.8	10.6	20.8
Ownership (USFS, NIP)	7.7	6.7	15.0	32.9
Historical Veg. (36CONOG, 00NONFOR)	1.4	2.8	16.5	33.1
Ecoregion and Geology (ECOVOL, ECOSED)	1.9	2.6	9.0	16.1

at the subwatershed level (Figure 3.5). At the level of watersheds, ownership and historical vegetation were of greatest importance and climate, topography, and historical vegetation were of secondary importance (Figure 3.5). At the coarsest scale of resolution (i.e. subbasins) multivariate patterns of dead wood were best explained by historical vegetation, ownership, and topography (Figure 3.5); current vegetation had relatively low explanatory power (Table 3.6). In general, the explanatory power of the models went down as the resolution of the analysis and variation among sample units increased (Table 3.6).

Discussion

Relationships with disturbance and management

In the Coastal Province, differences in management and forest history are generally reflected in patterns of land ownership. The fact that snag amounts on State-owned lands (e.g. the number of large snags) were similar to private ownerships is probably a reflection of the history of the State-owned forests. The Tillamook State Forest, for example, experienced a series of intense fires between 1929 and 1951, and was subsequently salvage logged. Because of the concerns for repeated fires in the area, most snags were felled during salvage operations (Levesque 1985). Typically higher amounts of dead wood on Forest Service lands than other ownerships is also reflective of differences in forest management and history. Much of the Siuslaw National Forest is between 120 and 150 years old, having regenerated naturally after fires. These forests are in the mature or understory reinitiation stage of forest development (Oliver and Larson 1990, Poage 1994, Impara 1997, Spies 1997), wherein dead wood generated by the present stand tends to be fairly large in size. The dramatically higher amounts of logs on forest industry vs. non-industrial private lands may reflect the tendency for non-industrial lands to be located in larger valley bottoms, where small-sized hardwoods may be more competitive with conifers (Hibbs et al. 1994) and the potential for large wood generation is thus lower. In addition, forest industry lands tended to be located where there historically were older, higher productivity forests.

The influence of management and history on snag and log amounts is not unexpected. Research in other regions has found similar results to this study in relationships of dead wood patterns with management history, disturbance, and climate (Sturtevant et al. 1997, Hely et al. 2000, Tinker and Knight 2000, Grove 2001, Rouvinen et al. 2002). In research on dead wood levels in unmanaged and managed stands of varying levels of management intensity (Green and Peterken 1997, Sturtevant et al. 1997, Duvall and Grigal 1999, Fridman and Walheim 2000, Grove 2001, Krankina et al. 2002), older or less-intensively managed stands had dead wood amounts more similar to those of natural stands, and disturbance history was important. For example, in boreal Fennoscandia, higher dead wood volumes were found in natural and selectively logged stands than in managed stands (Rouvinen et al. 2002). Higher amounts were also found in areas with a more recent history of forest utilization where more structural carryover remains present, and in colder climates where decomposition rates may be lower. Similar results were found in Russian forests (Krankina et al. 2002). In a study of Midwestern U.S. old-growth deciduous forests, dead wood volume increased with increasing forest productivity (site index) across the region (Spetich et al. 1999). Significant positive relationships were present between snag and log amounts and time since fire and basal area of live trees in southern Canadian boreal forests (Hely et al. 2000). However, log volumes did not vary significantly between stands of different ages in Australian mountain ash *(Eucalyptus regnans)* forests, possibly because of legacy logs in regrowth sites (Lindenmayer et al. 1999). Dead wood amounts were not found to be related to environmental factors in mature ponderosa pine (*Pinus ponderosa*) stands in Colorado (Robertson 1999).

The fact that ownership was of some importance at both fine and coarse scales in the multivariate models describing overall dead wood gradients and their relationship to explanatory factors indicates that ownership and related management patterns are relevant across a broad range of scales. I found that ownership was among the most the important factors explaining multivariate patterns of dead wood at the broad scales of watersheds and subbasins. At the subbasin scale, it was of roughly equal importance with topography and historical vegetation, and at the watershed scale it was of roughly equal importance with historical vegetation. Ownership was of less importance than current vegetation to explaining variation in overall dead wood gradients at the finer levels of plots and subwatersheds, as described by CCA, but it was of moderate importance nonetheless. The importance of ownership reflects in part the inherent scale of patterns of ownership in the Coastal Province. A single ownership, and therefore a single management strategy, dominates in many subwatersheds, especially for Forest Service, State, and forest industry ownerships. On the other hand, BLM lands in the Coastal Province tend to occur as a checkerboard, where individual parcels may be as small as 2.25 km^2, interspersed by or within larger blocks of forest industry lands. Additionally, non-industrial private lands tend to have more linear configuration in the landscape, reflecting their location near larger streams. But the Forest Service, State, and forest industry are the major land owners in the Coastal Province, so larger blocks predominate and ownership is largely patterned at coarser scales.

Wimberly and Ohmann (2004) found that ownership was always the most important predictor variable related to change in large conifer forest cover over a 60-year period across a similar range of scales in the Coastal Province. My results imply that there are more complex influences on dead wood patterns evaluated at these scales than those affecting change in large conifer forests as indicated by Wimberly and Ohmann (2004). This finding could reflect both the diversity of disturbance types that can create dead wood, and the long time period dead wood tends to persist in this region.

Current and historical vegetation

Current vegetation was by far the most highly related factor to total explained variation in dead wood gradients at fine scales. This was not surprising given that the majority (though not all) of dead wood present in Coastal Province forests originated from present-day stands and not from previous stands. The finding of a strong positive relationship at the plot level of snag abundance with current-stand factors such as tree size or stand basal area is consistent with other studies across temperate, tropical, and boreal forests (Gale 2000, Hely et al. 2000, Muller 2003).

The importance of historical vegetation is evidenced by the fact that legacy logs comprised over one-third of the volume of logs in the Coastal Province. Although the area of forest stands in the Coastal Province that was coniferous old-growth in 1936 has declined to about 44% of their prior amounts through conversion to younger forest cover (Wimberly and Ohmann 2004), dead wood from these past older forests provides an important contribution to today's dead wood pools at broad scales. The inverse relationship of historically (1900) nonforested (but presently forested) areas with large dead wood abundance at subwatershed, watershed, and subbasin scales (Figure 3.4) likewise indicates that aforestation of the last century may not yet producing high quantities of large dead wood.

It was not surprising that log amounts were more closely associated with historical vegetation and climate than current vegetation and snag amounts were more closely tied to current stand conditions. Though some larger snags may remain in PNW forests for a century or more, snags tend to stand for relatively short periods (e.g., decades) before falling to become logs (Harmon et al. 1986). Logs, especially large logs, tend to persist longer and would therefore more likely be related to historical disturbance events and longer-term vegetation patterns. The lower overall explanatory power of regression models for logs is probably in part a factor of the longer residence time of logs compared to snags, and the potential for more and a greater variety of disturbance events to have an effect.

Relationships with climate

The importance of climate, as represented by moisture stress index, to the variability in log volume in the Coastal Province probably reflects a complex of influences including productivity: sites with lower summer moisture stress in the Coastal Province are more productive and have the capacity to generate larger pieces of dead wood (Franklin and Dyrness 1988, Runyon et al. 1994). They may also have lower decay rates, resulting in longer retention times for dead wood (Harmon et al. 1986).

It was somewhat unexpected that climate was of only moderate importance in explaining the variation in multivariate dead wood gradients at the broadest level of resolution (i.e. subbasins). I expected climate to be important at broad scales because changes in climate, as indicated by the climate variables used in this study, are somewhat gradual across the region. Factors related more directly to disturbance, including ownership and historical vegetation, superceded climate in importance to multivariate dead wood gradients at the broadest level of resolution.

Importance of topography

The potential importance of topography to amounts of dead wood has been noted (Harmon et al. 1986, Spies et al. 1988, May and Gresswell 2003), but there have been conflicting reports of the effects of topography (Gale 2000, Clark et al. 2002). Higher topographic positions in stands and landscapes have been shown to have higher potential for tree death and higher mass and volume of dead wood (Gale 2000, Muller 2003). The number and basal area of snags increased with increasing slope position from valleys to ridges, with the volume of snags four times higher on ridge tops compared with valley and midslope positions, in a study of four tropical rain forests in Borneo and Ecuador (Gale 2000). But in that study, log volume did not vary with slope position (Gale 2000). Muller (2003) found that the species distribution of live trees in temperate deciduous old-growth forests also varied with topographic position, and this influenced the likelihood of mortality. However, there no significant differences were found in volume, biomass, or number of snags and logs along a topographic gradient of flat old alluvial terraces, steep slopes, and flat ridgetops in a tropical rain forest landscape in Costa Rica (Clark et al. 2002). This was hypothesized to be resulting from high inter-site variability in tree mortality or high inter-annual variability in dead wood inputs and temperature over the three-year study period (Clark et al. 2002).

In the present study, topography did not explain much variation in snag or log regression models at the plot level. This was somewhat unexpected given the high amount of topographic relief in the Coastal Province region, and the documented importance of topography to dead wood volume at landscape scales (Kennedy and Spies in prep). However, other factors such as current and past vegetation and ownership overrode the potential influence of topography. At broader levels of resolution, variables related to topography (nearness to streams and percent slope) were related to dead wood amounts. This is not unexpected given that areas near low-order streams are known sources for large quantities of dead wood in the mountainous areas of the Coastal Province (May and Gresswell 2003, Kennedy and Spies in preparation).

Importance of related factors according to scale

The differential importance of biophysical and ownership variables according to scale illustrates the complexity of dead wood patterns. In addition, the factors themselves may have inherent scales of variation. For example, patterns of ownership vary according to the size of the land unit under each ownership, and patterns of management within these land units vary according to the distribution of land allocation types. On private lands, for instance, clearcuts are typically placed in upslope areas, in blocks as large as 49 ha, and areas of no action or thinning only occur in long, narrow riparian areas.

The lack of resolution differences between plots and subwatersheds in relationships of dead wood attributes to explanatory factors probably reflects the small size of subwatersheds and the small number of plots in many subwatersheds. Many subwatersheds contained only a few plots (mean number of plots at the subwatershed scale=2.7, min n=1, max n=12) and so mean values at the subwatershed scale may not differ much from those of individual plots. It is possible that if sampling densities were higher in subwatersheds, more divergent patterns would result between plot and subwatershed levels since a broader range of conditions in the subwatershed would be sampled.

Developing models to predict total dead wood volume requires determining the important factors related to dead wood abundance, and the scales at which these factors are most relevant. My research indicates that at the subbasin level, patterns of dead wood volume may be best predicted by knowledge of subbasin ownership. At finer levels of resolution, however, climate may be a better predictor of total dead wood volume than ownership, but total dead wood volume may not be as predictable overall as it is at broader levels of resolution.

The differences in results between the total dead wood volume regression analysis and the multivariate dead wood CCA analysis are not surprising. Most of the volume of dead wood in the Coastal Province is in the form of large logs. Therefore, the dead wood regression models in large part described factors important to log abundance at the different scales. The introduction of numerous response variables related to snags introduced new complexity to the models in the CCAs. Since snag abundance is strongly positively associated with live vegetation, I expected that there would be more influence of live vegetation in relation to climate and ownership in the CCAs, and this is what I observed.

Scale effects

Introducing additional complexity in dead wood patterns through the multivariate lens brought insights about how the explanatory factors varied across scales in the relative strength of their relationships to dead wood gradients (Figure 3.6). I found that current vegetation, historical vegetation, and ownership had

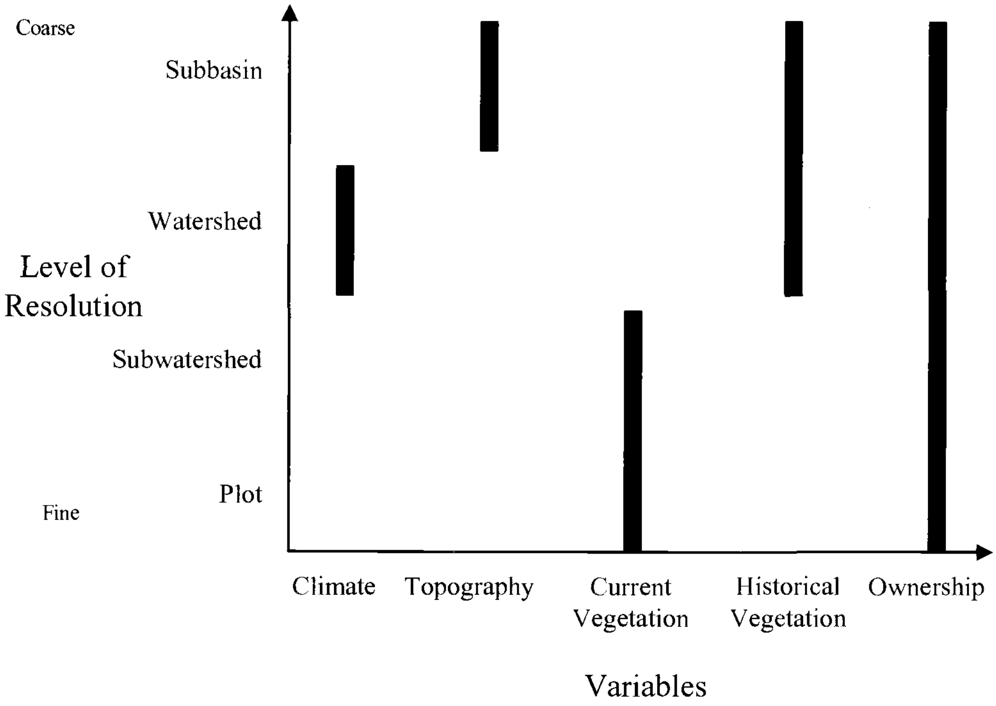


Figure 3.6. Range of importance of explanatory factors to dead wood patterns according to scale in the Coastal Province of Oregon. Bars indicate the approximate range of strong relationship, as indicated by Canonical Correspondence Analyses conducted at each level of resolution.

broad ranges of importance to multivariate dead wood patterns and were important across multiple levels of resolution. This is probably because these three features are the strongest descriptors of forest development and disturbance in the Coastal Province. Topography's importance at subbasin levels may reflect the characteristics and inherent scales of variation of the two topography variables that were considered. At the subbasin level, a higher density of streams was associated with more dead wood. This is probably because subbasins spanned a wide range of sizes, as dictated by the characteristics of the stream network, and there was higher variability in the number of plots (and thus of plots within 100 m of streams) per subbasin than per subwatershed or watershed. "Drier" subbasins might have less dead wood, both via less concentration of dead wood in stream areas, and potentially lower productivity through higher summer moisture stress. The fact that climate had a narrow range of importance in this analysis, and was only of high relative importance at intermediate scales (watersheds) was somewhat unexpected. However, I considered climate to be representative of other gradients related to dead wood abundance such as habitat types and productivity, so it is likely that the other variable sets such as current vegetation captured these attributes better than climate at the other levels of resolution.

Comparison with dead wood amounts from other research

The findings for dead wood amounts in this study were similar to those from other research in the Coastal Province (Spies et al. 1988, Ohmann and Waddell 2002), when sampling differences were taken into account. The estimated amounts for mean snag volume and dead wood volume (26.3 and 186.5 m^3 ha^{-1}, respectively) across the plots in the Coastal Province were lower than those of Spies et al. (1988) (126 and 302 m^3 ha^{-1}, respectively, in that study, based on a weighted average of the mean values for dead wood amounts in plots in 3 different age classes). However, their plots were located in natural stands on public lands. They sampled proportionately more old-growth stands (56% of their sample), all their plots occurred in areas of stand-replacing wildfire, and they included slightly smaller pieces in their sample (10.0 vs. 12.5 cm minimum threshold). Old-growth forests characteristically have much higher dead wood volumes than younger forests (Spies and Franklin 1988, Spies et al. 1988). In addition, stands which originate after wildfire typically have many more snags than those originating after harvest, because in managed forests most snags are commonly felled during logging. The log volume estimates of this study (160.2 m^3 ha^{-1}) were higher than those of Spies et al. (1988) (104 m^3 ha^{-1}). This may be because there was not as much legacy wood on the lands studied by Spies et al (1988). It may also be that differences in disturbance history in the areas they studied resulted in a higher proportion of dead wood volume remaining as snags (42% of total dead wood volume was snags in their study, compared to only 14% in the present study). The number of large snags estimated in this study (4.7 ha^{-1}) was also much lower than that found by Spies et al. (17 ha^{-1}). The number of large snags estimated in this study was similar to that estimated for all successional stages in westside conifer-hardwood forests (5.5 ha^{-1}) (Ohmann and Waddell 2002). I estimated slightly higher log volumes than Ohmann and Waddell (2002) (131.8 m^3 ha^{-1}), but their study also included high elevation westside forests in the Cascade Range, which might be expected to have smaller trees than the relatively low elevation, highly productive coastal forests.

Implications for regional biodiversity and future dead wood patterns

Management for dead wood on lands currently depauperate in dead wood would increase habitat for dead wood associates and promote regional biodiversity. Snags and logs provide habitat for a wide array of plant, animal, and fungal species in the Pacific Northwest (Rose et al. 2001, Hayes and Hagar 2002, Mellen et al. 2003) and elsewhere (Jonsson and Kruys 2001, Kouki et al. 2001, MacNally et al. 2002, Heilmann-Clausen and Christensen 2003). Large snags and logs are important features of old growth forest structure (Franklin et al. 1981, Spies and Franklin 1988). In younger forests, legacy snags and logs provide continuity and may be important to biodiversity (Franklin 1990, Lindenmayer and Franklin 2002). In the Coastal Province region, we found that the State had the highest total dead wood volume and large log volume and the Forest Service had the highest number and volume of large snags. If other forest attributes promoting the dead wood associated species are present, we would expect that biodiversity of dead wood associated species would be higher on State and Forest Service ownerships than on the other ownerships, if other habitat requirements of the species are present. Non-industrial private lands, with their low amounts of dead wood, probably provide a small contribution to dead-wood-associated biodiversity, though their lands may be important to other components of biodiversity, such as hardwoods in the coniferous landscape (Kennedy and Spies 2005), or in-stream elements of dead-wood-related biodiversity.

Some of the management practices in the Coastal Province have been in effect for a few years to decades, and future dead wood patterns of abundance may differ from those of today. For example, federal land management to promote the development of late successional and old-growth forests under the Northwest Forest Plan began in the mid-1990s. Likewise, the effect through multiple rotations of industrial management's focus on efficiency and commodity production on forest productivity and dead wood amounts has yet to be seen. Patterns of live vegetation will undoubtedly more strongly follow patterns of ownership with these differences. It is likely that as ownerships diverge more in their management practices, the patterns of dead wood abundance, as well as the types and sizes of dead wood present, will differ even more by ownership than they do today. Without broad-scale natural disturbances in the region such as large fire events, the signature of historical vegetation on dead wood amounts may be expected to even more strongly resemble patterns of ownership than it does at present. Thus, we might expect to see an even greater influence of ownership on dead wood patterns of abundance in future years than we do today.

Chapter 4: Modeling potential future dead wood dynamics under different forest management regimes in the Coastal Province of Oregon, USA

Introduction

Large dead wood, in the form of standing dead trees and down wood, is important to the ecosystem processes, structural complexity, and biodiversity of forests (Maser and Trappe 1984, Harmon et al. 1986, Jonsson and Kruys 2001). In recent years, managing forests with consideration for dead wood has increased (Hagan 1999, Laudenslayer et al. 2002), but our understanding of the effects of management is limited. Changes in dead wood over time in a region, or differences between ownerships in dead wood amounts or characteristics, can have effects on ecosystem processes and biodiversity; for example, some species may require particular characteristics of dead wood for habitat, or sizeable contiguous blocks of forested habitat containing large dead wood (Mellen et al. 2003). Knowledge of how forest management affects long-term dead wood dynamics is needed by managers.

In ecologically diverse multi-ownership landscapes such as the Coastal Province of Oregon, management effects on dead wood can be complex and variable over time and space. Patterns of dead wood have been found to vary widely across ecoregions (Ohmann and Waddell 2002), and future patterns may be dramatically different from those of present day because of management (Ranius et al. 2003). The Coastal Province of Oregon is a region dominated by private lands, and has a history of fire and logging. Recent policies governing forest management on federal and private lands in the Province (U.S. Department of Agriculture Forest Service and U.S. Department of the Interior Bureau of Land Management. 1994a, Oregon Department of Forestry 2001) are quite different from those of previous decades. There are provisions for dead wood management in the policies relevant to forest management on Federal, State, and private lands in the Coastal Province. Additionally, federal policies are oriented toward the development of older forest structure and high quality aquatic habitat, of which dead wood is an important component.

It is also important to consider the historical context of today's forest stands when evaluating the potential impacts of future management on dead wood abundance. Differences in future amounts of dead wood from those of present-day may result from differences in the initial conditions of the live stands producing dead wood. In particular, future older forests in parts of the Pacific Northwest region may be very different structurally from today's older forests, because live tree densities of today's young stands (both natural and managed) are higher than those of the stands that produced today's old-growth forests (Dowling 2004). The imprint of ecological history is also visible in the amount of legacy (pre-fire) dead wood present in today's forest stands. In the Coastal Province, there is a large amount of legacy (pre-fire) dead wood remaining in some parts of the Coastal Province, relative to the amount produced by present-day stands. Additionally, current amounts of dead wood in the Coastal Province may be toward the lower end of the historical range of variability of dead wood amounts in the region (Nonaka 2003). Finally, little older forest remains in the Province because of past fires and logging, and what remains mainly occurs on Federal lands. Thus, the potential effects of current forest policies on future dead wood amounts are mediated by the amount of dead wood present today, and the status of today's forest stands and their potential developmental trajectories.

The interaction of new policies and ecological histories lead to the questions: What will the effects of these new policies be on future dead wood amounts? What are the differences in management approaches with relation to dead wood? What will be the duration of the legacy wood? What is the importance of initial conditions to future dead wood amounts? Given the current status of forest stands, and potential older forest development, will there be increases in dead wood? Will there be changes in the structure (size, type) of dead wood that vary according to management?

In this study, I used simulation modeling to explore variation in potential management effects on future dead wood dynamics in the Coastal Province of Oregon over a time period of 300 years. I evaluated differences among ownerships in dead wood patterns because ownership has been shown to be a key factor determining forest patterns in this region (Kennedy and Spies 2004, Wimberly and Ohmann 2004, Johnson et al. accepted). In the Coastal Province, dead wood patterns and dynamics are influenced by intensive management on private lands, management for old growth on federal lands, and the existence of large amounts of legacy wood from past old-growth forests in some areas. My goal was to evaluate how dead wood amounts might change in the region, and how these changes in dead wood amounts might be related to ownership and management practices. I used a 300-year period as the temporal extent of the simulation exercise because in this region the residence time of large pieces of dead wood and the time of older forest development may be hundreds of years. Further, I wanted to track current dead wood and newly created dead wood separately to better understand transitions from historical conditions to conditions under future management practices. The simulation modeling approach allowed for the exploration of potential maxima of future dead wood amounts given model assumptions and constraints.

I hypothesized that dead wood would show relative declines on ownerships whose management for timber creates small amounts of dead wood and has shorter rotations, and increases on ownerships that foster dead wood creation with longer rotations, large dead wood creation, and/or reserve areas. I also hypothesized that these differences among management practices would be more pronounced when current legacy large dead wood was lost from the system through decay. Given the implementation of new forest policies mandating dead wood creation and retention, I hypothesized that there would be increases in the amount of dead wood in the Province.

To investigate these hypotheses, I used two existing models: a dead wood dynamics model (Coarse Wood Dynamics Model) (Mellen and Ager 2002), and a growth and yield model (ZELIG) (Urban and Shugart 1992, Garman et al. 2003), and regional field plot data, to simulate how dead wood attributes may change across the Coastal Province and according to ownership over the next 300 years. Simulation modeling can be a valuable tool for investigating hypotheses related to management effects on dead wood dynamics (Tinker 2001). It can be useful to incorporate a spatial component, so that dead wood patterns over small (Tinker 2001) or large areas may be evaluated. One approach to incorporating a spatial component, which I followed in this study, is to use plot data collected over a broad geographic extent as the source data for the modeling exercise, and then to conduct a post-hoc evaluation of differences in patterns across the area by evaluating differences among types of landscape features such as ecoregions (Ohmann and Waddell 2002) or ownerships.

