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Decaying Wood in Pacific Northwest Forests: Concepts and Tools for Habitat Management

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Introduction

Decaying wood has become a major conservation issue in managed forest ecosystems.[16, 64, 69a, 149, 201] Of particular interest to wildlife scientists, foresters, and managers are the roles of wood decay in the diversity and distribution of native fauna, and ecosystem processes. Numerous wildlife functions are attributed to decaying wood as a source of food, nutrients, and cover for organisms at numerous trophic levels.[231, 232, 234, 346, 369] Principles of long-term productivity and sustainable forestry include decaying wood as a key feature of productive and resilient ecosystems.[10, 229, 291, 293, 386] In addition to a growing appreciation of the aesthetic, spiritual, and recreational values of forests, society increasingly recognizes ecosystem services of forests as resource "capital" with tangible economic value to humansy, such as air and water quality, flood control, and climate modification.[15, 262, 290]

The ecological importance of decaying wood is especially evident in coniferous forests of the Pacific Northwest. In this region, the abundance of large decaying wood is a defining feature of forest ecosystems, and a key factor in ecosystem diversity and productivity.[127] Native forests west of the Cascade Crest are highly productive and accumulate large amounts of live and dead wood—a result of the temperate climate that favors tree growth.[125, 126, 395] Large accumulations of decaying wood provide wildlife habitat and influence basic ecosystem processes such as soil development and productivity, nutrient immobilization and mineralization, and nitrogen fixation.[85, 115, 218, 233] Forests east of the Cascade Crest are also strongly influenced by accumulations of decaying wood that set the stage for ecosystem disturbances from fire, insects, and disease.[56, 137, 390]

Decaying wood has a pivotal role in both estuarine and coastal marine ecosystems, supporting complex trophic webs from benthos to higher vertebrates. More than half of the total organic carbon content of Washington's off-shore, midshelf sediment originates from coniferous forests.[139] Inputs of decaying wood are crucial to most aspects of stream processes, such as channel morphology, hydrology, and nutrient cycling.[233, 260, 262, 354] Although knowledge of these processes is incomplete, decaying wood in freshwater and marine food webs illustrates the potentially far-reaching implications of terrestrial wood management.

Historical interest in decaying wood has centered mainly on impediments to reforestation and on economic consequences of decay to timber production. In the first half of this century, wood decay or "decadence" was viewed simply as an undesirable attribute of overmature forests at increased risk of damage by fire, insects, or disease. Recognition of the diverse ecological benefits derived from decaying wood in aquatic and terrestrial ecosystems has grown appreciably over the past two decades.[56, 198, 201, 234] Wood decay in forests of the Pacific Northwest has recently become a topic of renewed interest at national and global scales, regarding the role of terrestrial carbon storage in the reduction of atmospheric CO^2 (a greenhouse gas). In light of recent projections for accelerated climatic warming during the next several decades,[255] regulatory targets for terrestrial carbon storage are being considered.[16]

New research over the past three decades has emphasized the significance of decaying wood to many fish and wildlife species,[48, 56, 230, 233, 234, 369] and to overall ecosystem function.[389] The importance of decaying wood to ecosystem biodiversity, productivity, and sustainability is a keynote topic in two recent regional ecosystem assessments in Oregon and Washington.[114, 225] These, and other publications address both the specific roles of wood decay in ecosystem processes and functions, as well as ecological functions of wildlife species associated with wood decay.[13, 68, 216, 250]

Interactions among wildlife, other organisms, and decaying wood substrates are essential to ecosystem processes and functions. In the process of meeting their needs, animals accomplish ecosystem "work" with respect to transformation of energy and cycling of nutrients in wood. For example, chipmunks and squirrels disperse mycorrhizal fungi which play key roles in nutrient cycling for tree growth; birds, bats, and shrews consume insects that decompose wood or feed on invertebrates and microbes; beavers and woodpeckers create habitats by modifying physical structures; arthropods build and aerate soil by decomposing wood material. Relations between wood decay and wildlife have been examined in several recent analyses.[56, 225, 282, 283, 284, 286] Species-specific associations have been identified for some tree species, types of decay fungi, and different forms of wood, such as bark piles at the base of snags, hollow living trees, and broomed trees. Simplified classification schemes and inventory procedures have been developed for decaying wood, particularly wood habitat structures relevant to wildlife.[56]

Wildlife species associated with wood decay, and their ecosystems are affected by management activities. Intensively managed forest plantations have replaced old-growth throughout most of the commercial forest land base in Oregon and Washington.[41, 42] Intensive forest management regimes have substantially altered the abundance and composition (species, size, decay class) of decaying wood in forest ecosystems in the Pacific Northwest. Managed forests, on average, have lower amounts of large down wood and snags than do natural forests.[59, 81, 82, 114, 154, 225, 276, 344, 368] Furthermore, in forests east of the Cascade crest, fire suppression has altered stand dynamics and produced accumulations of fine fuels conducive to stand-replacement fires.[5, 211, 302] Forest health problems and declining populations of some vertebrate and invertebrate wildlife species have coincided with changes in forest structure. These changes have raised concerns about the future biodiversity, productivity, and sustainability of the region's forests, particularly in coastal and eastside forests.[21, 170, 187, 222, 367]

Since the publication of Thomas et al.[369] and Brown,[48] new research has indicated that more snags and large down wood are needed to provide for the needs of fish, wildlife, and other ecosystem functions than was previously recommended by forest management guidelines in Washington and Oregon. For example, the density of cavity trees selected and used by cavity-nesters is higher than provided for in current management guidelines.[53, 102] Reductions in the wood content of estuarine and marine environments, and consequences to assorted aquatic organisms have also been documented.[139] Reductions in forest productivity linked to management practices such as stem removal, slash burning, and soil disturbance have also been recognized.[10, 13, 44, 198, 199]

Critical ecosystem functions of wood, coupled with incomplete knowledge