There were three specific objectives of this study. They were to: 1) characterize the projected future change in dead wood amounts in a multi-ownership Province; 2) determine the longevity of present-day dead wood of different types and sizes in relation to amendments from management and stand development; and 3) evaluate differences in management approaches to transitional dynamics and long-term patterns of dead wood.

Study area

The Coastal Province of Oregon is an area of highly productive coniferous forest characterized by a maritime climate, steep, mountainous terrain, and a dense network of perennial and intermittent streams. The coastal margin, which occurs in the Sitka spruce (*Picea sitchensis)* vegetation zone (Franklin and Dyrness 1988), is cooler and wetter than the interior, which falls within the western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) vegetation zone (Franklin and Dyrness 1988). The coniferous forests are dominated by Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) (PSME), western hemlock (TSHE), western redcedar (*Thuja plicata* Donn) (THPL), with Sitka spruce (PISI) occurring near the coast. Hardwood trees such as red alder (*Alnus rubra* Bong.) (ALRU) and bigleaf maple (*Acer macrophyllum* Pursh) (ACMA) are also present, and red alder often dominates near-stream areas (Hibbs et al. 1994).

Land ownership of the area is dominated by federal (USDA Forest Service (FS) and Bureau of Land Management (BLM)), state, and private (forest industry (FI) and non-industrial (NIP)) ownerships (Figure 4.1). Forested lands are managed mainly for timber production (private and state) or for old-growth-related biodiversity and aquatic habitat (federal). In the past several decades, most changes in land ownership have been within and not among these broad ownership types (Azuma et al. 2002); therefore we assumed that future management trends will be somewhat spatially coherent with respect to current patterns of ownership.

Present-day human settlement occurs mostly along the coast and in the Willamette Valley, to the east of the Coast Range, and is projected to expand locally near existing population centers rather than to result in the conversion of large amounts of forest land to urban use in the next century (Kline et al. 2003).

Fires that occurred during the last two centuries in the Coastal Province have affected current forest vegetation structure in many ways including the production of large amounts of dead wood. Historically, fires tended to be stand-replacing and occurred with a mean return interval of 200-300 years (Agee 1993, Impara 1997, Weisberg and Swanson 2003). Fires have occurred in several areas in the past two centuries, primarily on lands currently owned by the State of Oregon (Tillamook and Clatsop State Forests, multiple fires between 1929-1951, Elliott State Forest, fire in 1868), and the Forest Service (Siuslaw National Forest, multiple fires between 1850s-1880s). Fire suppression in the Coastal Province commenced in the early-to-mid 1900s. For the projection modeling I assumed continued fire suppression in the future.

Methods

I simulated snag and log production and decomposition in the Coastal Province under current forest management practices over a 300-year period in the future. For each of the management scenarios analyzed, I generated data on the amount of snags and logs produced over time. I used two models, one that projects the development of the forest stand (Urban and Shugart 1992, Garman et al. 2003), and one that projects the dynamics of dead wood (Mellen and Ager 2002). To initialize the models, I used data obtained from a systematic grid of vegetation plots located throughout the Coastal Province. Results from the forest stand development model were input to the dead wood dynamics model to provide information about management and stand development effects on the production of future dead wood. Current plot data were also input to the dead wood dynamics model to provide information about the loss of current stores of dead wood.

Source data

Data on dead and live vegetation were obtained from surveys of a systematic grid of field plots established for regional forest inventories: Current Vegetation Survey (CVS) (Siuslaw National Forest, measured 1993-1996), Forest Inventory and Analysis (FIA) (nonfederal lands, measured 1997), Natural Resources Inventory (NRI) (Bureau of Land Management, measured 1997) (Figure 4.1). The total number of plots in the sample was 930. The distribution of plots by category of ownership was as follows: Forest Service, n=309; Bureau of Land Management, n=118; State of Oregon, n=84; Forest industry, n=274; Non-industrial private, n=145. All plots were located on a systematic grid of 5.5 km spacing excepting CVS plots (2.75 km spacing), were of about 1 ha in area, and were on forested lands. I combined data from the three sources into a consistent format and summarized individual records to a units per hectare basis for the uniform land cover condition classes in each plot. The minimum size of snags in the input data was 12.5 cm diameter at breast height (dbh); the minimum size of logs was 12.5 cm large-end diameter (led) because those were the minimum sizes that were uniform across source datasets.

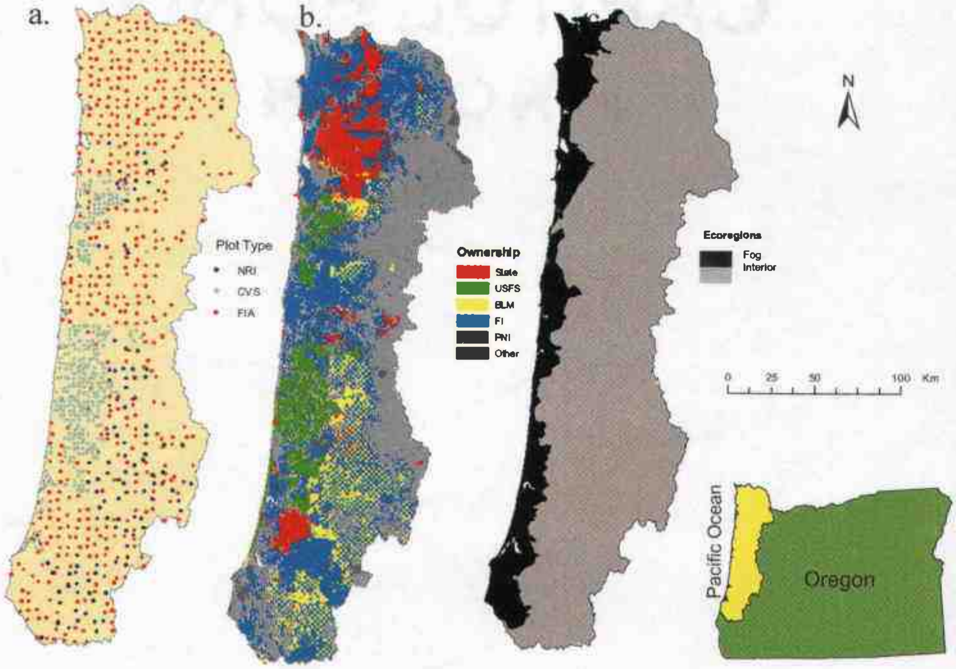


Figure 4.1. (a) Location of current vegetation reference plots whose live tree and dead wood characteristics were used in simulation modeling of dead wood dynamics; (b) distribution of main ownership groups in the Coastal Province; (c) generalized ecoregion types used in forest growth modeling. For more information about reference plot types see text.

Plot values for ownership and ecoregions was obtained from GIS grids. Plot locations (~1ha in area) were superimposed on 30-m-resolution GIS grids of each variable and maximum values for ownership and ecoregions were obtained for each plot. Land ownership data used in this study originated from a GIS coverage based on a variety of data sources including fire protection district maps and county assessor plats and was considered current for 1990-1996. Ecoregions originated from a digitized map of Pacific Northwest Ecoregions (Woods et al. Unpublished).

Simulating snag and log dynamics

I used a revised version of the Coarse Wood Dynamics Model (CWDM) (Mellen and Ager 2002) to simulate changes in amounts of snags and logs over time. CWDM simulates the dynamics of individual pieces of dead wood using species- and size-specific decay rates. The model predicts fall, height loss and decay of snags, and decay of logs based on values from the literature, and has been validated using field data (Mellen and Ager 2002). The model is parameterized for two species types: slow-decaying (Douglas-fir type) and fast-decaying (western hemlock type). It runs on a 5-year timestep for a 300-year period. The model can be used to track dead wood occurring at the beginning of the simulation period, and that produced during the simulation period, such as by management activities. The model has a minimum size requirement for snags of 10 cm diameter at breast height (dbh) and height of 1.4 meters. Model parameters (Appendix C) were set based on values from the literature which were presumed to be averages (see Mellen and Ager 2002 for more details) and thus the model is appropriate for use across broad areas such as landscapes.

Several modifications to the model were made to increase efficiency and improve model performance. The timestep function was relativized to correct a model tabulation error. Codes were added so that species other than Douglas-fir and western hemlock could be processed. I corrected a problem with the calculation of snag heights. A routine was added to fell a proportion of new snags immediately to better reflect field-measured rates (J. Ohmann, USFS, personal communication, April 2003; (Appendix C)). I changed the volume equation for snags from the Smalian to the Kozak equation (Avery and Burkhart 1994); although the Smalian equation tends to overestimate volumes by about 10% (Avery and Burkhart 1994), I retained the use of the Smalian equation for logs to maintain consistency among models. This is also the equation used to calculate the volume of logs in the forest stand development model used in this study, and these logs were subsequently processed by CWDM. I added missing coefficients for the western hemlock species type based on the literature (Graham 1981). The model was reprogrammed into C++, and a few other minor changes were made to increase processing efficiency and accuracy.

For this study, I tabulated output by various size classes for snags and logs for each 5-year increment of the 300-year simulation period. Log volume, snag volume and number of snags were summarized by size class. Units for all volume estimates were cubic meters per hectare. Units for numbers of snags were numbers per hectare. Snag volume was tabulated for all snags, but numbers of snags were tallied for all snags with a minimum height of 5 meters, to ensure compatibility with concurrent wildlife modeling efforts (Spies et al. accepted). I differentiated between dead wood present at model initiation ("initial") and that produced during the simulation period ("new").

Simulating stand growth and yield

To simulate stand growth and yield, I used a version of the gap model ZELIG (Urban et al. 1999) developed to study the growth of stands and the production of dead wood in the Coastal Province of Oregon. This version was calibrated and parameterized for the Coastal Province of Oregon (Pabst et al. In preparation) (Appendix E) and was a modification of ZELIG.PNW (3.0) which had been developed for use in the Pacific Northwest (Hansen et al. 1995, Busing and Garman 2002, Garman et al. 2003). ZELIG models individual tree regeneration, growth, and mortality. Tree regeneration and growth are modeled by estimating maximum potential behavior and then constraining this potential by limiting light, soil moisture, soil fertility, and ambient temperature. Two variants of the model were used to differentiate among generalized ecoregions occurring in the Coastal Province (fog and interior; Figure 4.1); assignment of each plot to a variant was made based on plot location. Growth efficiencies were increased in this version of ZELIG to better reflect the rapid development of large trees in the

Coastal Province. The modeling of mortality included both density-dependent (suppression) and density-independent (ambient) mortality. I also simulated the effects of management including the retention of live trees and snags and the creation of logs at harvest. Densities and species composition of post-harvest plantations were specific to each management scenario. The model did not include wildfire, insect, and disease outbreaks. Consequently dead wood amounts in older late succession al forests should be considered as maxima or upper bounds of what might develop. The model was run on a 1-year timestep, for a period of 300 years, five times. Then the output of the five runs was averaged for each 5-year increment of the 300-year period. I summarized mortality output including species, size class, height or length class, and an expansion factor for pieces per unit area. Log and snag lengths were averaged by 3 m increments and diameters by 5 cm increments.

Simulation strategies

Three general strategies were used to evaluate the effects of management on dead wood dynamics. First, all plots in the Coastal Province (n=930) were simulated based on location (ownership and land allocation) in the landscape. This provided a depiction of potential dead wood dynamics in the Province based on the application of current management practices of each ownership (see below) to lands presently under that ownership. Second, to control for the effects of different initial conditions among ownerships, I created a uniform starting condition by randomly selecting a subset of the plots (n=100) for simulation under each of the five ownership-based management scenarios. Third, I ran the same 100 plots through the models under two additional scenarios: a natural development scenario, wherein no management action was taken; and a high intensity management scenario, where there were short rotation harvests and no treatment to promote dead wood.

Management practices

I developed management scenarios for each ownership type (Forest Service, BLM, State, Forest Industry, and Non-Industrial Private) and for the grow-only and high intensity management options (Tables 4.1 and 4.2). Scenarios for each ownership type were developed after consultation with representatives of each landowner group (Appendix C). Scenarios were specific to each land allocation found on each ownership, and were applied in proportion to how management activities would be applied by landowners on that land allocation unit. For example, if an owner indicated to me that they would thin and create a certain amount of logs in riparian areas, I assigned the specifics of their thinning and log creation regime to plots that were located in the riparian allocation class on those lands. Where necessary, I modified prescriptions slightly from how they were described by managers, to accommodate modeling constraints in ZELIG. In addition, I addressed the constraint that CWDM is suited for application across broad areas such as landscapes, To do this, I first assigned the specifics of the management regimes to each plot, based on its location within a land allocation unit, in the analysis of model output. Then I evaluated the effects of management activities of each ownership as a whole on dead wood, not differentiating between effects of individual prescriptions within ownership group. Each ownership group had a characteristic style of management, as described below.

Forest Service

Most Forest Service lands in the Coastal Province are currently in Late Successional Reserve or riparian reserve(henceforth termed LSR Riparian) status (97% of Forest Service plots). No action was taken on all lands greater than 80 years old and those with mixed species (conifer basal area <70% or relative density of conifers <30). Two thinning strategies were applied to the remaining reserve lands (Table 4.1). Matrix plots (3% of Forest Service plots) were harvested on a 70-year rotation with moderate amounts of green tree retention relative to the other ownership scenarios leaving green tree retention. Snag and log creation were conducted at high levels at thinning and harvest relative to other ownerships (Table 4.2).

Table 4.1. Description of prescriptions, by ownership: plot characteristics, frequency of harvest, plantation criteria, and thinning regime. When proportions of plots were allocated among similar prescriptions, plot assignment was random. Ba is basal area. 'Proportional' ('prop.') means the thinning was applied across all size classes in proportion to their abundance. 'From below' means the smallest trees were selected first. Those prescriptions with n/a in all categories in both Tables 4.1 and 4.2 were no-action alternatives.

Prescription owner, allocation	Plot criteria: age and allocation	Harvest frequency (years)	Plantation criteria (trees ha^{-1})	Thinning regime
FS LSR Riparian 1	> 80 years old, or mixed species	n/a	n/a	n/a
FS LSR Riparian 2	40% of non-LSR Riparian 1	n/a	n/a	age 35 to 124 tph from below, age 55 to 13.8 m^2 ba proportional
FS LSR Riparian 3	60% of non-LSR Riparian 1	n/a	n/a	age 35 to 198 tph from below, age 55 to 18.4 m^2 ba proportional, age 75 to 23 m^2 ba proportional
FS Matrix	FS Matrix, 1/7 of plots per 10-year period for plots >70 y.o. at initiation	70	1236, 90% PSME, 10% mix of ALRU, THPL,	age 45 to 247 tph from below
BLM Matrix 1	General Forest Management Area alloc., 1/8 per 10-year period for plots >80 y.o.	80	1236, 90% PSME, 10% mix of THPL,	age 12 to 494 tph from below, age 45 to 198 tph from below
BLM Matrix 2	Connectivity Diversity Block alloc., 1/15 per 10-year period for plots > 150 y.o.	150	1236 tph, 90% PSME, 10% mix of THPL,	age 12 to 494 tph from below, age 45, 75, 105, 135 to 136 tph from below
BLM LSR Riparian 1	1/6 of <80 y.o. plots in BLM LSR Riparian alloc.	n/a	n/a	age 40 to 198 tph from below
BLM LSR Riparian 2	1/6 of <80 y.o. plots in BLM LSR Riparian alloc.	n/a	n/a	age 40 to 247 tph prop., age 50, 60, 70 to 247 tph proportional
BLM LSR Riparian 3	1/6 of <80 y.o. plots in BLM LSR Riparian alloc.	n/a	n/a	age 40 to 124 tph proportional
BLM LSR Riparian 4	1/2 of <80 plots in BLM LSR Riparian alloc., all plots =80 y.o.	n/a	n/a	n/a

Table 4.1 contd. Description of prescriptions, by ownership: plot characteristics, frequency of harvest, plantation criteria, and thinning regime.

Prescription owner, allocation	Plot criteria: age and allocation	Harvest frequency (years)	Plantation criteria (trees ha^{-1})	Thinning regime
FI Upland	FI Upland alloc., 1/4 per 10-year period for plots >40 y.o.	40	1075 tph, 90% PSME, 10% mix of TSHE ALRU THPL	n/a
FI/NIP Rip. 1	50% FI/NIP Riparian alloc.	n/a	n/a	age 35 to 33.3 m^2 ba proportional
FI/NIP Rip. 2	50% FI/NIP Riparian alloc.	n/a	n/a	n/a
NIP Upland	NIP Upland alloc., 1/6 per 10-year period for plots exceeding 60 y.o.	60	1075 tph, 90% PSME, 10% mix of ALRU THPL TSHE	age 45 remove 35% ba from above
State Upland 1	Coos Matrix 2, non-Coos Matrix 2 allocs., 1/11 per 10-year period for plots >110 y.o.	110	1075 tph, 70% PSME, 20% TSHE, 10% THPL	age 35 to 29.2 m^2 ba prop., age 55 to 32.4 m^2 ba prop., age 80 to 36.3 m^2 prop.
State Upland 2	Focused 1, Focused 2, Coos Matrix 1, Non-Coos Matrix 1, 50% Non-Coos Thin allocs., 1/11 per 10-year per. for plots >110 y.o.	110	1075 tph, 70% PSME, 20% TSHE, 10% THPL	age 35 to 29.2 m^2 ba prop., age 55 to 32.4 m^2 ba prop., age 80 to 36.3 m^2 prop.
State Riparian	Special, 50% Non-Coos Thin allocs.	n/a	n/a	age 35 to 29.2 m^2 ba prop., age 55 to 32.4 m^2 ba, prop.
State Withdr.	Withdrawn, Coos Thin allocs.	n/a	n/a	n/a

Table 4.2. Description of prescriptions, by ownership: Green tree retention at harvest, snag creation and log creation during thinnings and at harvest, and treatment of initial snags and logs at harvest, as conducted in ZELIG. 'Proportional' means trees were selected evenly from across the size distribution of the trees in the stand. 'From above' indicates the largest trees in the stand were selected first. In the simulations, snags were selected first, then logs, then green trees.

Prescription name by owner and allocation	Green tree retention (ha^{-1})	Snag creation (tph or m^3 ha^{-1} as noted)	Log creation (tph or m^3 ha^{-1} as noted)
FS LSR Riparian 1	n/a	n/a	n/a
FS LSR Riparian 2	n/a	age 35 create 38.6 m^3 ha^{-1} from above	age 35 create 38.6 m^3 ha^{-1} from above
FS LSR Riparian 3	n/a	age 35 create 38.6 m^3 ha^{-1} from above	age 35 create 38.6 m^3 ha^{-1} from above
FS Matrix	15% prop.	at age 45 create 5 tph from above, at harvest create 5 tph from above	at harvest create 33.6 m^3 ha^{-1} from above
BLM Matrix 1 (GFMAs)	17 conifers prop.	at harvest create 4 tph from above	at harvest create 33.6 m^3 ha^{-1} from above
BLM Matrix 2 (CDBs)	37 conifers prop.	at harvest create 4 tph from above	at harvest create 33.6 m^3 ha^{-1} from above
BLM LSR Riparian 1	n/a	at age 40 create 38.6 m^3 ha^{-1} from above; ages 50, 60, 70 create 13 tph proportional	at age 40 create 38.6 m^3 ha^{-1} from above; ages 50, 60, 70 create 12 tph proportional
BLM LSR Riparian 2	n/a	at age 40 create 38.6 m^3 ha^{-1} from above; ages 50, 60, 70 create 13 tph proportional	at age 40 create 38.6 m^3 ha^{-1} from above; ages 50, 60, 70 create 12 tph proportional
BLM LSR Riparian 3	n/a	at age 40 create 38.6 m^3 ha^{-1} from above; ages 50, 60 create 13 tph proportional	at age 40 create 38.6 m^3 ha^{-1} from above; ages 50, 60 create 12 tph proportional
BLM LSR Riparian 4	n/a	n/a	n/a
FI Upland	5, 50% conifer, from above	n/a	at harvest create 5 tph proportional
FI/NIP Riparian 1	n/a	n/a	n/a
FI/NIP Riparian 2	n/a	n/a	n/a
NIP Upland	5, 50% conifer, from above	n/a	at harvest create 5 tph proportional

Table 4.2 contd. Description of prescriptions, by ownership: Green tree retention at harvest, snag creation and log creation during thinnings and at harvest, and treatment of initial snags and logs at harvest, as conducted in ZELIG.

Prescription name by owner and allocation	Green tree retention (ha^{-1})	Snag creation (tph or m^3 ha^{-1} as noted)	Log creation (tph or m^3 ha^{-1} as noted)
State Upland 1	12 from above	at harvest create 5 tph from above	at harvest create 52.5 m^3 ha^{-1} from above
State Upland 2	14 from above	at age 80 create 5 tph from above	at age 80 create 52.5 m^3 ha^{-1} from above; at harvest create 52.5 m^3 ha^{-1} from above
State Riparian	n/a	at age 55 create 5 tph from above	at age 55 create 52.5 m^3 ha^{-1} from above
State Withdrawn	n/a	n/a	n/a

BLM

BLM lands currently fall into three main land allocation classes, Matrix General Forest Management Areas (GFMs) (34% of BLM plots), Matrix Connectivity Diversity Blocks (CDBs) (8% of plots), and LSR Riparian status (63% of plots). GFMs were harvested on an 80-year rotation with two thinnings, a high amount of snag and log creation, and a medium-high amount of green tree retention at harvest. CDBs were harvested on a 150-year rotation, had heavier thins during the later thinnings, identical snag and log creation amounts, and higher green tree retention levels. LSR Riparian plots were managed under four different regimes: no action (42% of plots) and three levels of thinning (20% of plots), to simulate the variability of approaches the BLM takes in these areas. All thinnings involved high amounts of snag and log creation relative to other ownerships (Table 4.2).

State

Forests owned by the State of Oregon were modelled with four main management approaches, two for upland sites (75% of State plots), one for riparian areas (13%), and one for withdrawn areas (12%). The two upland regimes were approximately equally applied to the upland plots. Both required harvest on a 110-year rotation, with three thinnings prior to harvest. The first upland regime had a slightly higher amount of green tree retention than the second, and the first required snag creation at the last thinning and log creation at both the last thinning and at harvest, whereas the second required snag and log creation only at harvest. Both had fairly high amounts of snag and log creation in relation to the other ownerships, and high levels of green tree retention at harvest (Table 4.2).

Forest Industry

Industrial private lands were simulated as managed primarily for timber production on a 40-year rotation with no thinning (99% of forest industry plots). All snag and log creation for industrial and non-industrial private owners followed the rules established by the Oregon Forest Practices Act (Oregon Department of

Forestry 2001). A low amount (volume) of logs was to be created under these guidelines. Snag occurrence relied on the death of a small number of green trees retained at harvest; no snags were created intentionally by management. Although industrial ownerships may create snags, I followed this approach because the forest practices rules indicate an owner can either leave live trees or snags and our model would not accommodate this conditional approach. A few forest industry plots, based on their location in riparian areas, were managed under a riparian regime which had thinning instead of harvest but no manual log or snag creation. Due to model constraints, no snags were felled during harvest on this or any other ownership, so the number of snags is probably not underestimated on industry lands.

Non-Industrial Private

Most (about 90%) of non-industrial private lands were uplands managed on a 60-year rotation with one thinning at age 45. Snag and log creation and green tree retention was identical to that of the forest industry upland regime. The remainder of non-industrial private plots were riparian plots managed under a no-action approach.

Controlling for differences in starting conditions

In the second strategy of my simulation plan, I controlled for differences in starting conditions. I applied each ownership's management regime to the same set of 100 plots and projected this over time. The 100 plots were selected at random from the sample population of 930 plots in the Coastal Province. Management prescriptions (Table 4.1) were applied at random to the 100 plots, in proportion to their application to the full sample population of plots. For example, in the first strategy of my simulation plan, the no-action prescription FS LSR Riparian 1 was applied to 158 of the 309 plots under Forest Service ownership (51% of FS plots). Therefore, for the second strategy, I assigned this prescription to 51 of the 100 randomly sampled plots for the test of Forest Service management practices. I did this for each ownership.

Potential upper and lower bounds for dead wood dynamics

In the third simulation strategy, I established potential upper and lower bounds for dead wood amounts. For the upper bound, I simulated the effect of natural conditions ("natural development") on the 100 randomly sampled plots. Here, no management actions were taken, and stand development that included natural regeneration and snag generation was simulated in ZELIG. Initial snags and logs, and naturally generated snags, were decayed over time in CWDM. For the lower bound, I simulated the 100 plots under clearcut harvest conditions not subject to the requirements of the Oregon Forest Practices Act (Oregon Department of Forestry 2001) which promote some green tree retention/snag creation, and log creation. Thus, in this scenario ("intensive management w/o dead wood"), stands were clearcut on a 40-year rotation and then planted with the densities and species composition of the FI Upland prescription (see Table 4.1). However, there were no green trees retained and no logs created at the time of harvest under this scenario.

Data analysis

For each 5-year increment of the 300-year simulation period, I obtained summary statistics for each plot for the number of snags of various sizes, volume of snags (m^3 ha^{-1}) of various sizes, volume of logs of various sizes. I differentiated between dead wood present at model initiation ("initial") and that produced during the simulation period ("new"). Because plot sampling densities were non-uniform across the ownerships (for example, higher densities on Forest Service lands), for any area-based measures of dead wood I calculated weighted mean values.

I calculated mean and median values for each plot for each dead wood variable for the entire Coastal Province and for each ownership type. To test for differences between ownership groups, I performed two-sided Wilcoxon rank-sum tests on the medians, because dead wood data are commonly skewed and therefore tests of difference between means would not meet normality assumptions (Ohmann and Waddell 2002). However, reporting of means for dead wood amounts is commonplace (Spies and Cline 1988, Ohmann and Waddell 2002), so I report mean values, as well as results from the Wilcoxon rank-sum tests of difference among medians, to increase facility of comparison with other studies.

Results

Province-wide trends

The average volume (m^3 ha^{-1}) of logs and snags increased greatly, by about three and nine times, respectively, over the 300-year simulation period across the Coastal Province (Table 4.3). All sizes of dead wood showed marked increases in volume and number early in the simulation period. The amount of mid-sized snags and logs increased, both in terms of volume (logs and snags) and number (snags), until about midway in the simulation period, then decreased slightly. The mean volume per hectare of large snags and logs increased greatly (Table 4.3).

Most of the volume of dead wood was comprised by large snags and logs (>50 cm dbh or led), whether the source was dead wood present at model initiation (Figure 4.2 a, c) or that produced during the course of the simulation period (Figure 4.2 b, d). The residence time of large pieces of dead wood was long (maximum of about 225 years for large logs and 175 years for large snags from simulation year 0); this combined with management and stand development to lead to increases in the mean volume of large snags and logs (Figure 4.2 a-d). Medium-sized logs made up about 17% of the total log volume at simulation year zero and declined to about 13% by year 300 (Figure 4.2 a, Table 4.3). Snag patterns for medium-sized snags were similar. The largest sizes of snags were those the least commonly created by management or through stand development (Figure 4.2 f); these were also the sizes in lowest numbers at model outset (Figure 4.2 e). Small snags were produced in the highest numbers, with the greatest fine-scale temporal variability of amount among different-sized snags, as forest stands went through cycles of development and harvest (Figure 4.2 f).

Ownership-related patterns

'New' logs, those produced through management or forest development, comprised most of the volume of dead wood over the simulation period, regardless of ownership type (Figure 4.3). However, there were large differences in the amount of dead wood produced by different owners during this time (Table 4.4). Federal ownerships (FS and BLM) showed steady increases in both log and snag volumes and consistently had the highest amounts (Figure 4.3 b, c). The State of Oregon had amounts that were also quite high but fluctuated more because of their tendency toward a long-rotation harvest (110 years), and non-reserve approach to

Table 4.3. Mean amount of various dead wood attributes over time, per hectare, in the Coastal Province of Oregon, given that forest management is applied according to land ownership. Volume is cubic meters. Standard errors are shown in italics in rows below mean values. For snags, dbh is diameter at breast height. For logs, led is large-end diameter.

Dead wood		Simulation Year						
attribute		0	50	100	150	200	250	300
Total log volume	mean	172.57	281.08	356.06	405.20	471.54	500.24	549.56
	s.e.	*5.73*	*6.20*	*7.24*	*8.66*	*10.64*	*12.03*	*13.64*
Log volume 30-50	mean	30.14	70.11	84.92	86.02	85.43	75.53	74.13
cm led	*s.e.*	*1.00*	*1.61*	*1.58*	*1.65*	*1.70*	*1.61*	*1.65*
Log volume >50	mean	120.26	151.68	197.76	233.43	292.80	327.90	377.91
cm led	*s.e.*	*5.13*	*5.23*	*6.70*	*8.41*	*10.66*	*12.41*	*14.14*
Total snag volume	mean	26.74	97.81	129.07	157.87	189.76	214.49	236.67
	s.e.	*1.75*	*2.94*	*3.93*	*5.16*	*6.39*	*7.56*	*8.43*
Snag volume 30-50	mean	3.19	24.64	25.06	26.31	24.89	24.95	24.54
cm dbh	*s.e.*	*0.29*	*1.32*	*1.85*	*2.27*	*2.73*	*3.17*	*3.63*
Snag volume >50	mean	19.69	58.98	91.75	122.30	157.52	183.27	207.98
cm dbh	*s.e.*	*1.62*	*2.74*	*3.92*	*5.27*	*6.66*	*7.93*	*8.86*
Number of snags	mean	25.37	65.96	58.84	57.99	60.44	56.53	61.53
>10 cm dbh	*s.e.*	*1.74*	*1.37*	*0.87*	*1.01*	*1.10*	*1.11*	*1.31*
Number of snags	mean	2.39	5.62	6.98	8.07	9.26	8.76	8.68
>50 cm dbh	*s.e.*	*0.18*	*0.21*	*0.26*	*0.32*	*0.37*	*0.37*	*0.35*
Number of snags	mean	0.62	5.15	6.70	7.43	7.97	7.07	6.91
>50 cm dbh, >15 m	*s.e.*	*0.07*	*0.19*	*0.26*	*0.30*	*0.32*	*0.30*	*0.27*
Number of snags	mean	1.53	2.00	3.09	4.23	5.41	5.88	6.00
>75 cm dbh	*s.e.*	*0.13*	*0.11*	*0.14*	*0.19*	*0.24*	*0.27*	*0.28*
Number of snags	mean	18.17	44.65	36.75	35.72	38.94	35.95	41.59
10-25 cm dbh	*s.e.*	*1.59*	*1.27*	*0.93*	*1.14*	*1.20*	*1.22*	*1.38*
Number of snags	mean	4.81	15.69	15.11	14.19	12.24	11.82	11.26
25-50 cm dbh	*s.e.*	*0.41*	*0.41*	*0.34*	*0.28*	*0.34*	*0.30*	*0.32*
Number of snags	mean	0.86	3.62	3.89	3.84	3.85	2.88	2.68
50-75 cm dbh	*s.e.*	*0.08*	*0.13*	*0.16*	*0.16*	*0.16*	*0.13*	*0.12*

management (Figure 4.3 d), and because many of their forests were of similar age so were harvested at similar times. Private landowners had by far the lowest dead wood amounts through the course of the simulation period, although forest industry commenced the simulation period with dead wood amounts similar to those of the federal ownerships (Table 4.4). The amount (volume) of dead wood stayed about the same over the simulation period on forest industry lands (Figure

4.3 e). Non-industrial private owners, on the other hand, started out with the lowest amounts of dead wood and then increased substantially from starting levels (Figure 4.3 f). The proportion of dead wood that was present as snags increased over time on all ownerships. In addition, the volume of logs increased greatly relative to initial conditions on all but forest industrial lands (Figure 4.3 a-f).

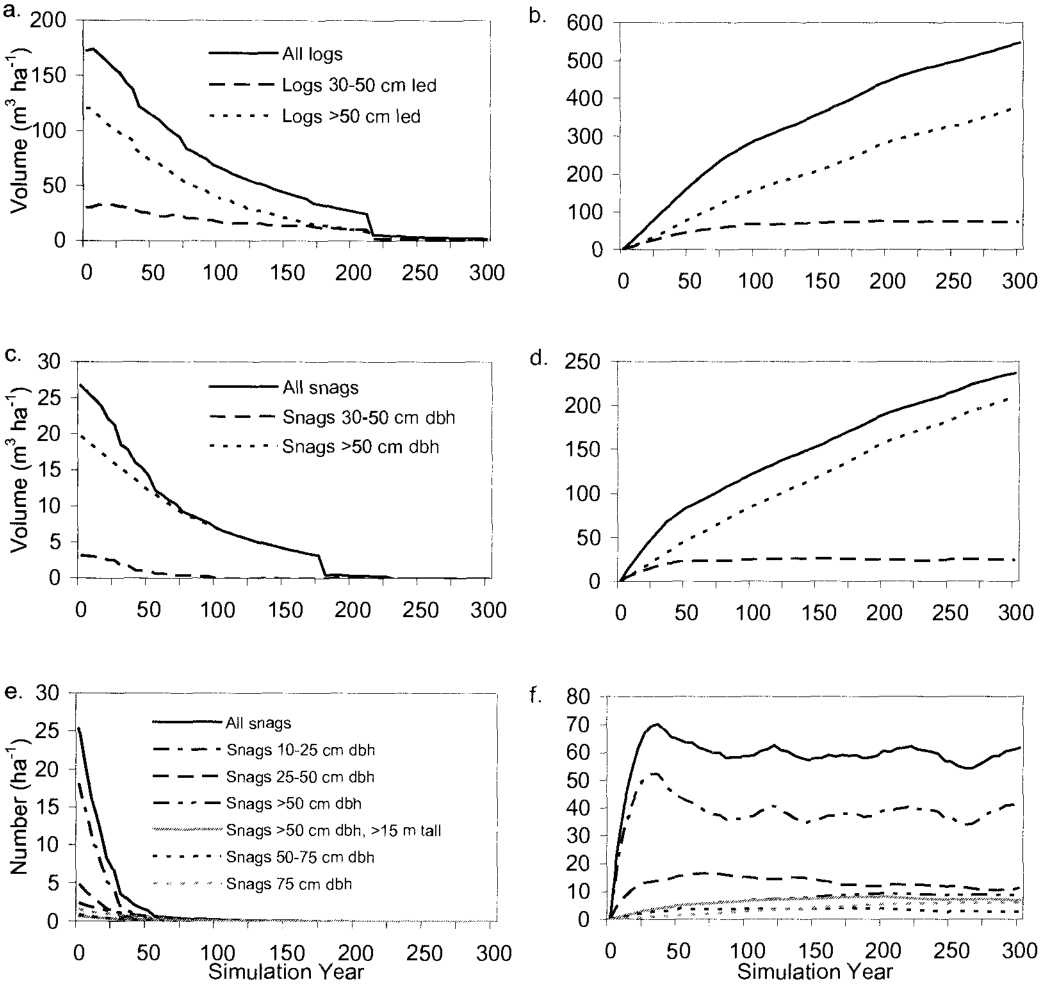


Figure 4.2. Projected future mean amount per hectare of (a) initial log volume, (b) new log volume, (c) initial snag volume, (d) new snag volume, (e) number of initial snags, (f) number of new snags, in the Coastal Province of Oregon. Legend for figures a and b is in figure a; legend for figures c and d is in figure c; legend for figures e and f is in figure e.

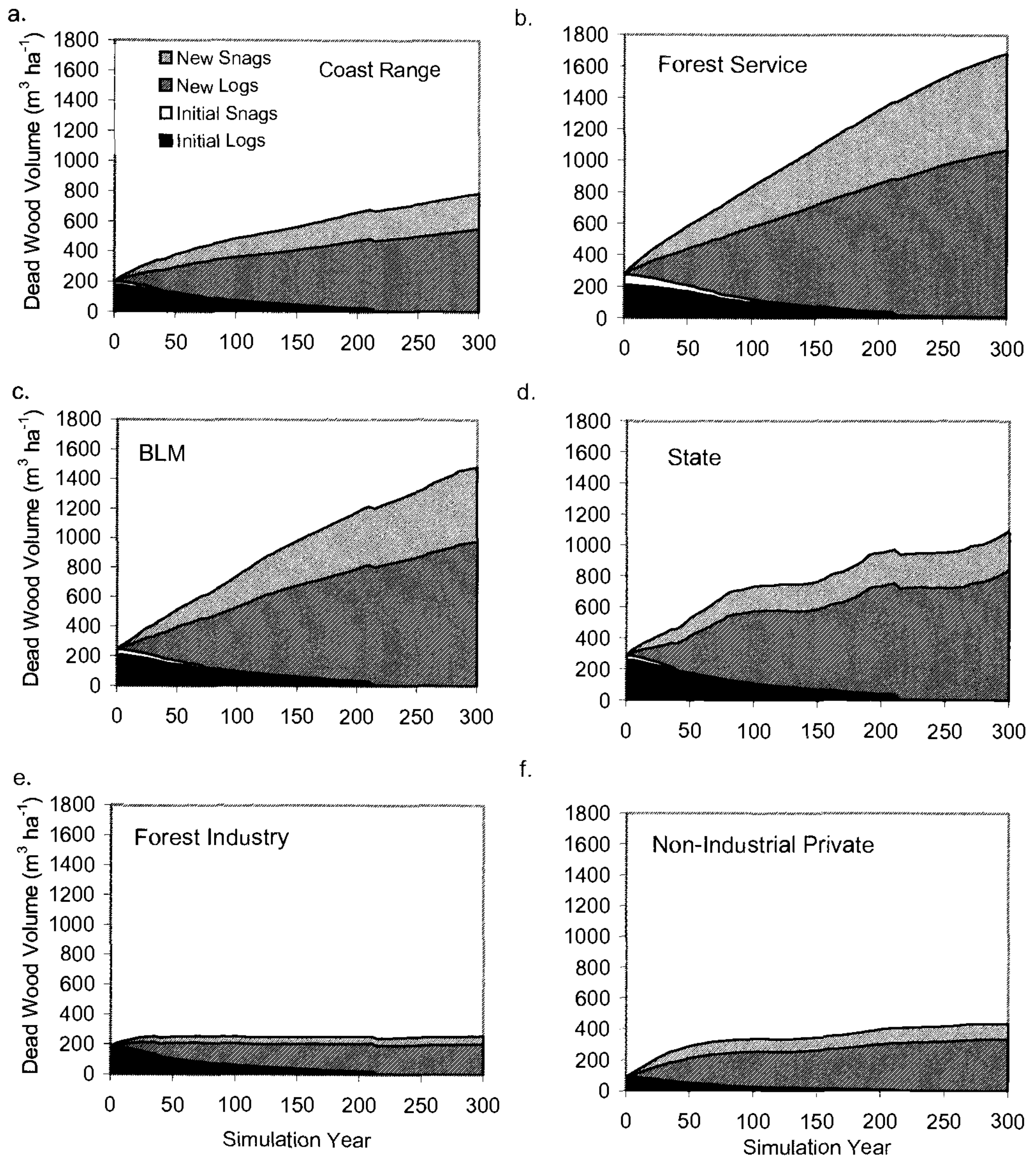


Figure 4.3. Projected future mean dead wood volume, differentiated by dead wood source and type, for the Coastal Province and by ownership: (a) Coastal Province, (b) USFS, (c) BLM, (d) State, (e) Forest Industry, (f) Non-Industrial Private. Legend for all figures is in (a).

The overall trends in volumes of different sizes of logs and snags with respect to ownerships were similar. Throughout the simulation period, Federal owners had the highest amounts. The State had intermediate amounts (with exceptions). The private lands had low amounts. The Forest Service and BLM tended to have the highest volume of both all logs and snags, and large logs and large snags (Figure 4 a, b, e, f). The Forest Service, which mainly thinned or took no action (natural development), had consistent declines in the volume of medium-sized (30-50 cm dbh) snags as stands matured and larger trees died (Figure 4 d). The State commenced the simulation period with the highest volume of large logs and of all logs, and was among the top 3 landowners for the volume of logs and snags, but State amounts fluctuated more than those on federal lands as State-owned stands matured and were harvested (Figure 4.4; Tables 4.1 and 4.2). Forest industry lands had very low amounts of large logs relative to the other ownerships (Table 4.4) as those present decayed away, but had moderate amounts of medium-sized logs consistently through the simulation period (Figure 4.4 c, e). Non-industrial private lands had fairly high amounts of both medium-sized logs and snags (Figure 4.4 c, d).

The private lands, both non-industrial and industrial, also had the highest number of all snags for most of the simulation period (Figure 4.5 a), mainly comprised by the smaller size classes (Figure 4.5 e, f). The State lands commenced the simulation period with the highest number of snags but by the end they had intermediate numbers of snags (Figure 4.5 a). The largest numbers of large snags occurred on Forest Service, BLM, and State lands, in that order (Figure 4.5 b, c, d). Snag numbers on State lands fluctuated more over time.

Table 4.4. Mean amounts of selected dead wood attributes by ownership, and differences among ownerships in median amounts over the 300-year simulation period in the Coastal Province of Oregon. Numbers in left column are simulation year. Volumes are cubic meters per hectare. Number are per hectare. Different letters after amounts indicate difference between medians significant at $p < 0.05$ level, from paired Wilcoxon Rank-Sum tests.

	FS			BLM			State			FI			NIP		
	Mean		s.e.	Mean		s.e.	Mean		s.e.	Mean		s.e.	Mean		s.e.
Volume of all snags															
0	68.4	a	4.2	39.5	b	7.1	29.1	b	4.4	14.3	c	1.8	13.1	c	3.2
50	183.8	a	6.5	144.7	b	9.5	125.9	b	7.2	48.5	c	2.5	86.0	d	6.5
100	277.5	a	7.9	227.6	b	11.2	167.4	c	8.6	48.0	d	1.9	85.3	e	5.6
150	374.0	a	8.3	312.6	b	12.9	186.6	c	11.0	47.0	d	1.8	81.7	e	6.4
200	468.8	a	8.2	387.4	b	15.4	219.4	c	13.9	49.1	d	2.1	92.5	e	8.5
250	554.6	a	8.7	445.5	b	18.0	233.2	c	16.9	52.7	d	2.7	96.1	e	10.6
300	612.4	a	8.9	504.0	b	19.6	256.7	c	19.2	55.3	d	2.7	98.8	e	11.7
Volume of snags > 50 cm dbh															
0	56.0	a	3.7	33.3	b	7.0	19.0	b	4.0	8.9	c	1.6	7.4	c	2.8
50	143.9	a	6.5	103.3	b	9.3	76.1	b	6.7	17.1	c	1.9	41.1	d	5.8
100	244.7	a	8.0	184.2	b	11.4	132.8	c	8.6	15.2	d	1.7	39.4	e	5.7
150	349.7	a	8.2	279.0	b	13.2	144.2	c	11.7	14.5	d	1.5	34.4	d	6.8
200	454.6	a	8.2	361.7	b	15.9	191.0	c	14.6	17.0	d	1.6	38.6	e	9.1
250	547.0	a	8.7	425.6	b	18.8	194.7	c	18.5	21.0	d	2.1	43.3	e	11.2
300	607.6	a	8.9	488.6	b	20.6	228.7	c	20.4	23.6	d	2.1	46.5	e	12.4
Number of snags > 50 cm dbh															
0	7.7	a	0.6	3.7	b	0.6	2.4	c	0.5	1.0	d	0.2	0.8	d	0.3
50	12.1	a	0.5	9.1	b	0.5	9.0	b	0.6	1.7	c	0.2	4.2	d	0.4
100	16.6	a	0.4	14.3	a	0.6	11.2	b	0.6	1.2	c	0.1	3.0	d	0.4
150	20.4	a	0.4	18.0	b	0.8	11.4	c	0.8	1.0	d	0.1	2.9	e	0.5
200	22.7	a	0.5	20.4	b	0.9	15.4	c	0.8	1.1	d	0.1	2.8	e	0.5
250	22.3	a	0.4	20.2	b	1.1	12.5	c	0.9	1.0	d	0.1	2.6	e	0.5
300	20.2	a	0.4	19.3	b	1.1	15.8	b	0.8	1.0	c	0.1	2.4	d	0.4
Volume of all logs															
0	206.8	a	10.2	204.7	ac	21.7	253.5	b	20.3	169.4	c	8.7	76.1	d	7.9
50	404.3	a	10.8	373.4	a	19.7	396.3	a	21.6	203.7	b	7.6	208.1	b	13.0
100	560.0	ab	12.8	520.6	a	18.3	566.7	ab	16.3	204.4	c	5.8	250.0	d	10.9
150	705.8	a	13.9	673.9	a	18.2	582.4	b	15.3	202.8	c	4.6	258.3	d	10.6
200	853.8	a	14.9	794.2	ab	20.0	731.3	b	17.5	204.5	c	4.3	296.5	d	13.1
250	975.4	a	15.7	872.7	b	24.4	726.8	c	17.4	197.1	d	4.2	313.2	e	14.9
300	1074.9	a	16.6	976.5	b	26.0	837.8	c	20.8	202.3	d	4.7	327.1	e	17.0

Table 4.4 contd. Mean amounts by ownership of selected dead wood attributes, and differences among ownerships in median amounts over the 300-year simulation period in the Coastal Province of Oregon.

	FS		BLM		State		FI		NIP	
	Mean	s.e.	Mean	s.e.	Mean	s.e.	Mean	s.e.	Mean	s.e.
Volume of logs > 50 cm led										
0	144.0 ^{a}	9.2	150.1 ^{a}	20.1	198.4 ^{b}	18.7	113.3 ^{a}	7.7	44.6 ^{c}	6.5
50	246.2 ^{a}	10.4	234.7 ^{a}	18.4	236.1 ^{a}	17.5	92.8 ^{b}	5.7	89.9 ^{b}	10.6
100	385.1 ^{ab}	12.7	344.7 ^{a}	18.5	395.3 ^{b}	15.1	65.8 ^{c}	4.2	89.6 ^{d}	10.0
150	542.0 ^{a}	13.2	491.4 ^{a}	18.3	395.5 ^{b}	14.3	45.1 ^{c}	3.4	74.5 ^{c}	11.2
200	709.6 ^{a}	13.4	612.1 ^{b}	19.4	539.2 ^{c}	15.8	39.2 ^{cd}	3.7	81.2 ^{d}	15.0
250	864.1 ^{a}	13.9	708.6 ^{b}	23.9	529.3 ^{c}	18.0	38.1 ^{c}	3.9	83.7 ^{d}	17.5
300	976.3 ^{a}	14.8	820.1 ^{b}	25.7	628.1 ^{c}	20.7	44.1 ^{c}	4.6	91.8 ^{d}	20.0

Effect of controlling for initial conditions

Differences in the effects of management were even more apparent when I applied the prescriptions to the same set of 100 plots. The State of Oregon showed the biggest differences from their patterns in the first simulation strategy, as they had much more generous production of large logs up until about 75 years in the simulation period when their prescriptions were applied to the random sample of plots (Figure 4.6 e vs. Figure 4.4 e). In addition, cyclic pulses of dead wood produced by the State in the landscape-wide scenario were dampened, as the age of live trees in the random sample of plots was of a wider range than the plots currently under State ownership. This meant that for the State, harvests were more spread out over time in the random sample than in the Province-wide scenario. The

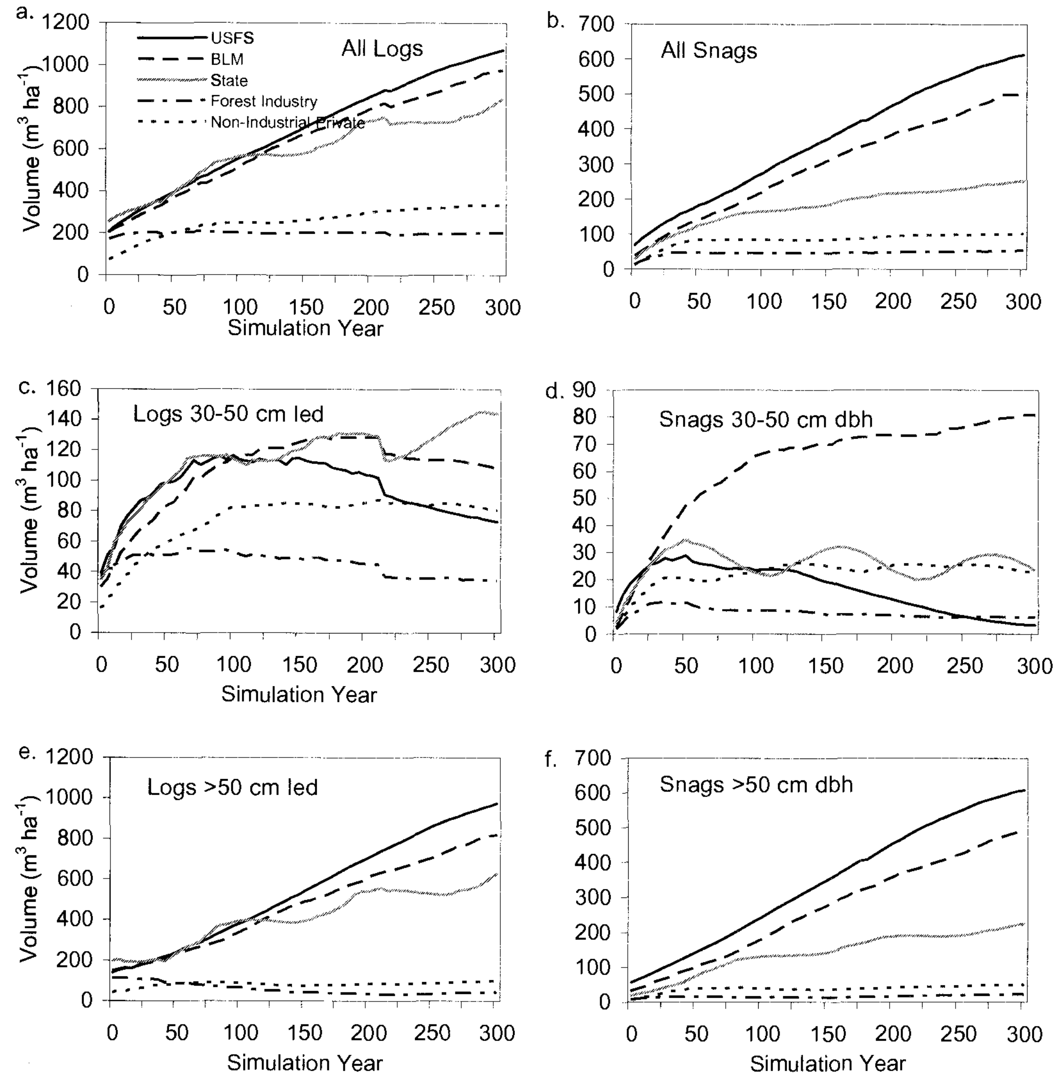


Figure 4.4. Projected patterns of dead wood volume per hectare for (a) all logs, (b) all snags, (c) logs 30-50 cm led, (d) snags 30-50 cm dbh, (e) logs >50 cm led, (f) snags >50 cm dbh, by ownership group, in the Coastal Province of Oregon. Legend for all figures is in figure (a).

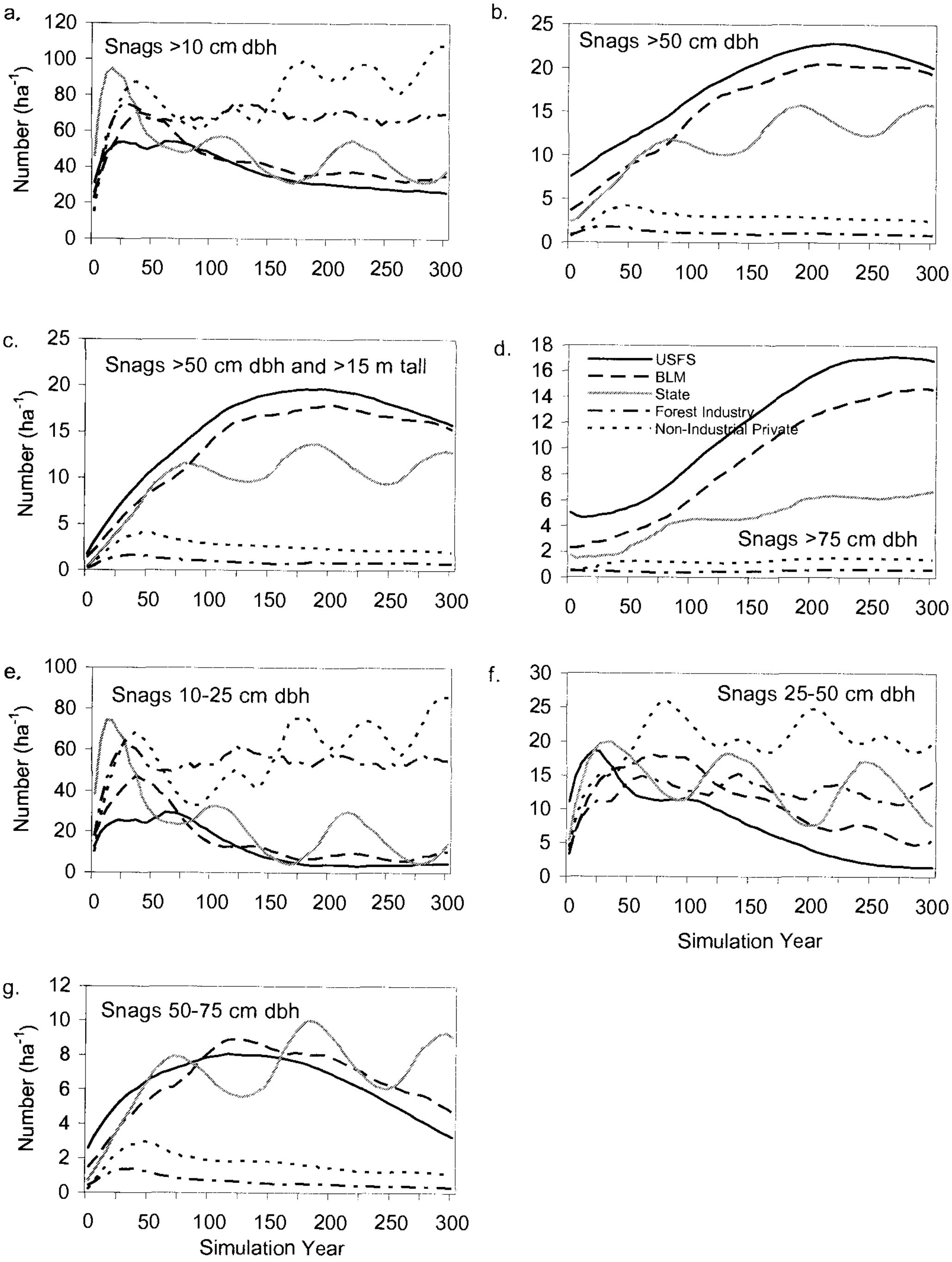


Figure 4.5. Projected number per hectare for (a) snags >10 cm dbh; (b) snags >50 cm dbh; (c) snags >50 cm dbh and >15 m tall; (d) snags >75 cm dbh; (e) snags 10-25 cm dbh; (f) snags 25-50 cm dbh; (g) snags 50-75 cm dbh, by ownership, in the Coastal Province of Oregon. Legend for all figures is in (d).

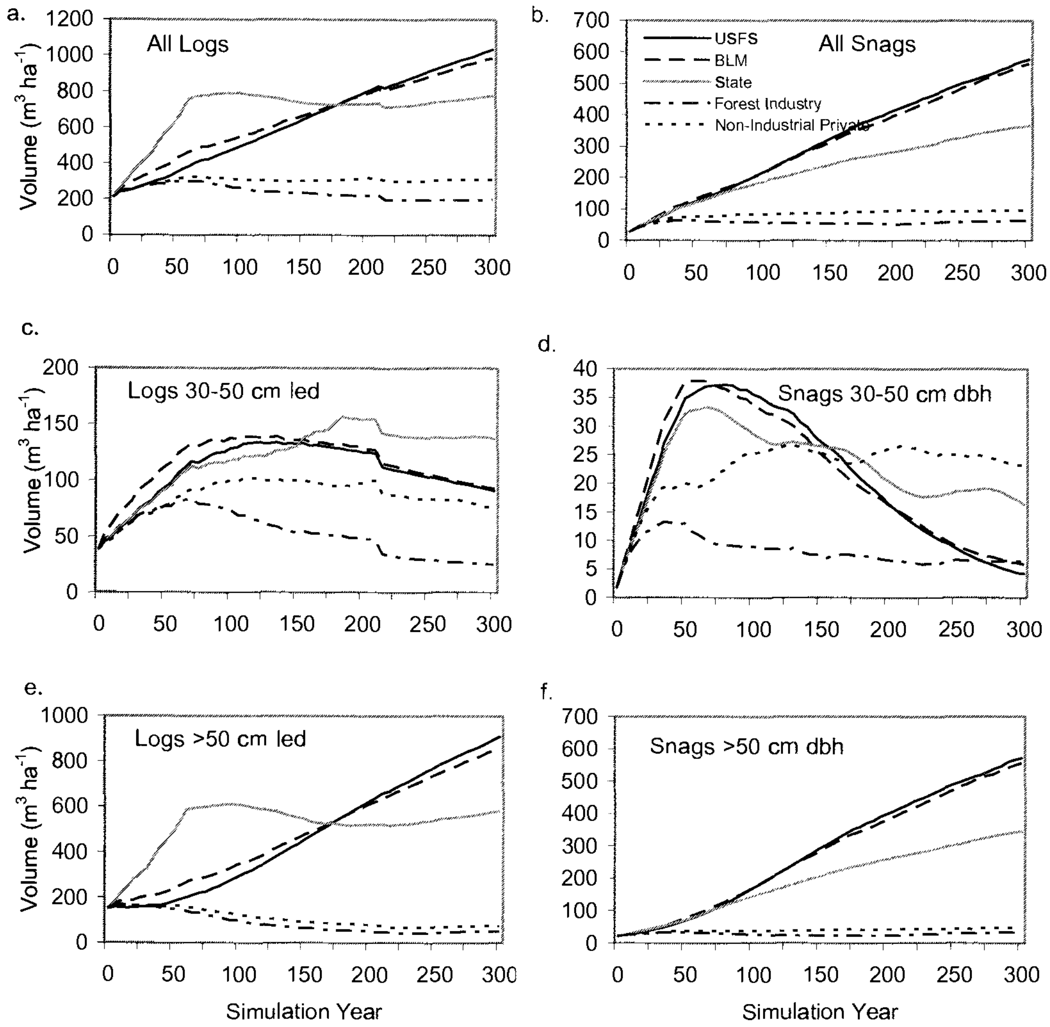


Figure 4.6. Projected volume per hectare for (a) all logs; (b) all snags; (c) logs 30-50 cm led; (d) snags 30-50 cm dbh; (e) logs >50 cm led; (f) snags >50 cm dbh in the Coastal Province of Oregon, assuming the same starting conditions on each ownership. Management scenarios of a given ownership were applied to a set of 100 plots and projected over time. Scenarios were applied in proportion to their potential application on that owner's lands. Legend for all figures is in (b).

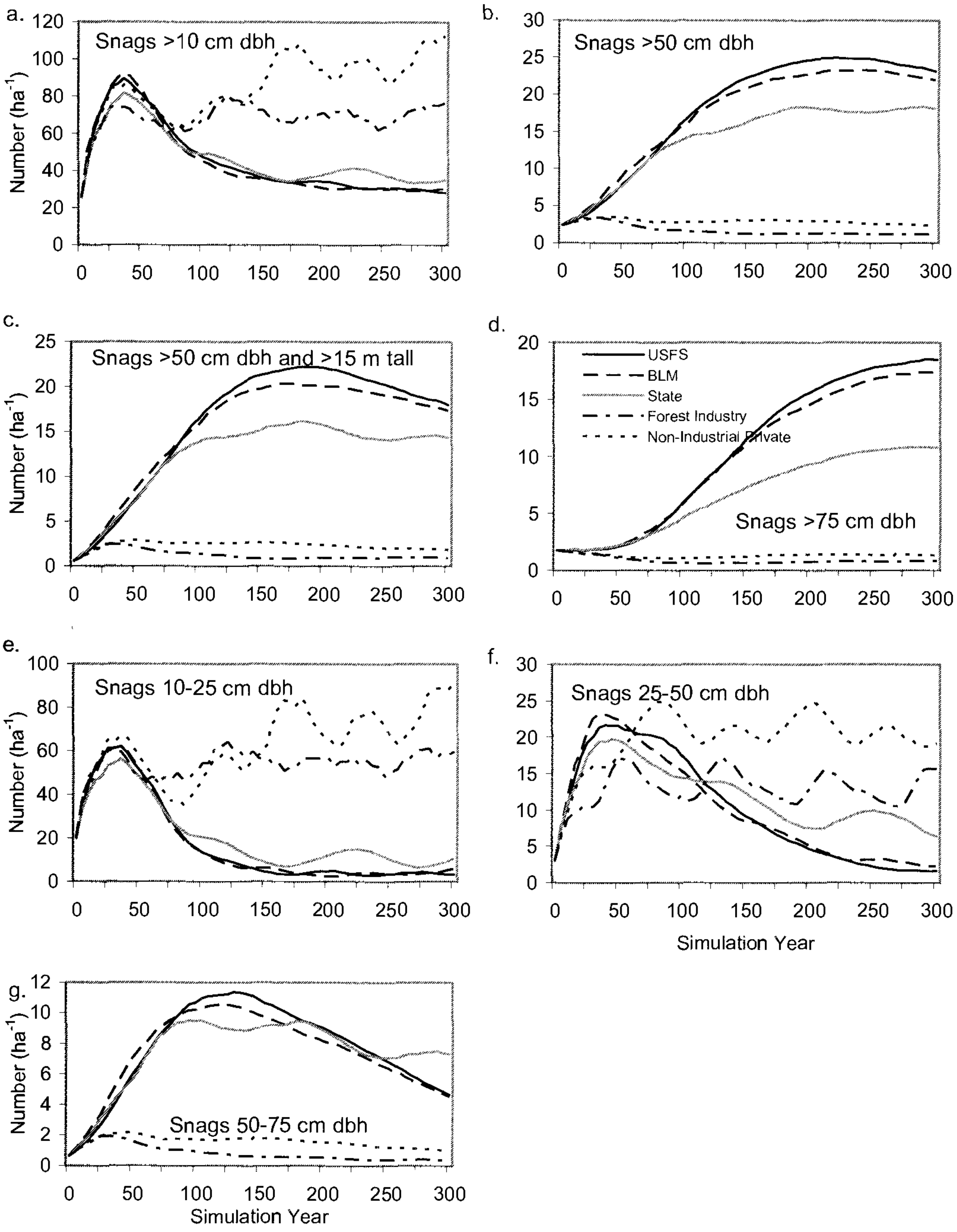


Figure 4.7. Projected number per hectare of (a) snags >10 cm dbh; (b) snags >50 cm dbh; (c) snags >50 cm dbh and >15 m tall; (d) snags >75 cm dbh; (e) snags 10-25 cm dbh; (f) snags 25-50 cm dbh; (g) snags 50-75 cm dbh in the Coastal Province of Oregon, assuming the same starting conditions on each ownership. Management scenarios of a given ownership were applied to a set of 100 plots and projected over time. Legend for all figures is in (d).

practices of the Forest Service and BLM were nearly identical to one another in the random sample of plots scenario, with only slight differences in the timing and amount of dead wood production (Figures 4.6 and 4.7). More large snags were produced by the midpoint of the simulation period on State, Forest Service, and BLM lands under the random sample of plots scenario, but these amounts declined to levels similar to the landscape-wide scenario by the conclusion of the simulation period (Figure 4.7 g). Patterns of dead wood amounts on forest industry and private non-industrial lands were similar for the most part with those of the landscape-wide scenario, but there were greater declines in large logs because there were more large logs at the start that decayed away over the first 100 years and were not replaced (Figure 4.6 e vs. Figure 4.4 e). Large increases in medium-sized snags on BLM lands observed in the landscape-wide scenario (Figure 4.4 d) were not observed when BLM management practices were applied to the random sample of plots (Figure 4.6 d). Aside from the new maxima mentioned for the State of Oregon, the relative ranking of ownerships in snag and log amounts remained similar to that of the landscape-wide scenario.

Maximal and minimal dead wood scenarios

The natural development simulation resulted in similar or higher dead wood amounts than any of the other simulations. The volume of logs and the rate

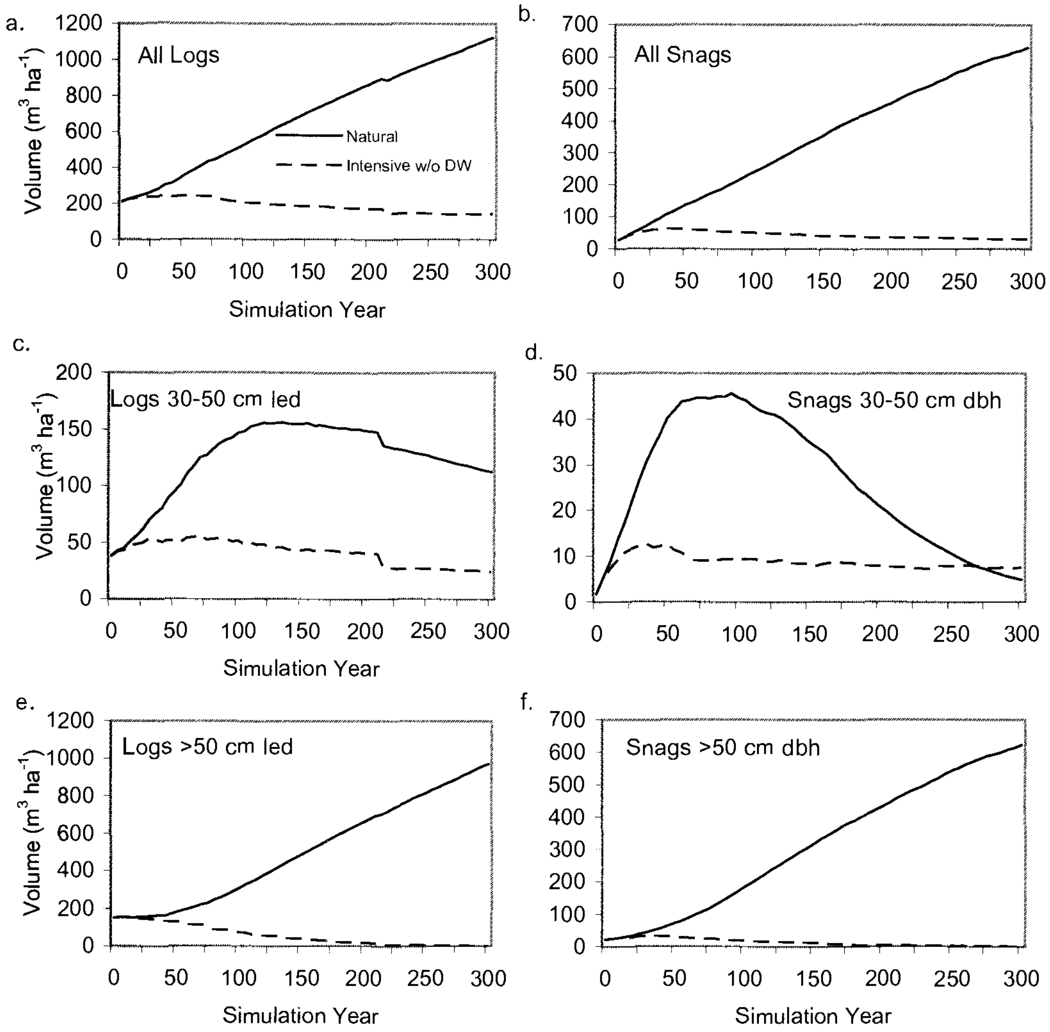


Figure 4.8. Projected volume per hectare of (a) all logs; (b) all snags; (c) logs 30-50 cm led; (d) snags 30-50 cm dbh; (e) logs >50 cm led; (f) snags >50 cm dbh, in the Coastal Province of Oregon, assuming the same starting conditions, for plots with only natural development ("Natural") and plots managed under a 40-year rotation with no green tree retention or dead wood creation at harvest ("Intensive w/o DW"). . Legend for all figures is in (a).

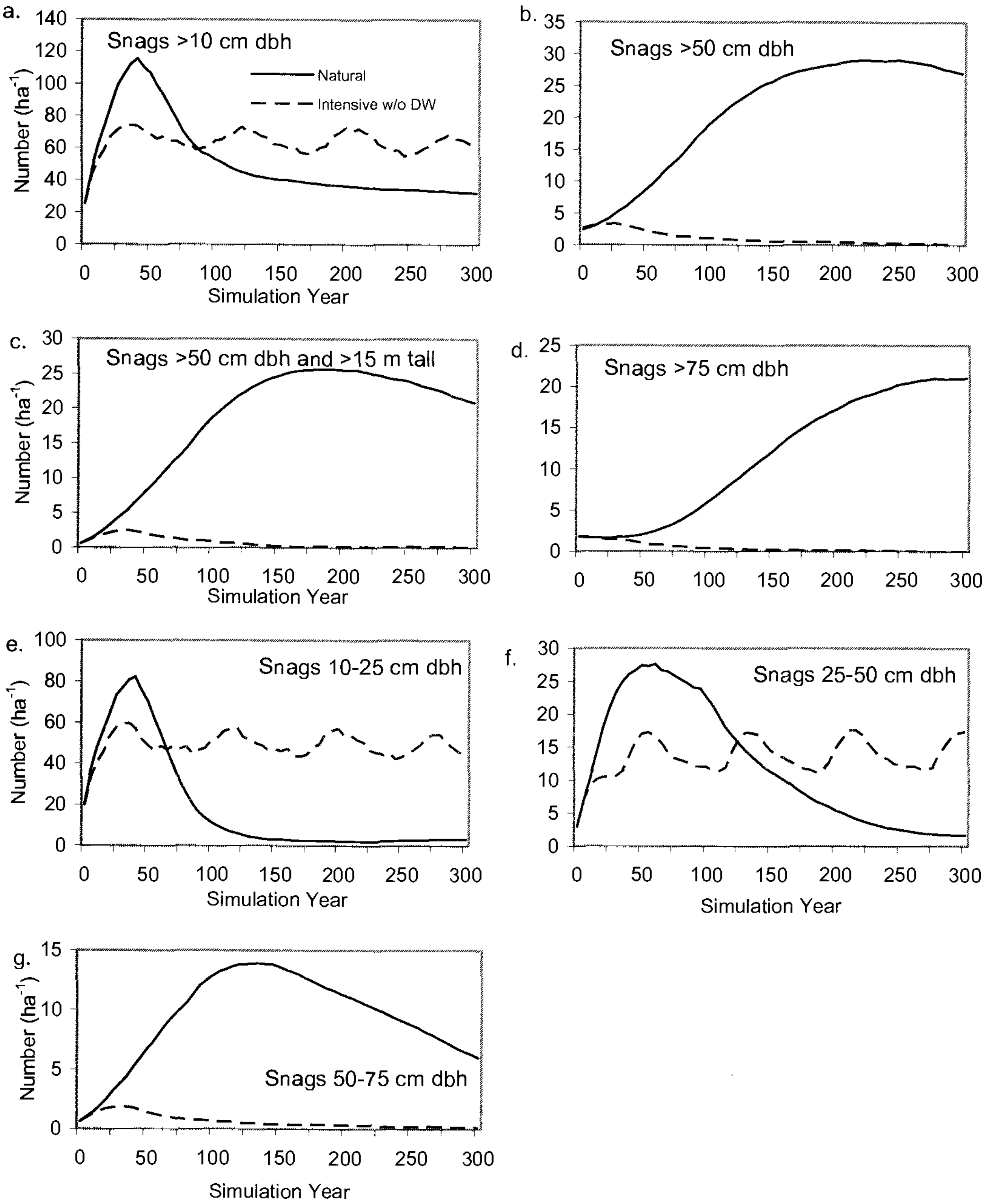


Figure 4.9. Projected number per hectare of (a) snags >10 cm dbh; (b) snags >50 cm dbh; (c) snags >50 cm dbh and >15 m tall; (d) snags >75 cm dbh; (e) snags 10-25 cm dbh; (f) snags 25-50 cm dbh; (g) snags 50-75 cm dbh, in the Coastal Province of Oregon, assuming the same starting conditions, for plots with no management actions ("Natural") and plots managed under a 40-year rotation with no green tree retention or dead wood creation at harvest ("Intensive w/o DW"). Legend for all figures is in (a).

of increase in total log volume were similar for natural conditions and the Forest Service and BLM management regimes (Figure 4.8 a vs. Figure 4.6 a). Large numbers of small and mid-sized snags were produced during the first 50 years of the simulation period (Figure 4.9 e, f). The number of large (50-75 cm dbh) and very large (>75 cm dbh) snags was higher than that projected in the other simulations using the same starting conditions. In natural stands, the maximum number of snags greater than 50 cm dbh was about 20% higher than the highest amount in the first simulation strategy, which occurred under the Forest Service management scenario (Figure 4.9 b vs. Figure 4.7 b). These occurred about 200 years into the simulation period, after which declines in the number of large snags (50-75 cm dbh) as trees grew into larger size classes before dying, resulted in slight declines in the number of snags >50 cm dbh.

Clearcutting on a 40-year rotation with no green tree retention or dead wood creation resulted in the production of high numbers of small (10-25 cm dbh) medium (25-50 cm dbh) –sized snags, relative to natural development (Figure 4.9 e, f). No large (>50 cm) logs or snags were produced, so volumes and numbers of pieces in these size classes declined to zero. This occurred by about 200 years (Figure 4.8 e, f; Figure 4.9 d). On exception was for large snags (50-75 cm dbh). A few snags were added to the number of snags of this size class early in the simulation period for the clearcut scenario, as not all plots initially exceeding 40 years of age were harvested during the first 5-year period. Thus, low numbers (<1 ha^{-1}) of snags of this size class remained by the end of the simulation period.

Discussion

My results indicate that projected future management of Coastal Province forests is likely to lead to great increases Province-wide in dead wood from today's amounts. These projected amounts are potential maxima given no disturbance events of large (i.e., fire) or middle size (i.e. windthrow, widespread beetle kill) for the 300-year simulation period, and no snag felling during thinning or harvest on any ownership. Including large- or mid-sized disturbances in the model might lead to increases or decreases in dead wood, depending on the type and magnitude of disturbance and the timing of the disturbance relative to the age of affected forest stands. With the addition of snag felling, snag amounts would be lower for those plots in which thinning or harvest occurred; the sizes of snags affected would again depend on the timing of snag felling relative to the age of the stand, with older forest stands having the potential to produce larger snags. Given these constraints, the results of this study should be considered as potential upper bounds on amounts that could develop under current policies or scenarios.

Policy effects

The Northwest Forest Plan, simulated on Federal lands, is projected to result in a dramatic increases in dead wood from current amounts. Managing for older forest structure and aquatic habitat, including creating snags and logs during young stand thinning, and handling older stands and riparian areas as no-action areas, appears to have very positive effects on dead wood abundance. As the average age of the forests increases on these lands, and very large trees develop (~100-250 cm dbh), with mortality of these very large trees an increasing amount of very large dead wood is projected for Federal lands.

Under the Oregon Forest Practices Act, intensively managed private lands are likely to maintain current dead wood amounts, though the large sizes are likely to decline. Large snags and logs were present at very low levels through the simulation period when large green trees and snags were retained at harvest under the intensive management scenario subject to the Oregon Forest Practices Act (OFPA).

Without the OFPA (no green tree retention, snag or log creation), numbers and volumes of large snags and logs (>50 cm dbh and led) began to decrease from levels produced under the OFPA simulation starting at about 100 years into the simulation. Under the intensive management w/o dead wood scenario, declines in snags and logs continued as initial wood decayed, until there were no large snags or logs remaining by about simulation year 200. The results of this scenario might be closer to those which would be produced with the felling of all snags at harvest, although even in the intensive management w/o dead wood scenario, snags produced during stand development remained standing until they decomposed. With felling, amounts of smaller snags under this scenario would probably be even lower than those reported here.

These simulation results indicate that even with the same starting conditions, differences in forest management can result in very divergent patterns of abundance of dead wood over time. In these simulations, under the same starting conditions, the Forest Service ended the 300-year period with about six times as much dead wood volume as forest industry (1610 vs. 262 m^3 ha^{-1}). Under Forest Service management, total dead wood volume was about 90% of the potential maximum amount estimated under the natural conditions scenario (1751 m^3 ha^{-1}).

Projected future change in dead wood amounts: spatial and temporal effects

Region-wide, dead wood amounts are projected to increase overall, but my results indicate that under current management there will be large differences in dead wood amounts among ownerships. On industrial ownerships the volume of large logs is projected to decline from current levels. Projected increases on federal and state lands mean that there is likely to be increased spatial divergence of dead wood amounts (number of snags and volume of snags and logs), types (snags vs. logs), and size classes across the region. Ownership-based differences for some types and sizes of dead wood are projected to develop in the first few decades and carry through for centuries thereafter. This indicates that management effects on dead wood at short time scales can leave a signature for many decades or even centuries. For example, the lack of replacement of present-day large legacy logs on industrial lands means the very large logs present today will not be present in future centuries; this is likely to have long-term effects on wildlife species that use these very large logs. State and non-industrial lands, on the other hand, provide timber volume through longer rotation harvests, along with some dead wood creation and/or higher levels of green tree retention, thereby increasing their dead wood amounts and increasing the number of large pieces from present-day dead wood quantities.

This modeling work also exemplifies one of the key attributes of dead wood: the long time periods required for extant dead wood to decay, and for new large logs and snags to develop. This is the case given the omission of fires that could consume decayed material, or other processes that might dead wood break up faster. I found that large logs already present in the initial, post-harvest stands persisted for over 200 years of the simulation period, and large snags for around 175 years. Legacy dead wood acted as a buffer in the change of dead wood types and amounts. The significance of this finding is that management effects causing declines to dead wood amounts or particular sizes of dead wood may not be readily apparent in specific stands if a large quantity of legacy wood is already present.

The large increases that I projected in the total volume of dead wood in the Coastal Province over the next 300 years should be considered in relation to the historical context. Present-day conditions in the Coastal Province, including the distribution among ownerships, of dead wood are the result of particular historical factors such as the timing and extent of fires, prior management, large windthrow events, and other forms of disturbance. Management and even land ownership has followed some of the patterns of vegetation in the area (e.g., the Tillamook State Forest was established after the Tillamook fires when private landowners defaulted on their taxes and these lands were turned over to the State (Levesque 1985)). Were these historical conditions different, patterns of initial vegetation and dead wood would probably differ from those that were observed, with consequences to future projected dead wood amounts.

Holding starting conditions constant among ownerships allowed me to describe differences in management under the same historical context. Simulated management practices on State lands, for example, seem to be tailored to the distribution of age classes present on those lands; when I applied their management practices Province-wide to the same-starting-conditions data, an unexpectedly large amount of large logs was produced very early in the simulation period. This is because older forests (from plots on federal lands) were harvested by the State early on and a large amount of large log volume creation at harvest was part of their management prescription.

In many areas of the Coastal Province, present-day dead wood amounts are a legacy of fire events of the past 50 to 150 years. The current levels of dead wood biomass in the Coastal Province are outside the historical range of variability, with more of the Province having low amounts and less of the Province having high amounts than were historically present, according to the results of simulation modeling of fire and live and dead wood biomass accumulation (Nonaka 2003). This means that current volumes of dead wood are probably much lower than the historical average. Current volumes in the Province may be anomalous based on the idiosyncrasies of history and the timing and magnitude of recent fires and other disturbances.

The consequence of potential shifting of the fire regime in future decades and centuries is also important to note. The pre-suppression fire return interval in the Coastal Province is on the order of 200-300 years (Agee 1993, Impara 1997). With fire suppression effectively removing the constraints of catastrophic fire on forest development, the maximum age of forest stands might be set by the limitations of stand development and of the lifespans of dominant conifer tree species, which in the *Tsuga heterophylla* forest vegetation zone in the Coastal Province range from 700-1000+ years (Fowells 1965, Burns and Honkala 1990). By the end of the simulated future 300-year period, the forests would not have reached these maxima, even on sites that regenerated naturally after the fires of 1850-1880. My results, which are based on a model of forest development that does not include fire, probably represent a landscape that is approaching the potential upper bounds of forest development and associated dead wood accumulation. This would be particularly relevant to those lands managed under the reserve (i.e., no action) approach, such as much of the Federal lands. Comparison of the projected potential maxima of dead wood amounts with the results of simulation modeling of the historical range of variability of live and dead wood accumulation in the Coast Range under a pre-European settlement fire regime (Nonaka 2003) indicates that the high amounts of wood produced in the present simulations are within the historical range of variability for dead wood accumulation, even with the inclusion of fire.

Future dead wood amounts are projected to increase steadily across the area, exceeding levels of present-day natural stands. Research indicates that the density of present-day naturally regenerated stands is higher than that of current old-growth stands in the Coastal Province of Oregon (Dowling 2004). With further development, these stands might be expected to produce larger amounts of dead wood than have been measured previously in older forest stands.

Comparison with other simulation results

The trends I report were similar to the results of a study in which the dynamics of logs were modeled in a simulated stand of even-aged Norway spruce (*Picea abies* (L.) Karst.) in Sweden (Ranius et al. 2003). There, the more biodiversity-oriented management approaches such as long rotation times and the retention of live trees resulted in the development of higher volumes of logs more continuously over the simulation period (one forest rotation). Ranius et al. (2003) also found that under the biodiversity-oriented Forest Certification Standard approach to management, the amount of large logs present in the stand would be almost three times higher than that found in present-day forests; this is similar to my findings for Coastal Province Forest Service and BLM lands (Figure 3).

Bragg (1997, 2000) simulated the effects of clearcutting, moderately intense fire, and spruce-beetle outbreak on dead wood delivery to a stream in Wyoming. Compared to the old-growth , after a small pulse in delivery, a clearcut (at simulation year 50) reduced delivery and the amount of logs in streams for about 200 years after harvest from control (old growth) conditions (Bragg 1997, Bragg 2000). In that study, a spruce-beetle outbreak caused a spike in recruitment that lasted for about 100 years. Fire caused two increases, one immediately after the fire and another a few decades later as fire-created snags fell, with delivery lasting also about 100 years (Bragg 2000). My simulations assumed multiple clearcutting events and so I would expect that declines in dead wood would be more extreme than those found in the Wyoming study, showing less legacy and less propensity for recovery, which is what I observed. Further, the Wyoming study consisted of a simulation of dead wood delivery to a stream, at a single site. Province-wide, clearcuts applied over time to forests adjacent to multiple streams might depress dead wood amounts in a manner more similar to those observed in this study.

Comparisons between simulation prediction and field data

My projection results were also qualitatively similar to those from studies of dead wood measured in managed forest stands. In northern hardwood forests, longer rotation stands contained higher mass of downed wood relative to those managed on shorter rotations (Gore and Patterson 1986). In boreal Fennoscandia, the highest volumes of dead wood were found in natural stands, intermediate in selectively logged stands, and lowest in intensively managed stands (Rouvinen et al. 2002). Intensively managed stands also lacked large snags. The duration of forest utilization also influenced dead wood volumes, as forests with shorter management histories contained more structural legacies from the pre-management, more natural conditions. Likewise, in managed forests in the UK, managed stands had volumes of a maximum of about one-third those of natural stands (Green and Peterken 1997). This difference is less than the difference I found emerging over time between private and federal dead wood amounts at the end of our simulations. This may be in part because of the potentially large size of dead wood in the Coastal Province.

Inferences from stand-level field studies of current stores dead wood may be constrained by the timing of sampling in relation to stand harvest and the subsequent degree of decay of residual material. Dead wood amounts in managed stands might be observed to be higher than old-growth amounts if the sampling is conducted shortly after logging. Alternatively, dead wood amounts might be observed to be lower than old-growth amounts, if logging residue has decayed and there is a deficit of newly generated dead wood (Harmon et al. 1986, Spies et al. 1988, Grove 2001). Some researchers have taken a chronosequence approach to address this issue, sampling stands of varying ages and comparing them (e.g. (Spies et al. 1988, Duvall and Grigal 1999, Idol et al. 2001)). Simulation modeling is an alternate approach which may corroborate these studies and yield additional insights. The results of this simulation modeling research indicate that the lack of production (or retention) of large boles in intensively managed forests leads eventually to a decline in the mean diameter of dead wood and lower dead wood amounts than those found in stands managed for older forest structure. This is consistent with the predictions of many researchers (Gore and Patterson 1986, Spies et al. 1988, Sturtevant et al. 1997, Duvall and Grigal 1999, Wilhere 2003).

Model performance and uncertainties

In general, the models performed as expected, resulting in stand development and mortality production (ZELIG) and dead wood decay (CWDM) at rates fairly consistent with the literature on which model development was based. The frequency distribution of the basal area of live trees at 300 years of this simulation had a maximum that was slightly higher than that found at present in the Coastal Province: the maximum for the 930 plots under simulated conditions at 300 years was 136.7 m^2 ha^{-1} (min. 55.9) whereas that of the initial (field-measured) conditions for the same plots was 121.3 m^2 ha^{-1} (min. 1.7). In part, the difference in frequency distributions of live trees differed because in the simulation at 300 years there were more older trees than there are in the Province at present (data not shown). It is also true that the omission of catastrophic disturbance events that have affected today's landscape creates a frequency distribution of basal areas at the upper end of what could occur. Thus the high amounts seen at the end of the simulation period may reflect a potential maximum for these forests.

The fact that the models were not run for extremely long time periods (i.e. 1000 years) is a potential limitation, since the simulated processes of stand development and dead wood accumulation and decay typically may occur in this region over long time periods of multiple centuries. In the CWDM simulations, large dead wood of the Douglas-fir species type continued to increase without leveling off or declining as might be expected. Model time frames may be too short for these sizes. However, the rates of decay and fragmentation of these large pieces are consistent with the values reported in the literature (Harmon et al. 1986), and smaller Douglas-fir pieces and western hemlock pieces of all size classes did reach steady state conditions, where inputs were equal to losses, during the 300-year simulation period (Appendix C). Some effects depicted in the results such as this one might be minimized if a longer simulation period had been used. However, some short-term effects depicted, such as increases of snag or log amounts during the first 50 years of the simulation period through snag and log creation, are important management effects. In general, evaluation of the results should emphasize toward the end of the simulation period to avoid potential transient effects of the models.

Another, alternative approach to modeling is to simulate the historical conditions and develop parameter values that would lead to present-day patterns in a given landscape or region. These parameter values are then used to simulate potential future conditions in the same area. This approach has the potential benefit of avoiding the errors of applying parameter values for processes such as decay or fragmentation that were developed in different landscapes that may have a very different historical context than the landscape being simulated. However, a potential pitfall of this approach is that there may be many combinations of parameter values that could be applied to a potential historical condition that could lead coincidentally to present-day observed patterns. It would be difficult to determine which combination of parameter values would be most appropriate to apply. Therefore this alternative approach was not taken in this study.

There is some uncertainty about the ZELIG model parameters related to mortality. In recent calibration and testing of ZELIG for the Coastal Province, overall mortality rates were found to be somewhat higher than those seen in independent data (Pabst et al. In preparation). However, it was not clear whether this was derived from how density independent (ambient) mortality or density dependent mortality was modelled, or from other model factors. In ZELIG, the probability of ambient mortality is a function of the maximum age attained by each species, and is applied equally in each timestep to all stems of a species regardless of growth rate or size. Some research indicates that ambient mortality functions such as the one used in ZELIG may be too simplistic in how they are applied, and should instead be a function of tree size and stand density (Sievanen et al. 2000, Monserud 2003). Ambient mortality rates used in this simulation were lower than combined ambient and density dependent mortality rates reported across some stands in the Coastal Province used for calibration and testing of ZELIG (Harcombe 1986, Greene et al. 1992). ZELIG also did not incorporate the effects of intermediate-sized disturbances such as windthrow, pests and pathogens, or landslides, which also influence mortality.

Other uncertainties in ZELIG model parameters have to do with regeneration rates and growth efficiencies. Regeneration rates in ZELIG are probably somewhat higher than those found in natural stands (Pabst et al. In preparation). Growth efficiencies for shade-tolerant conifers (Sitka spruce, western hemlock, western redcedar) were increased in this version of ZELIG but were still not rapid enough to account for the development of large trees observed in independent data (Pabst et al. In preparation). In terms of dead wood production, higher regeneration rates would increase the number of stems, but might also increase mortality through increased competition. Growth efficiencies could increase the size of boles, with consequent increases in log and snag volumes. However, increased growth efficiencies could also increase competition, resulting in higher mortality rates among smaller size classes, and fewer large stems.

Another uncertainty related to ZELIG is the effect of simulation time. This version of ZELIG was calibrated based on a simulation time of 100 years, but I used a 300-year simulation period. A chronosequence approach would probably be required to calibrate the model for 300 years, and there are limitations with the chronosequence approach such as potentially variable historical conditions and differences in site characteristics. It is uncertain what differences would be required in model parameters to reflect stands managed for a 300-year period, either under intensive management or under more natural conditions. Further, it is not certain what the long-term effects of management for multiple rotations might be; in our simulations, for example, some forest industry plots would be harvested up to seven times during the 300-year period. Merchantable yield decreased slowly under multiple 30-year rotations, and faster if old-growth dead wood was removed initially, in simulation modeling of a highly productive site in the Coastal Province (Harmon et al. 1986). Under natural conditions, without catastrophic disturbance, it remains unknown what the trends in productivity might be in the Coastal Province. It may be that more than one set of model parameters is necessary; one for those conditions similar to those observed at present-day in the Coastal Province, and another for new conditions such as multiple rotations under intensive management or multiple centuries of natural development without fire. Climate change was also not considered in the model, and it could have large effects on model parameters such as decay rates.

CWDM seemed to perform in a manner consistent with decay rates found in the literature. To evaluate this, I tested the revised version of CWDM by simulating the trajectories for individual pieces of dead wood and of dead wood on individual plots. I used data from an earlier dataset similar to the one used in this study. I found that logs and snags tended to decay at rates, and to transition between states (snag to log, snag to duff, log to duff), in a manner consistent with the literature (Graham 1981, Sollins 1982, Harmon et al. 1986). I also conducted a sensitivity analysis of the decay rate parameters and found that rate deviations of +/- 10% did not result in great differences in dead wood volume (Appendix C). A 10% increase in decay rates for medium and large Douglas-fir logs resulted in steady-state conditions during the simulation period (Figure Appendix C-2). Based on this and the validation of the model conducted by Mellen (Mellen and Ager 2002), I am fairly confident that CWDM was generally consistent with our current knowledge of dead wood decay and state transition dynamics.

Some of my estimates for dead wood amounts would have differed had I used different equations or different summarization methods. The use of the Smalian equation for log volume in both CWDM and ZELIG resulted in an overestimate of probably about 10% in log volume (Avery and Burkhart 1994). Snag volumes are probably more accurate than log volumes because they were calculated using the Kozak equation (Avery and Burkhart 1994), which is an equation better tailored to variation in size along the bole. Snag numbers I reported include only those snags greater than 5m in height and so total snag numbers would exceed the amounts reported here. An evaluation of initial conditions data indicates that snag numbers would probably have been about 29% higher for all size classes of snags, and about 33% higher for snags greater than 50cm dbh, had shorter snags been included.

A few other assumptions are worthy of note in relation to this simulation of dead wood dynamics. First, mortality rates in ZELIG were assumed to be consistent through the simulation period, and not accelerated by new disease vectors, high wind events, etc. Second, effects of topography, microclimate, etc. were not considered explicitly, but were only reflected in the data obtained by the studies on which model development was based. Thus individual sites on particular ownerships could vary from these results because of site-specific conditions that deviate from the mean. Third, the results of this study do not apply to wood in streams; studies and data on which the dead wood decay model was based were not in-stream studies and plot data was not obtained from aquatic locales. Fourth, translation of management intentions to model form was assumed to accurately represent projected actions.

Application of results

Because of the model components and uncertainties described above, dead wood amounts produced in simulation modeling research should best be considered as relative and potential amounts and not as absolutes. The results of this research are probably best suited for comparison among management scenarios, instead of for the projection of actual amounts of dead wood into the future. My results for log volume under the natural development scenario at the end of the 300-year simulation period were about three times the amount found in old-growth stands in the Oregon Cascades (1123 vs. 346 m^3 ha^{-1}) where production rates are lower but decay rates may be lower as well, and about 5 times the amount found in old-growth stands in the Oregon Coastal Province(28 m^3 ha^{-1}) (Spies et al. 1988). The mean volume of snags was about two-and-one-half times and four-and-one-half times the amount, respectively (629 m^3 ha^{-1} in this study, vs. 248 m^3 ha^{-1} in the Cascades, vs. 148 m^3 ha^{-1} in the Coastal Province). For snags greater than 50 cm dbh and greater than 5m tall, the amount found in the present study was about twice that of the Cascades and almost three times that of the Coastal Province old-growth stands (27 vs. 14 vs. 10 snags ha^{-1}, respectively). Field data include processes that were not included in the simulation. Thus, it may be most appropriate to evaluate the results of this simulation exercise by comparing amounts among scenarios used in this research rather than against field data. The amounts in the present study might be higher because I simulated multiple centuries of natural development without fire. Fire could reduce dead wood amounts in two ways: by creating more of a mix of age classes, and by consuming dead wood.

This research also presumes management and other effects on vegetation dynamics will remain unchanged over the next three centuries. Therefore, this simulation modeling exercise provides a baseline for estimation of management effects on dead wood. Management practices and land use patterns could change with changes in laws and regulations or changes in timber markets. Climate change, and the potential for other factors modifying forest structure and composition such as introduced pathogens or invasive species, are not also taken into account. Climate change can affect forests by altering the timing, frequency, and intensity of disturbances such as fire, introduced species, and windstorms (Dale et al. 2001). If these conditions change, results may very as managers might be expected to adjust their treatments and planting accordingly. Further research would be required to incorporate modifications to management over time, changes in climate, alterations in species composition or growth rates, or shifts in disturbance regimes.

Conclusion

The results of this study provide an estimate of the maximum potential amounts of dead wood in Coastal Province forests under current policies and forest management. Increases in dead wood were great under recently established policies on federal and state lands. Total dead wood amounts were fairly level over time on forest industry lands under the Oregon Forest Practices Act with the additional retention of all snags at harvest, but large sizes of dead wood declined. Ownerships diverged greatly over time in amount and type (size, snag vs. log) of dead wood. Legacy dead wood remained present for centuries under the simulations, buffering adverse management effects on large dead wood amounts. Simulation of natural conditions and intensive management with no green tree retention or snag or log creation provided estimates of the potential upper and lower bounds of dead wood amounts in these forests.

This research highlights the importance of long-term simulations of forest dynamics as a tool to increase our understanding of management effects on important forest attributes such as dead wood. Contrasting management approaches can result in very large differences in dead wood amounts and types. There is a lag effect to dead wood management: management effects on dead wood amounts and types may not appear for time periods as long as 100-200 years because of the potential persistence of large legacy dead wood. Variation across landscapes in starting conditions means that contrasting management approaches, such as those of the State of Oregon, may have differential effects on long-term dead wood dynamics depending on where they are applied. Therefore, it is crucial to take a long-term view and understand the starting conditions when managing for dead wood. Simulation modeling results indicate that future forest conditions, such as very large increases on Federal lands, may diverge greatly from those of the recent past, which resulted from recent fire and other disturbances. However, present day amounts may be outside (lower than) the historical range of variability of dead wood. Policies such as the Northwest Forest Plan which are designed to promote the maintenance or increase of dead wood amounts may have a strong positive influence on dead wood abundance in parts of a region that are also under intensive management, and may bring the region closer to the historical range of variability in dead wood amounts.

Chapter 5: Conclusions

In this research, I evaluated the relationship of dead wood abundance to biophysical characteristics and forest management in the Coastal Province of Oregon. I collected and analyzed field data from two landscapes with different forest histories to evaluate relationships of dead wood abundance with history and biophysical characteristics. I focused a portion of the research on dead wood relationships with topography. I analyzed a regional dataset to explore relationships of dead wood with biophysical characteristics and ownership at multiple levels of spatial resolution from plots to subbasins, and region-wide. I used simulation modeling of forest growth and dead wood decay dynamics to project potential future dynamics of dead wood abundance under current forest policies and management across the region and according to ownership. The major conclusions of this research are the following:

- The total volume of dead wood in two landscapes with different disturbance histories was the same, but the allocation among types (sizes, origin) of dead wood differed. Overall similarity of dead wood volume was probably the result of post-fire salvage in one landscape. However, in that landscape, high amounts of legacy wood remained even after salvage, probably because the pre-fire forests were primarily old-growth and contained many very large trees.

- Topography is strongly related to landscape-level dead wood patterns, and streams contain disproportionately high amounts of dead wood in relation to their area in the landscape. Upper and mid-slope positions are source areas for dead wood, and stream areas are sinks.
- At the landscape level, legacy wood can persist for more than two centuries, both resulting from the slow decay of large pieces, and through the averaging of stand-level variability in the timing and amount of dead wood production following large disturbance events.
- Climate-related patterns and processes may be of increasing relevance to dead wood patterns in landscapes as time since catastrophic disturbance increases.
- Current vegetation, historical vegetation, and ownership were important at multiple levels of resolution to multivariate dead wood patterns across the Province. This is probably because these three features are the strongest descriptors of forest development and disturbance in the Coastal Province.
- Live vegetation was the most highly related factor to total explained variation in dead wood gradients at all scales of resolution across the Coastal Province. Live vegetation was also very important to describing the variation in snag abundance, and the variation in log abundance, in the Province.
- Historical vegetation and ownership were also very important to explaining variation in multivariate dead wood patterns. Spatial patterns of ownership

in the Province reflect both historical vegetation and current vegetation, since land ownership in many cases followed historical natural disturbance patterns, and forest management has impacted current vegetation patterns.

- Topography and climate were highly related factors to multivariate patterns of dead wood at some scales of resolution in the Province. Topography was associated with intermediate and fine scales, and climate with intermediate scales. This is consistent with the finding that topography and climate were important in the two sampled landscapes.
- Simulation modeling indicates that amounts of dead wood are likely to increase greatly Province-wide under current forest policies and management, with the assumption of no fire or other large- to mid-scale disturbances or climate change.
- Simulation modeling indicates that forest management, which currently differs by land ownership, is likely to result in very large differences in dead wood amounts and types on lands of different ownerships across the Province. This is consistent with the evaluation of current dead wood patterns differing according to ownership found in the analysis of current regional data.
- Understanding the starting conditions is important when managing for dead wood. Management approaches, such as those of the State of Oregon, may have differential effects on long-term dead wood dynamics depending on

where they are applied, since current dead wood patterns of abundance and live vegetation characteristics vary across the Province.

- Simulation modeling indicates that even with the same starting conditions, differences in forest management can result in very divergent patterns of abundance of dead wood over time, with great increases on some ownerships. In these simulations, even with the same starting conditions, the Forest Service ended the 300-year period with about six times as much dead wood volume as forest industry (1610 vs. 262 m^3 ha^{-1}).
- Under the natural conditions simulation, the maximum potential amount of dead wood volume for the Coastal Province was approximately 1750 m^3 ha^{-1}. This potential maximum could be altered by factors not considered in the simulation models such as disturbances like fire, windthrow, pests and pathogens, and shifts in climate or tree species distributions.
- Simulation modeling illustrates that there is a lag effect to dead wood management: management effects on dead wood amounts and types may not appear for time periods as long as 100-200 years because of the potential persistence of large legacy dead wood. Therefore, taking a long-term view when managing for dead wood is essential.
- The Oregon Forest Practices Act (OFPA) may serve to maintain current total dead wood amounts on industrial lands once legacy wood present there is lost through decay, if snags are not felled at harvest or during thinning operations. Simulation modeling indicated that without OFPA

rules, under industrial management total volumes of large snags and logs declined to zero after legacy wood was lost. With the OFPA, the present-day average amount of total dead wood volume on forest industry lands was maintained through the simulation period. It is not clear whether the lack of snag felling at harvest would have any effect on total dead wood; felling might decrease dead wood decay rates for affected pieces.

- Understanding the historical context of ecological systems in which current policies are applied is important. Simulation modeling results indicate that future forest conditions, such as very large increases of dead wood volume on Federal lands, may diverge greatly from those of the recent past, which resulted from recent fire and other disturbances. However, present day amounts may be outside (lower than) the historical range of variability of dead wood. Policies such as the Northwest Forest Plan which are designed to promote the maintenance or increase of dead wood amounts may have a strong positive influence on dead wood abundance in parts of a region that are also under intensive management, and may bring the region closer to the historical range of variability in dead wood amounts.

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APPENDICES

Appendix A. Regression models of dead wood variables on biophysical and ownership variables in the Coastal Province of Oregon

Table A-1. Regression models of dead wood variables on biophysical and ownership variables in the Coastal Province of Oregon. Explanatory variables were selected using the stepwise regression procedure with $p<0.05$ required to enter and $p<0.05$ required to stay.

Dead Wood Variable	Variable Name	Partial R^2	Regression equation	Model R^2	Model p
Total Dead Wood					
Dead wood volume (ln)	SMRTP	0.18	8.68 - 1.76 (SMRTP) + 0.002 (LBIOMASS) - 1.02 (NONFOR) + 0.45 (CONOG) - 0.90 (DEPO) + 0.30 (RIVBUF100)	0.37	<0.0001
	LBIOMASS	0.09			
	NONFOR	0.06			
	CONOG	0.02			
	DEPO	0.02			
	RIVBUF100	0.01			
Dead wood >50 cm led or dbh (ln)	SMRTP	0.15	9.74 - 2.41 (SMRTP) + 0.006 (LBIOMASS) - 1.27 (NONFOR) + 0.80 (CONOG) - 2.60 (SUBALP) - 0.03 (BAAALL)	0.32	<0.0001
	LBIOMASS	0.09			
	NONFOR	0.04			
	CONOG	0.02			
	SUBALP	0.02			
	BAAALL	0.02			
Logs					
Volume of logs (m^3) (ln)	SMRTP	0.16	8.48 - 1.72 (SMRTP) - 1.04 (NONFOR) + 0.001 (LBIOMASS) + 0.55 (CONOG) - 0.92 (DEPO) + 0.32 (RIVBUF100)	0.30	<0.0001
	NONFOR	0.07			
	LBIOMASS	0.03			
	CONOG	0.02			
	DEPO	0.02			
	RIVBUF100	0.01			
Volume of logs >25 cm led (m^3) (ln)	SMRTP	0.14	8.67 - 1.92 (SMRTP) - 1.17 (NONFOR) + 0.002 (LBIOMASS) + 0.65 (CONOG) + 0.37 (RIVBUF100)	0.26	<0.0001
	NONFOR	0.05			
	LBIOMASS	0.03			
	CONOG	0.02			
	RIVBUF100	0.01			
Volume of logs >50 cm led (m^3) (ln)	SMRTP	0.10	8.60 - 2.23 (SMRTP) + 0.98 (CONOG) - 1.21 (NONFOR) + 0.002 (LBIOMASS) -2.38 (SUBALP) + 0.46 (RIVBUF100)	0.23	0.0004
	CONOG	0.04			
	NONFOR	0.02			
	LBIOMASS	0.02			
	SUBALP	0.01			
	RIVBUF100	0.01			
Volume of logs 12.5-25 cm led (m3) (ln)	DIST	0.06	4.95 - 0.008 (DIST) - 0.65 (SMRTP) + 0.33 (FI) + 0.03 (BAA3) - 0.0006 (PRR) - 0.08 (DDI)	0.15	0.0003
	SMRTP	0.03			
	FI	0.02			
	BAA3	0.01			
	PRR	0.02			
	DDI	0.01			
Volume of logs 25-50 cm led (m3) (ln)	SMRTP	0.08	5.57 - 1.11 (SMRTP) - 0.77 (NONFOR) + 0.001 (LBIOMASS) + 0.40 (FI)	0.14	<0.0001
	NONFOR	0.03			
	LBIOMASS	0.02			
	FI	0.02			

Table A-1, contd. Regression models of dead wood variables on biophysical and ownership variables in the Coastal Province of Oregon. Explanatory variables were selected using the stepwise regression procedure with $p<0.05$ required to enter and $p<0.05$ required to stay.

Dead Wood Variable	Variable Name	Partial R^2	Regression equation	Model R^2	Model p
Volume of logs 50-75 cm led (m3) (ln)	SMRTP	0.08	6.31 - 1.58 (SMRTP) + 0.90 (CONOG) - 1.13 (NONFOR) + 0.001 (LBIOMASS) - 0.80 (BLM) - 1.10 (ECOLEV4_11)	0.18	0.0007
	CONOG	0.04			
	NONFOR	0.02			
	LBIOMASS	0.02			
	BLM	0.02			
	ECOLEV4_11	0.01			
Volume of logs 75-100 cm led (m3) (ln)	SMRTP	0.06	6.33 - 1.97 (SMRTP) + 0.87 (CONOG) + 0.79 (STATE) + 0.44 (RIVBUF100)	0.11	0.0013
	CONOG	0.03			
	STATE	0.01			
	RIVBUF100	0.01			
Volume of logs >100 cm led (m3) (ln)	STATE	0.04	3.57 + 1.54 (STATE) + 0.79 (FI) + 0.25 (BAC5 (ln)) + 0.56 (RIVBUF100) - 0.001 (ANNGDDD)	0.11	<0.0001
	FI	0.09			
	BAC5 (ln)	0.02			
	RIVBUF100	0.02			
	ANNGDDD	0.01			
Log biomass (kg) (ln)	NONFOR	0.16	14.69 - 1.61 (NONFOR) - 1.97 (SMRTP) - 1.69 (DEPO) + 0.73 (CONOG) + 0.002 (LBIOMASS) - 2.51 (ECOLEV4_33) - 2.53 (SUBALP)	0.31	<0.0001
	SMRTP	0.05			
	DEPO	0.03			
	CONOG	0.02			
	LBIOMASS	0.02			
	ECOLEV4_33	0.02			
	SUBALP	0.01			
Log carbon (kg C) (ln)	NONFOR	0.17	13.95 - 1.54 (NONFOR) - 1.93 (SMRTP) - 1.59 (DEPO) + 0.73 (CONOG) + 0.001 (LBIOMASS) - 2.34 (ECOLEV4_33) - 2.38 (SUBALP)	0.31	<0.0001
	SMRTP	0.06			
	DEPO	0.03			
	CONOG	0.02			
	LBIOMASS	0.02			
	ECOLEV4_33	0.02			
	SUBALP	0.01			
Volume of legacy logs (m^3) (ln)	QMDADOM1	0.16	8.725 - 0.016 (QMDADOM1) - 0.002 (ANNGDDD) + 0.99 (CONOG) - 0.25 (DDI) + 1.13 (STATENEW) + 0.23 (REMPCTL(ln))	0.30	<0.0001
	ANNGDDD	0.07			
	CONOG	0.02			
	DDI	0.02			
	STATE	0.02			
	REMPCTL (ln)	0.02			
Percent of all logs that are legacy logs (ln)	QMDADOM1	0.18	7.89 - 0.01 (QMDADOM1) - 2.02 (SMRTP) - 0.71 (USFS) - 0.23 (DDI) + 0.68 (CONOG) + 0.18 (REMPCTL (ln))	0.31	<0.0001
	SMRTP	0.05			
	USFS	0.03			
	DDI	0.02			
	CONOG	0.02			
	REMPCTL (ln)	0.01			

Table A-1, contd. Regression models of dead wood variables on biophysical and ownership variables in the Coastal Province of Oregon. Explanatory variables were selected using the stepwise regression procedure with $p<0.05$ required to enter and $p<0.05$ required to stay.

Dead Wood Variable	Variable Name	Partial R^2	Regression equation	Model R^2	Model p
<u>Snags</u>					
Number of snags (ln)	LBIOMASS	0.32	0.58+ 0.003 (LBIOMASS) + 1.01 (PUBLIC) + 0.03 (BAA2) + 0.04 (BAA3)	0.43	<0.0001
	PUBLIC	0.05			
	BAA2	0.05			
	BAA3	0.02			
Number of snags >50 cm dbh (ln)	LBIOMASS	0.32	2.67 + 0.006 (LBIOMASS) + 0.37 (USFS) + 0.34 (VEG1900_9) - 0.84 (SMRTPD) - 0.02 (BAAALL)	0.47	<0.0001
	USFS	0.07			
	VEG1900_9	0.03			
	SMRTP	0.02			
	BAAALL	0.02			
Number of snags >50 cm dbh and >15m tall (ln)	QMDADOM1	0.30	-0.22 + 0.006 (QMDADOM1) + 0.02 (BAA4) + 0.01 (BAA5) + 0.004 (SLPPCT)	0.38	<0.0001
	BAA4	0.04			
	BAA5	0.02			
	SLPPCT	0.01			
Volume of snags (m^3) (ln)	LBIOMASS	0.40	-5.13 + 0.005 (LBIOMASS) + 0.64 (PUBLIC) + 0.42 (VEG1900_9) - 0.04 (BAA1) + 1.06 (SMRPRED) + 0.22 (BAH2 (ln))	0.52	<0.0001
	PUBLIC	0.05			
	VEG1900_9	0.02			
	BAA1	0.01			
	SMRPRED	0.01			
	BAH2 (ln)	0.01			
Volume of snags >50 cm dbh (m^3) (ln)	BAC5(ln)	0.36	4.27 + 0.69 (BAC5(ln)) -1.37 (SMRTP) + 0.04 (BAA3) + 0.61 (USFS)	0.46	<0.0001
	SMRTP	0.05			
	BAA3	0.04			
	USFS	0.02			
Volume of snags 12.5-25 cm dbh (m3) (ln)	BAA2	0.17	-0.09 + 0.03 (BAA2) + 0.03 (BAA3) + 0.26 (PUBLIC)	0.25	<0.0001
	BAA3	0.06			
	PUBLIC	0.02			
Volume of snags 25-50 cm dbh (m3) (ln)	LBIOMASS	0.32	0.24 + 0.002 (LBIOMASS) + 0.51 (USFS) + 0.03 (BAA3) - 0.02 (BAA1)	0.41	<0.0001
	USFS	0.04			
	BAA3	0.04			
	BAA1	0.01			
Volume of snags 50-75 cm dbh (m3) (ln)	LBIOMASS	0.30	-0.03 + 0.001 (LBIOMASS) + 0.59 (USFS) + 0.03 (BAA4) + 0.001 (DEM) - 0.14 (BAC1 (ln))	0.40	<0.0001
	USFS	0.06			
	BAA4	0.02			
	DEM	0.02			
	BAC1 (ln)	0.01			
Volume of snags 75-100 cm dbh (m3) (ln)	BAA4	0.24	- 2.01 + 0.05 (BAA4) -0.24 (BAC5 (ln)) -0.65 (SMRTP) + 0.34 (USFS)	0.30	0.0002
	BAC5 (ln)	0.04			
	SMRTP	0.02			
	USFS	0.01			
Volume of snags >100 cm dbh (m3) (ln)	BAC5 (ln)	0.28	-8.12 + 0.31 (BAC5 (ln)) + 1.53 (SMRPRED) +0.006 (LBIOMASS) -0.02 (BAAALL) + 0.42 (VEG1900_9)	0.38	<0.0001
	SMRPRED	0.05			
	LBIOMASS	0.02			
	BAAALL	0.01			
	VEG1900_9	0.01			

Table A-1, contd. Regression models of dead wood variables on biophysical and ownership variables in the Coastal Province of Oregon. Explanatory variables were selected using the stepwise regression procedure with $p<0.05$ required to enter and $p<0.05$ required to stay.

Dead Wood Variable	Variable Name	Partial R^2	Regression equation	Model R^2	Model p
Snag biomass (kg) (ln)	LBIOMASS	0.29	2.93 + 0.009 (LBIOMASS) + 2.60 (PUBLIC) + 0.52 (BAH2(ln)) - 1.54 (VEG1900_1)	0.41	<0.0001
	PUBLIC	0.10			
	BAH2 (ln)	0.02			
	VEG1900_1	0.01			
Snag carbon (kg C) (ln)	LBIOMASS	0.30	2.66 + 0.009 (LBIOMASS) + 2.40 (PUBLIC) + 0.48 (BAH2(ln)) - 1.43 (VEG1900_1)	0.42	<0.0001
	PUBLIC	0.09			
	BAH2 (ln)	0.02			
	VEG1900_1	0.01			
Number of legacy snags (ln)	QMDADOM1	0.06	2.12 - 0.009 (QMDADOM1) - 0.61 (SMRTP) + 0.14 (REMPCTL (ln)) + 0.22 (PUBLIC)	0.17	<0.0001
	SMRTP	0.05			
	REMPCTL (ln)	0.05			
	PUBLIC	0.02			
Volume of legacy snags (m^3) (ln)	REMPCTL (ln)	0.07	3.16 + 0.27 (REMPCTL (ln)) - 0.91 (SMRTP) - 0.01 (QMDADOM1) + 0.38 (ECOLEV4_14)	0.17	0.0003
	SMRTP	0.05			
	QMDADOM1	0.04			
	ECOLEV4_14	0.01			
Percent of all snags that are legacy snags (ln)	QMDADOM1	0.07	- 10.40 - 0.02 (QMDADOM1) + 2.53 (SMRPRED) + 0.29 (REMPCTL (ln)) -0.38 (CONTPRED)	0.17	<0.0001
	SMRPRED	0.04			
	REMPCTL (ln)	0.04			
	CONTPRED	0.02			

Appendix B. Weighted mean amount of dead wood characteristics per hectare, by ownership class, in the Coastal Province of Oregon

Table B-1. Weighted mean amount of dead wood characteristics per hectare, y ownership class, in the Coastal Province of Oregon.

	USFS (n=309)		BLM (n=118)		State (n=84)		Forest Industry (n=274)		Non-Industrial Private	
Variable	Mean	*s.e.*	Mean	*s.e.*	Mean	*s.e.*	Mean	*s.e.*	Mean	*s.e.*
Total Dead Wood										
Total dead wood volume >12.5 cm dbh or led*	259.8	*12.5*	232.1	*25.2*	265.0	*20.1*	170.1	*9.2*	78.9	*8.0*
Total dead wood volume >50.0 cm dbh or led*	191.7	*11.4*	176.1	*23.9*	204.9	*18.8*	113.4	*8.1*	47.2	*6.8*
Logs										
Volume of logs >12.5 cm led (m^3)	192.0	*10.2*	194.2	*22.2*	235.3	*19.0*	156.3	*8.5*	67.5	*7.1*
Volume of logs >25 cm led (m^3)	180.6	*10.2*	184.1	*21.9*	225.5	*18.9*	142.7	*8.4*	59.3	*6.8*
Volume of logs >50 cm led (m^3)	135.8	*9.4*	144.1	*20.9*	185.3	*17.6*	104.8	*7.5*	40.5	*5.9*
Volume of logs 12.5-25.0 cm led (m3)	11.5	*0.7*	10.1	*1.4*	9.8	*1.0*	13.6	*0.7*	8.2	*0.7*
Volume of logs 25.0-50.0 cm led (m3)	44.7	*2.3*	39.9	*3.7*	40.2	*3.1*	37.9	*1.8*	18.7	*1.8*
Volume of logs 50.0-75.0 cm led (m3)	51.7	*3.8*	36.1	*4.7*	65.8	*6.9*	41.7	*3.0*	16.9	*2.3*
Volume of logs 75.0-100.0 cm led (m3)	48.8	*5.0*	49.0	*8.8*	53.7	*7.3*	29.0	*2.8*	8.8	*1.9*
Volume of logs >100.0 cm led (m3)	35.3	*5.4*	59.0	*14.7*	65.8	*9.5*	34.1	*4.4*	14.9	*4.1*
Log biomass (Mg)	45.7	*2.6*	49.0	*5.5*	71.3	*6.0*	45.4	*2.5*	19.1	*1.9*
Log carbon (Mg C)	23.7	*1.4*	25.5	*2.8*	37.1	*3.1*	23.6	*1.3*	9.9	*1.0*
Volume of legacy logs >12.5cm led (m^3)	23.8	*3.8*	65.5	*11.8*	101.0	*12.4*	61.9	*5.9*	23.2	*4.8*
Percent of all >12.5 cm led logs that are legacy logs	9.5	*1.3*	18.9	*2.8*	33.1	*3.2*	27.2	*1.8*	14.7	*2.2*
Snags										
Number of snags >12.5 cm dbh	47.9	*3.0*	32.9	*3.8*	55.8	*9.2*	30.6	*4.1*	19.4	*3.7*
Number of snags >50 cm dbh	13.6	*0.9*	5.8	*0.8*	5.2	*0.8*	2.6	*0.3*	1.7	*0.3*
Number of snags >50 cm dbh and >15m in height	1.7	*0.2*	1.4	*0.3*	0.5	*0.2*	0.2	*0.1*	0.2	*0.1*
Volume of snags >12.5 cm dbh (m^3)	67.7	*4.2*	37.9	*7.1*	29.7	*4.4*	13.8	*1.8*	11.4	*2.8*
Volume of snags >50 cm dbh (m^3)	55.8	*3.7*	32.0	*7.0*	19.7	*4.0*	8.6	*1.6*	6.6	*2.6*
Volume of snags 12.5-25.0 cm dbh (m3)	2.2	*0.3*	2.7	*0.5*	4.9	*1.1*	2.6	*0.4*	1.5	*0.5*

Table B-1, contd. Weighted mean amount of dead wood characteristics per hectare, by ownership class, in the Coastal Province of Oregon.

	USFS (n=309)		BLM (n=118)		State (n=84)		Forest Industry (n=274)		Non-Industrial Private	
Variable	Mean	*s.e.*	Mean	*s.e.*	Mean	*s.e.*	Mean	*s.e.*	Mean	*s.e.*
Volume of snags 25.0-50.0 cm dbh (m3)	9.7	*0.8*	3.2	*0.5*	5.2	*1.2*	2.6	*0.4*	3.3	*0.9*
Volume of snags 50.0-75.0 cm dbh (m3)	8.7	*0.8*	4.9	*0.9*	2.6	*0.6*	1.5	*0.3*	0.6	*0.2*
Volume of snags 75.0-100.0 cm dbh (m3)	13.1	*1.2*	6.0	*1.2*	3.3	*0.9*	1.8	*0.3*	2.4	*0.9*
Volume of snags >100.0 cm dbh (m3)	34.1	*2.7*	21.1	*6.3*	13.7	*3.2*	5.4	*1.2*	3.7	*1.8*
Snag biomass (Mg)	17.7	*1.1*	11.6	*2.2*	8.4	*1.2*	3.9	*0.5*	3.4	*0.9*
Snag carbon (Mg C)	9.2	*0.6*	6.1	*1.2*	4.4	*0.6*	2.0	*0.3*	1.7	*0.5*
Number of legacy snags	1.7	*0.3*	1.7	*0.4*	2.4	*0.5*	1.2	*0.2*	0.7	*0.2*
Volume of legacy snags >12.5 cm dbh (m^3)	6.8	*1.3*	9.0	*3.0*	14.6	*3.5*	5.5	*1.1*	4.0	*2.3*
Percent of all >12.5 cm dbh snags that are legacy snags	22.4	*4.0*	17.4	*3.0*	28.5	*4.3*	19.9	*2.2*	15.1	*2.9*

Appendix C. CWDM Parameter Values and Sensitivity Analysis

This appendix contains parameter values and rates used in the Coarse Wood Dynamics Model (CWDM), graphs of volumes of individual logs and snags decayed in CWDM, and sensitivity analysis of decay parameters for snags and logs. For more information on CWDM and these parameters, see Mellen and Ager (2002).

Table C-1. Decay rates and other coefficients used in CWDM (adapted from Mellen and Ager 2002). Snag decay lagtimes and lagtime decay constants apply to newly created snags only. Log fragmentation, diameter reduction, and length reduction rates apply to class 4 and 5 logs only. Asterisks indicate rates that were set for the present study.

Snags

Species	Dbh class (cm)	Decay rate	Decay lagtime (years)	Lagtime decay constant	Decay to duff density (g cm^{-3})
Douglas-fir	<38.1	0.053	10	0.25	0.021
	38.1-63.5	0.033	15	0.14	0.013
	≥63.5	0.017	20	0.06	0.007
Western hemlock	<38.1	0.100	5	0.30	0.021
	38.1-63.5	0.088	10	0.25	0.013
	≥63.5	0.060	15	0.15	0.007

Logs

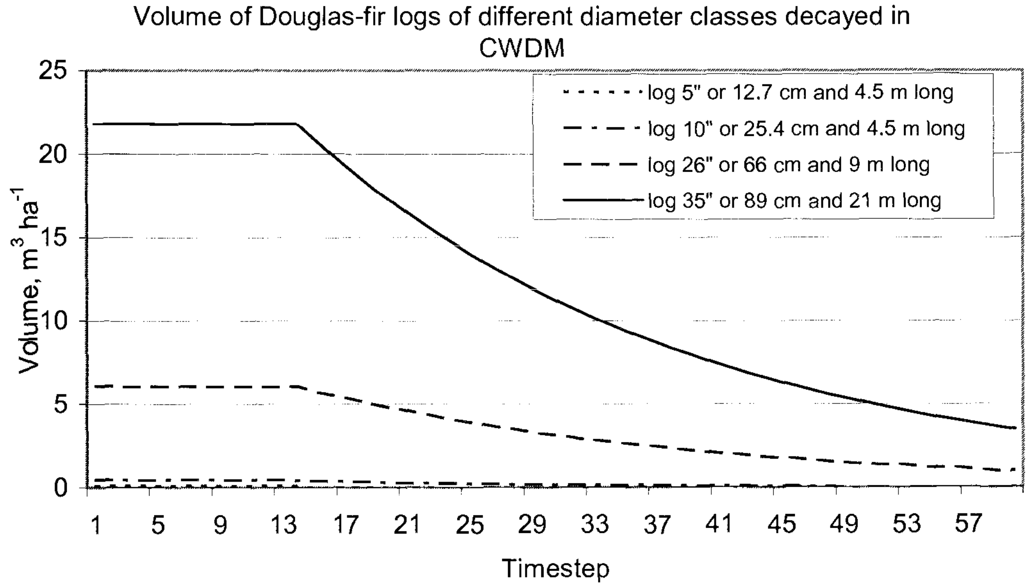
Species	Led class (cm)	Decay rate	Fragmentation rate	Diameter reduction rate	Length reduction rate	Decay to duff density (g cm^{-3})	Fragmentation density (g cm^{-3})
Douglas-fir	<15.2	0.026	-	-	-	0.073	-
	15.2-38.1	0.015	0.010	0.0037	0.0030	0.073	0.197
	≥38.1	0.012	0.008	0.0031	0.0026	0.073	0.197
Western hemlock	<15.2	0.030	-	-	-	0.125	-
	15.2-38.1	0.023	0.0153*	0.0049	0.0040*	0.125	0.180*
	≥38.1	0.019	0.0126*	0.0041	0.0034*	0.125	0.180*

Table C-2 . Snag fall rates and height loss proportions used in the Coarse Wood Dynamics Model (from Mellen and Ager 2002). Fall lagtimes were applied to newly created snags only. Decay classes reflect groups of the 5-stage system developed by Cline and others (1980). Hard = 1 and 2; Intermediate = 3; Soft = 4 and 5.

Species	Diameter class (cm)	Decay class	Fall rate	Height loss proportion	Fall lagtime (years)
Douglas-fir	<38.1	Hard	0.021	0.042	0
		Intermediate	0.043	0.056	
		Soft	0.054	0.063	
	38.1-63.5	Hard	0.013	0.033	10
		Intermediate	0.022	0.038	
		Soft	0.027	0.041	
	≥63.5	Hard	0.008	0.019	15
		Intermediate	0.008	0.019	
		Soft	0.008	0.019	
Western hemlock	<38.1	Hard	0.010	0.024	0
		Intermediate	0.017	0.029	
		Soft	0.021	0.031	
	38.1-63.5	Hard	0.020	0.035	0
		Intermediate	0.030	0.044	
		Soft	0.035	0.048	
	≥63.5	Hard	0.010	0.024	5
		Intermediate	0.017	0.029	
		Soft	0.021	0.031	

Table C-3. Proportion of new snags felled immediately in the Coarse Wood Dynamics Model (established for this study).

Species	Diameter class (cm)	Immediate fall proportion
Douglas-fir	<25	0.03
	≥25	0.04
Western hemlock	<25	0.04
	≥25	0.05



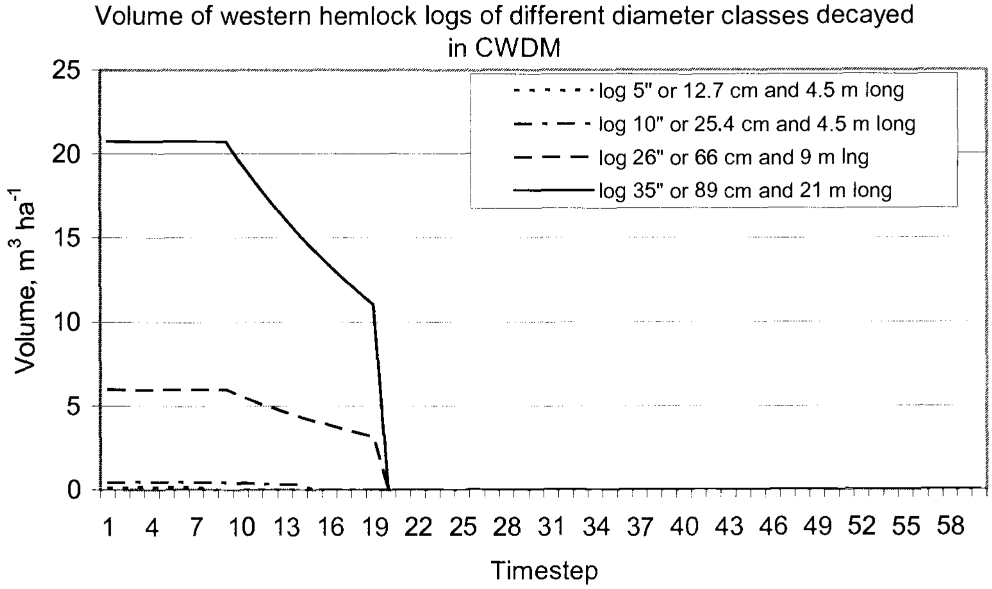


Figure C-1. Volume of individual Douglas-fir and western hemlock logs of different diameter classes decayed in CWDM over 60 timesteps (i.e., a 300 year simulation period).

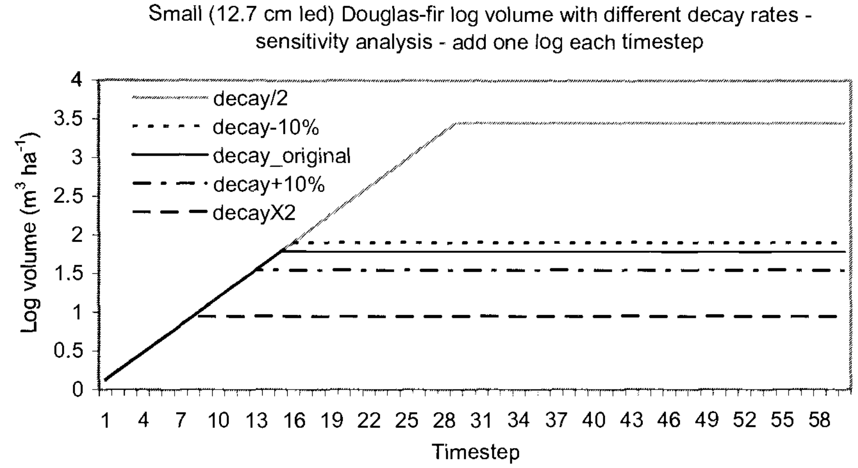
Sensitivity Analysis

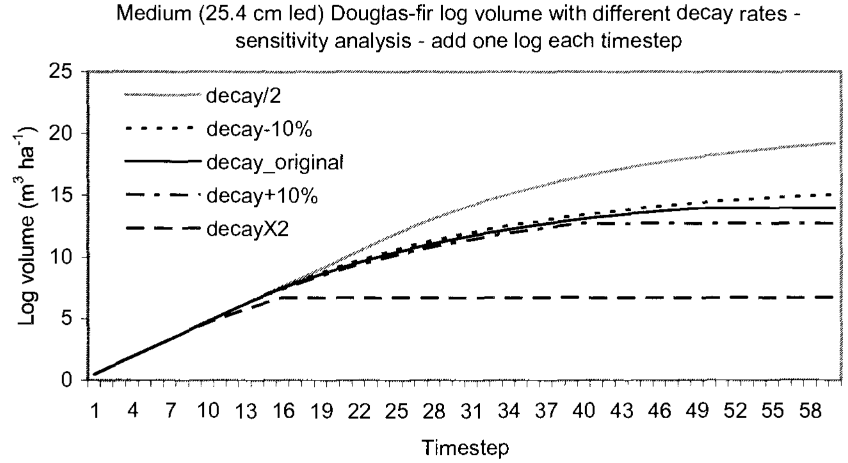
I also conducted an analysis of the sensitivity of volumes of dead wood produced with decay rates used in CWDM to changes of decay rate parameter values. To perform the sensitivity analysis, I evaluated volume of logs or snags over time given starting conditions of one piece of a given size class and species type, with one piece of the same type added at each timestep. I ran the sensitivity analysis for 60 timesteps (i.e., 300 years). I tested the original decay rate against an increase of 10% and a decrease of 10% in the decay rate. I also tested the effect of doubling and halving the decay rate for each size-species combination. Original and altered tested parameter values are shown in Table C-4. Results of the sensitivity analysis are shown in Figures C-2 through C-5. The sensitivity analysis indicated that given steady inputs, most types of dead wood reached steady state (line is flat, with inputs equaling outputs) by early to midway through the simulation period. A 10% increase in decay rates for medium and large Douglas-fir logs resulted in steady-state conditions during the simulation period (Figure C-2).

Table C-4. Decay rates used for logs and snags in sensitivity analysis of decay rates in CWDM, by species type and size class.

Logs			Sensitivity Analysis Decay Rates			
Species	Led class (cm)	original decay rate (kl)	original -10%	original +10%	50% of original	200% of original
Douglas-fir	<15.2	0.026	0.0234	0.0286	0.013	0.052
	15.2-38.1	0.015	0.0135	0.0165	0.0075	0.030
	=38.1	0.012	0.0108	0.0132	0.006	0.024
Western hemlock	<15.2	0.030	0.027	0.033	0.015	0.060
	15.2-38.1	0.023	0.0207	0.0253	0.0115	0.046
	=38.1	0.019	0.0171	0.0209	0.0095	0.038

Snags			Sensitivity Analysis Decay Rates			
Species	Dbh class (cm)	original decay rate (k)	original -10%	original +10%	50% of original	200% of original
Douglas-fir	<38.1	0.053	0.0477	0.0583	0.0265	0.106
	38.1-63.5	0.033	0.0297	0.0363	0.0165	0.066
	=63.5	0.017	0.0153	0.0187	0.0085	0.034
Western hemlock	<38.1	0.100	0.090	0.110	0.050	0.200
	38.1-63.5	0.088	0.0792	0.0968	0.044	0.176
	=63.5	0.060	0.054	0.066	0.030	0.120





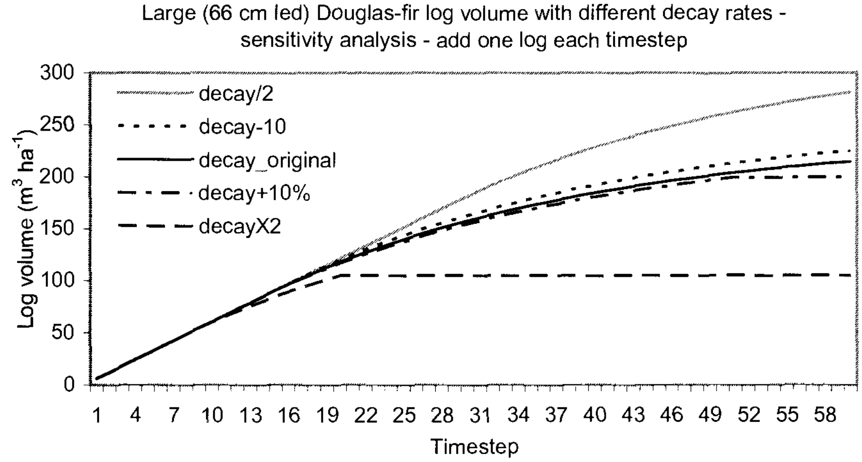
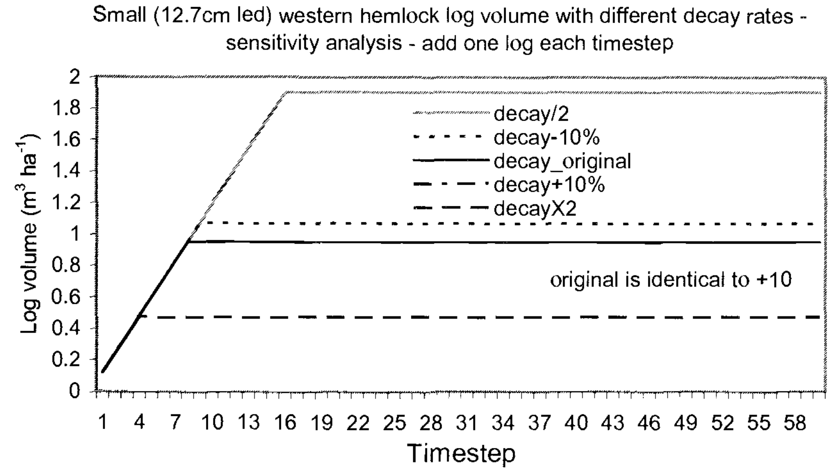
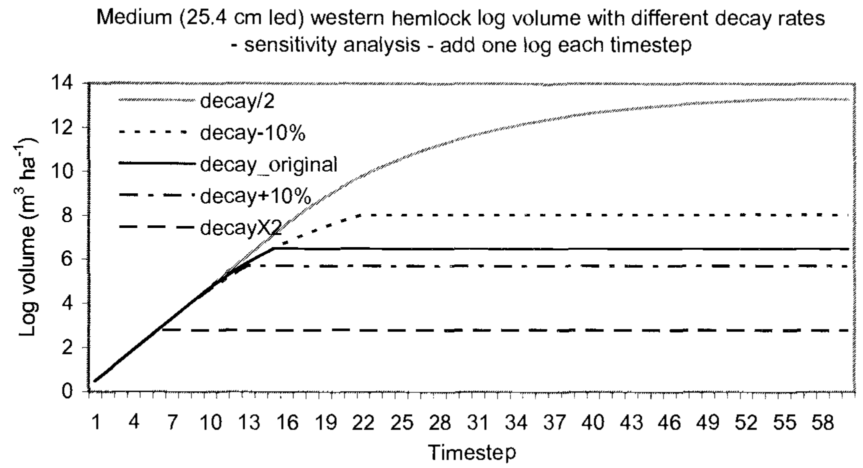


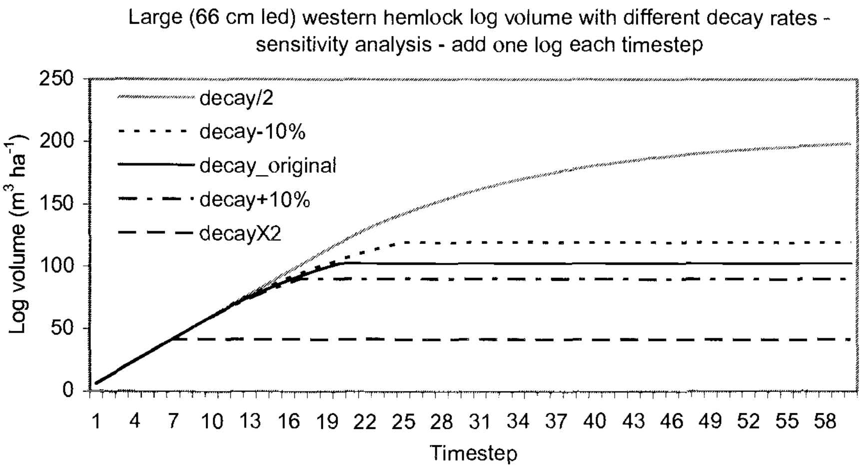
Figure C-2. Log volume produced by adding one log per timestep with different decay rates for three sizes of Douglas-fir logs in decay rates sensitivity analysis.



Small (12.7cm led) western hemlock log volume with different decay rates - sensitivity analysis - add one log each timestep

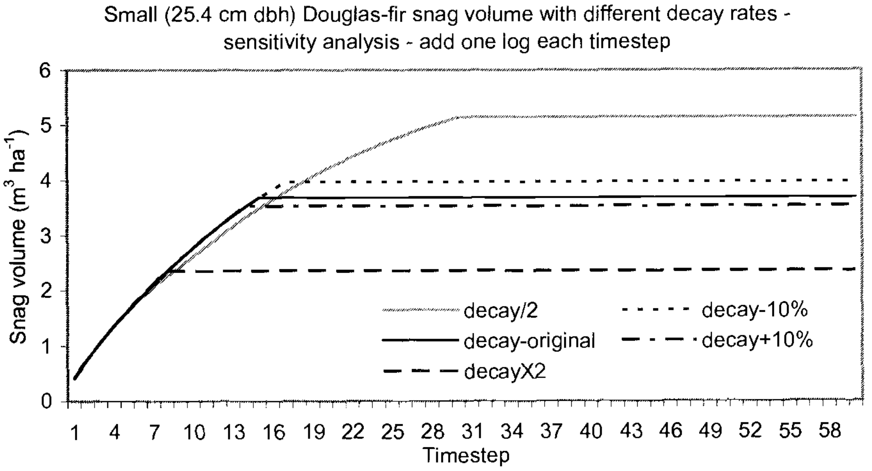


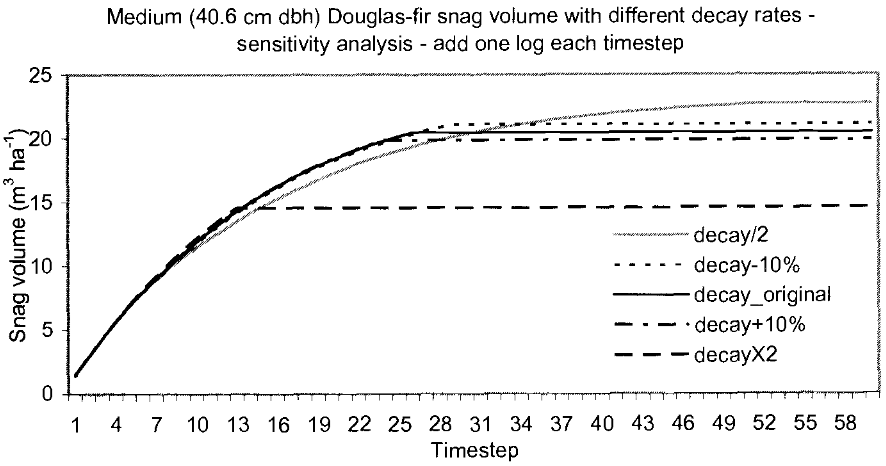
Medium (25.4 cm led) western hemlock log volume with different decay rates - sensitivity analysis - add one log each timestep



Large (66 cm led) western hemlock log volume with different decay rates - sensitivity analysis - add one log each timestep

Figure C-3. Log volume produced by adding one log per timestep with different decay rates for three sizes of western hemlock logs in decay rates sensitivity analysis.





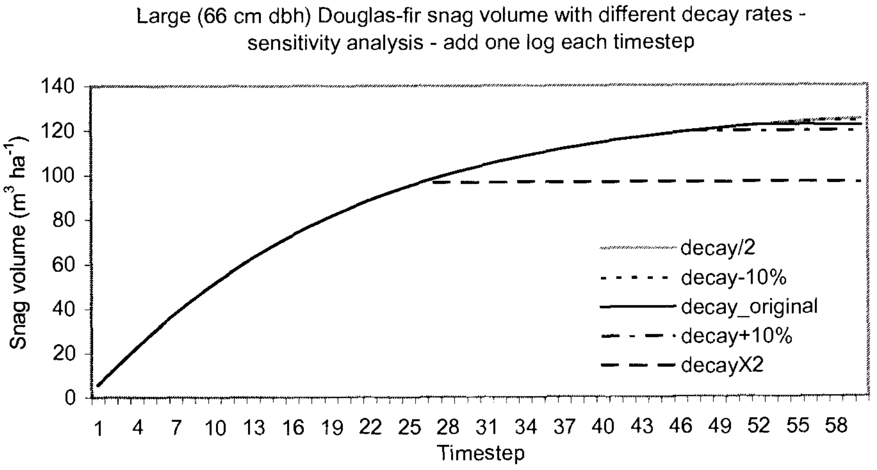


Figure C-4. Snag volume produced by adding one snag per timestep with different decay rates for three sizes of Douglas-fir snags in decay rates sensitivity analysis.

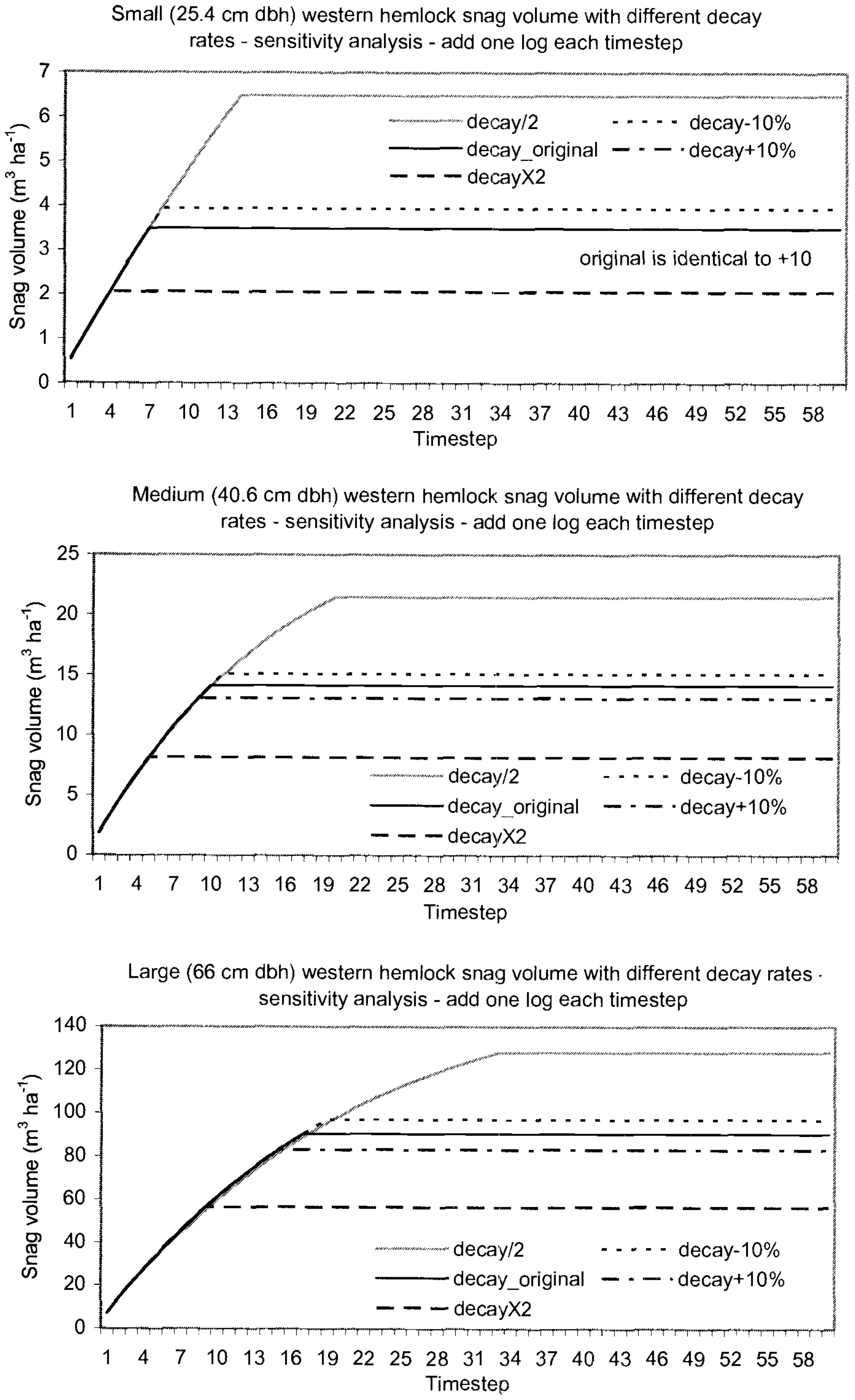


Figure C-5. Snag volume produced by adding one snag per timestep with different decay rates for three sizes of western hemlock snags in decay rates sensitivity analysis.

Appendix D. ZELIG Parameter Values and Simulation Results

This appendix contains parameter values and rates used in ZELIG, and simulation output from individual stands of low, medium, and high stocking. For more information on ZELIG parameter values and rates and ZELIG assumptions and limitations, see Pabst et al. in preparation.

Table D-1. Species parameters used in ZELIG simulations of conifer stands in the Coast Range. For scientific names of species please see main body of manuscript text.

Parameter	Bigleaf maple	Red alder	Sitka spruce	Douglas-fir	Western redcedar	Western hemlock
A_{max}	300	140	800	1100	1500	700
M_a	0.0154	0.0329	0.0058	0.0042	0.0031	0.0065
D_{max}	250	150	400	300	300	225
G	2976	2380	2600	2520	1963	1400
Lf	6	9	5	3	10	4
GDD_{min}	872	604	450	906	823	450
GDD_{max}	4141	3354	2494	3680	3111	2785
S_{tol}	2	4	2	3	1	1
D_{tol}	20	20	10	40	30	30
N_{tol}	2	0	2	2	2	2
SP	1	1	0	0	0	0
RegIc	2	5	0	5	2	3
RegIh	2	5	1	1	1	1
RegFc	2	5	4	3	2	3
RegFh	2	5	1	1	1	1

A_{max}	Maximum age attained by species (years)
M_a	Ambient annual mortality rate = -ln(0.1)/Amax
D_{max}	Maximum dbh attained by species (cm)
G	Growth efficiency (cm^2 of wood m^{-2} leaf area)
Lf	Leaf form
GDD	Growing degree days, minimum and maximum
S_{tol}	Shade tolerance ranking
D_{tol}	Drought tolerance ranking
N_{tol}	Soil nutrient tolerance ranking
SP	Sprouting potential indicator
Reg	Regeneration ranking. I=interior, F=fog. c=conifer, h=hardwood.

Table D-2. Regeneration rates used in dead wood simulations in ZELIG, by stand type and composition (Robert Pabst, Personal communication, April, 2005). STC is shade-tolerant conifers (Sitka spruce, western redcedar, western hemlock). Shade-tolerant conifers were considered to be seed-bearing if crown class was intermediate or above and non-seed bearing if crown class was suppressed. For scientific names of species please see main body of manuscript text.

	Conifer cover type			Hardwood cover type		
Species	Seed bearing STC	Non-seed-bearing STC	STC Absent	Seed bearing STC	Non-seed-bearing STC	STC Absent
Bigleaf maple	0.10	0.05	0.025	0.05	0.0375	0.025
Red alder	0.10	0.05	0.025	0.05	0.0375	0.025
Sitka spruce	0.10	0.05	0.025	0.03	0.0225	0.015
Douglas-fir	0.04	0.02	0.010	0.03	0.0225	0.015
Western redcedar	0.02	0.01	0.005	0.01	0.0075	0.005
Western hemlock	0.08	0.04	0.020	0.01	0.0075	0.005

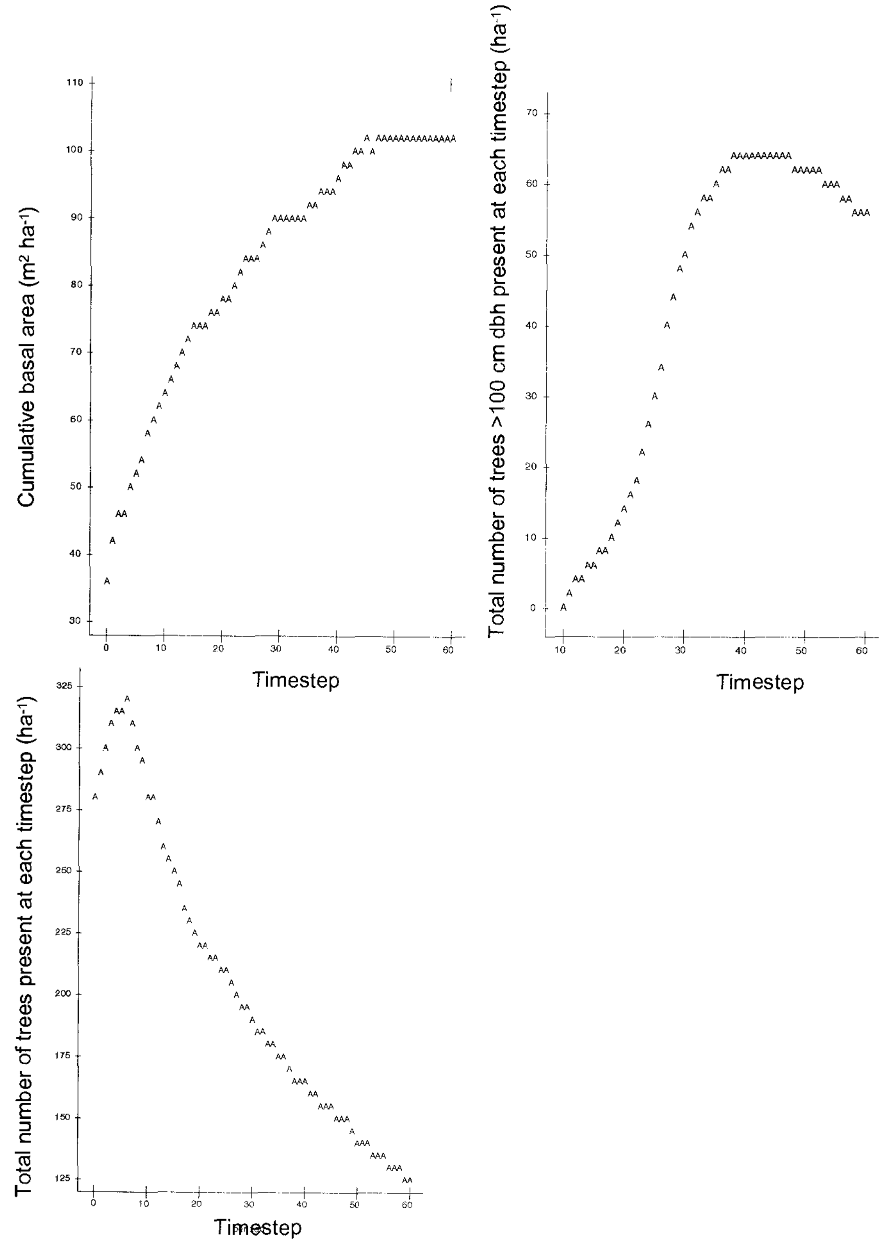


Figure D-1. Cumulative basal area over time, total number of large trees present at each timestep, and total number of trees present at each timestep, per hectare, as simulated by ZELIG under the natural conditions scenario over a 300-year simulation period, for a conifer-dominated (>=70% conifer) stand of initial young age (30-60 years old; this stand age: 48 years) with an initial low density of live trees (<300 tph; this stand density: 280 tph), located in the Coastal Province of Oregon.

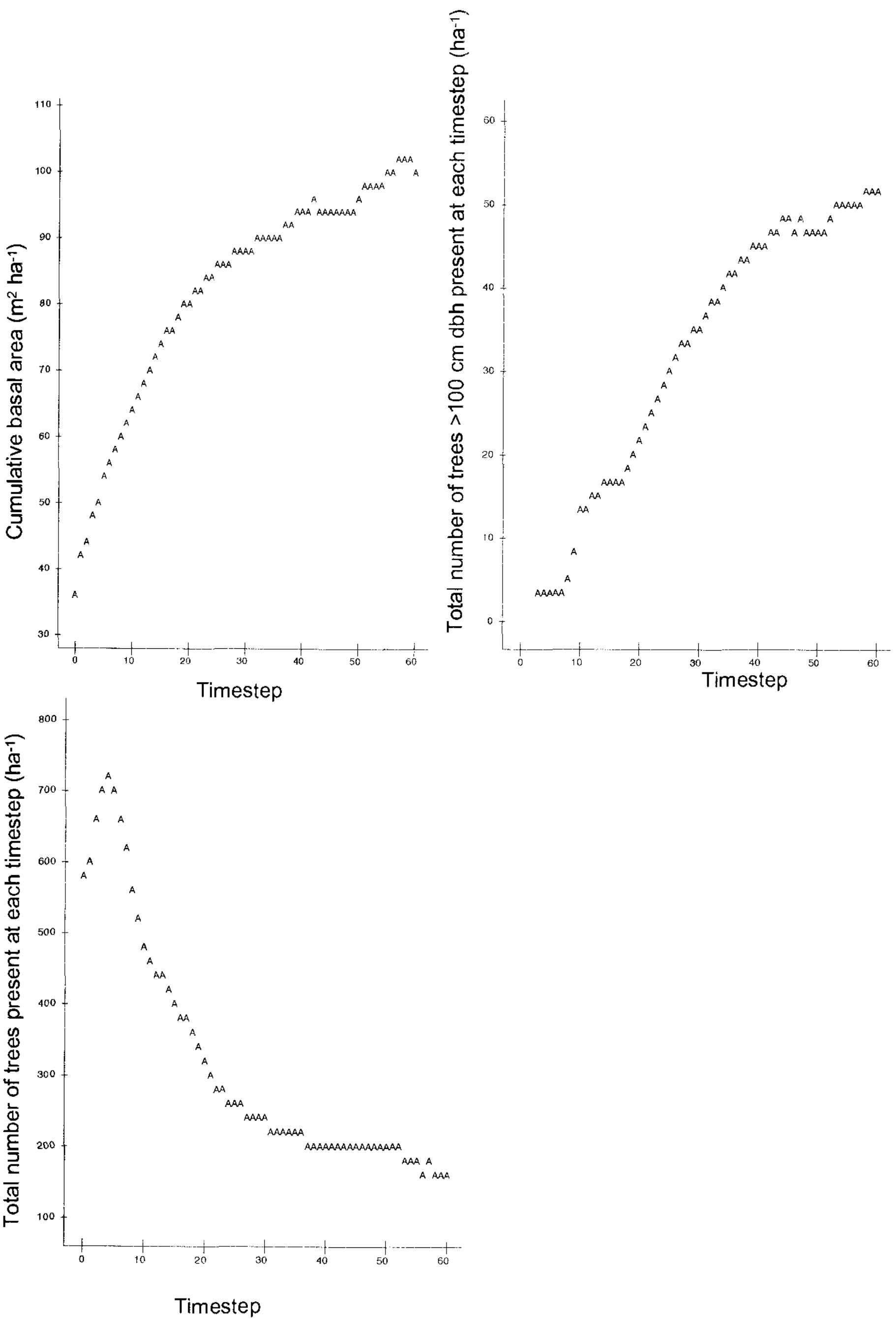


Figure D-2. Cumulative basal area over time, total number of large trees present at each timestep, and total number of trees present at each timestep, per hectare, as simulated by ZELIG under the natural conditions scenario over a 300-year simulation period, for a conifer-dominated (>=70% conifer) stand of initial young age (30-60 years old; this stand age: 45 years) with an initial medium density of live trees (500-650 tph; this stand density: 582 tph), located in the Coastal Province of Oregon.

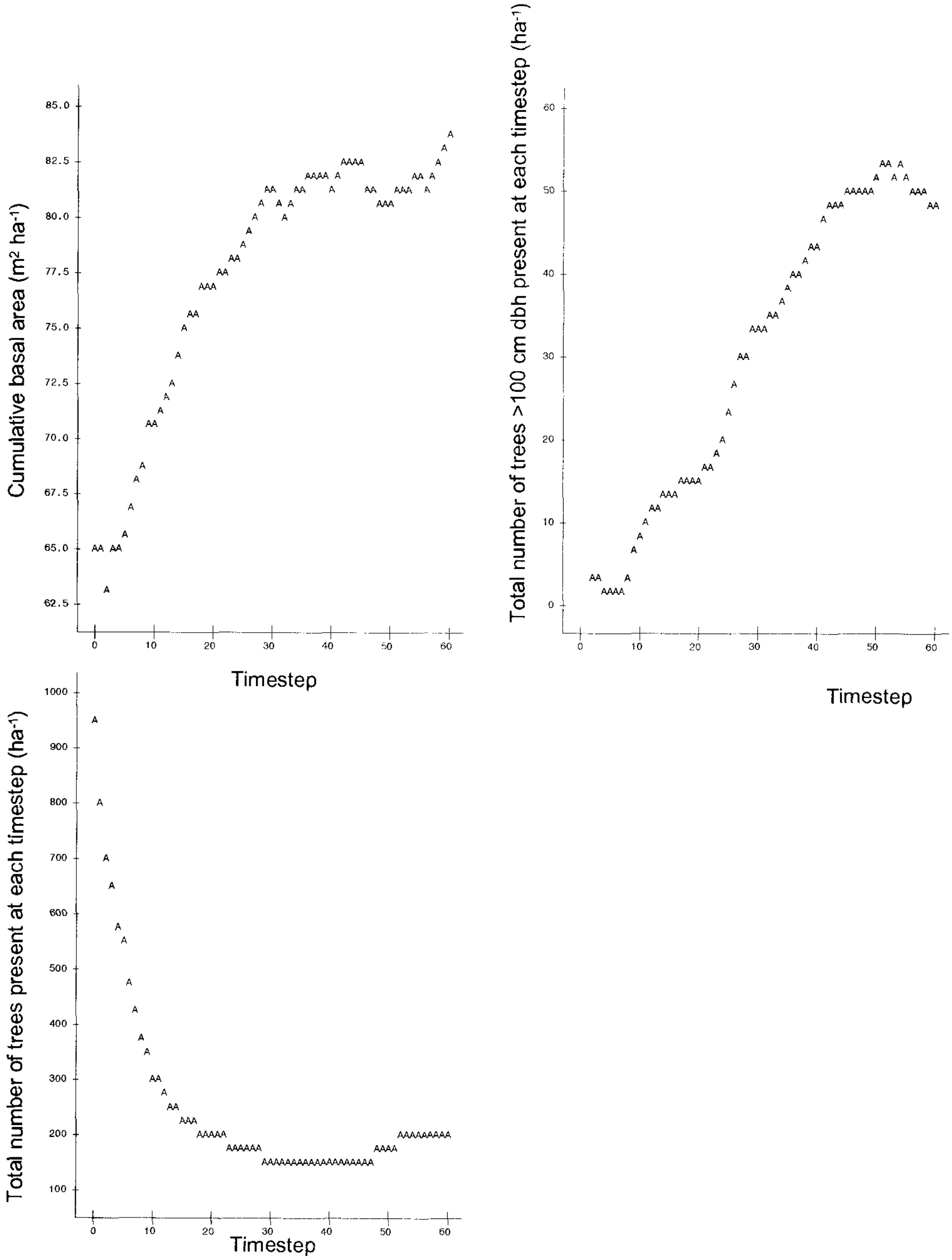
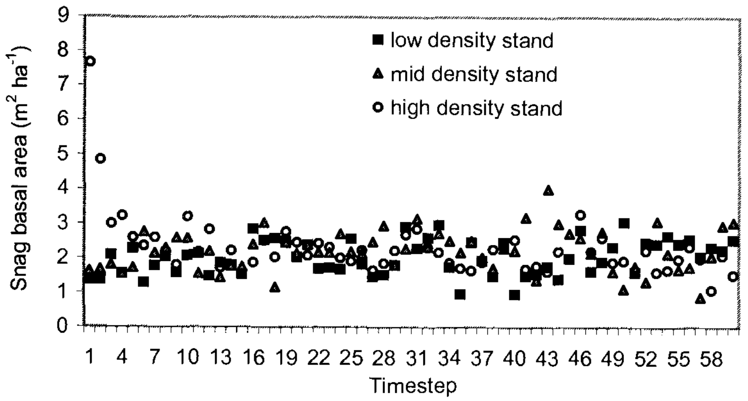
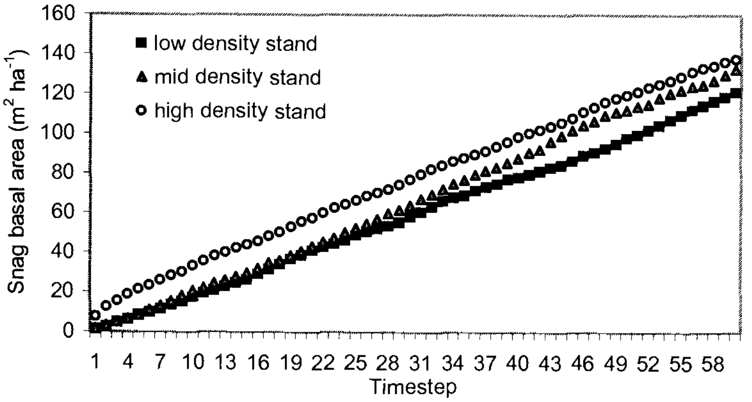


Figure D-3. Cumulative basal area over time, total number of large trees present at each timestep, and total number of trees present at each timestep, per hectare, as simulated by ZELIG under the natural conditions scenario over a 300-year simulation period, for a conifer-dominated (>=70% conifer) stand of initial young age (30-60 years old; this stand age: 51 years) with an initial high density of live trees (900-1050 tph; this stand density: 953 tph), located in the Coastal Province of Oregon.



Basal area of snags produced in each timestep for 3 stands with different initial densities of live trees



Cumulative snag basal area over time for 3 stands with different initial densities of live trees

Figure D-4. Basal area of snags produced at each timestep, and cumulative snag basal area over time, over 60 timesteps (300-year simulation period) as simulated by ZELIG under the natural conditions scenario, for 3 stands with different initial densities of live trees. For further description of each stand, see Figures D-1-D-3.

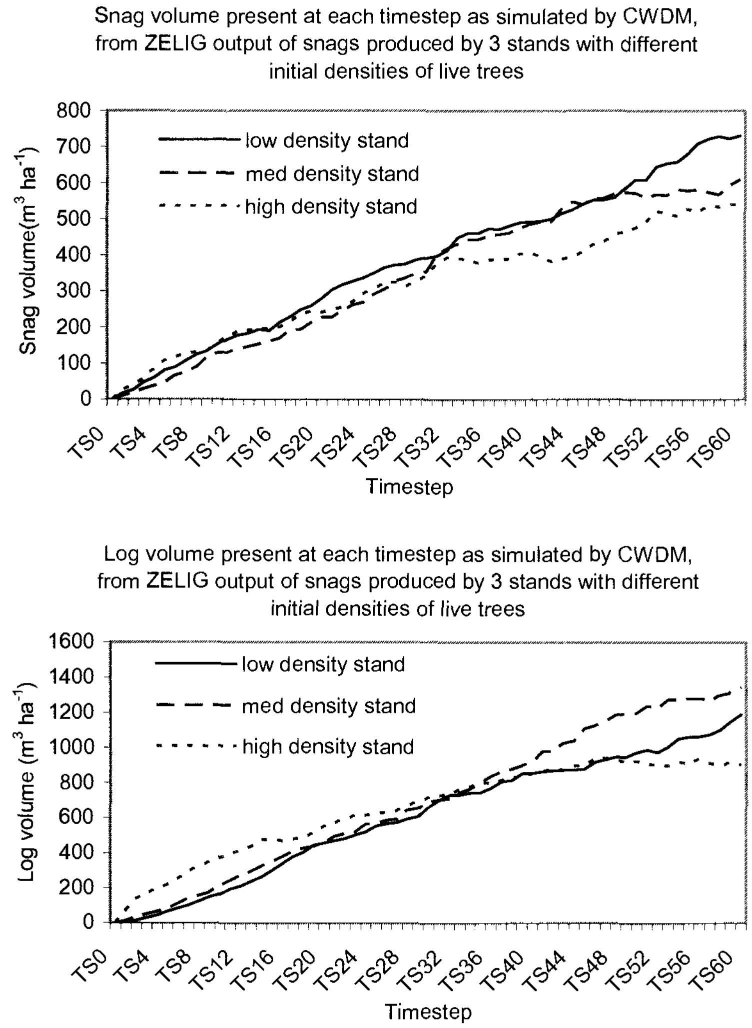


Figure D-5. Snag and log volume present at each timestep as simulated by CWDM, from ZELIG output of snags produced by 3 stands with different initial densities of live trees, over 60 timesteps (300-year simulation period) as simulated by ZELIG under the natural conditions scenario. For further description of each stand, see Figures D-1-D-3.

Appendix E. Management Scenarios Contacts

Table E-1. Names and affiliations of persons representing various ownership groups who were contacted during the development of management scenarios of major ownership groups in the Coastal Province of Oregon.

Ownership group	Name	Position	Affiliation
Forest Service	Stuart Johnson	Silviculturist	Forest Service, Siuslaw National Forest, Mapleton Ranger District
	Kimberly Mellen	Regional Wildlife Ecologist	Forest Service, Region 6
BLM	Hugh Snook	Silviculturist	Bureau of Land Management, Salem District
	Richard Hardt	Silviculturist	Bureau of Land Management, Eugene District
State of Oregon	Jeff Brandt	Head of Inventory and Monitoring for State Forests	Oregon Department of Forestry
	Doug Robin	Silviculturist	Oregon Department of Forestry
	Mike Schnee	Operations Manager	Oregon Department of Forestry
	Pam Overhulser	Resource Analyst	Oregon Department of Forestry
Private Industrial	Chris Jarmer	Director of Water Policy and Forest Regulations	Oregon Forest Industries Council
	K. Norman Johnson	Professor	Oregon State University, Department of Forest Resources
Non-Industrial Private	Liz Dent	Manager, ODF Forest Practices Monitoring Program; Riparian and Watershed Specialist	Oregon Department of Forestry
	Bill Arsonault	Member	Oregon Small Woodlands Association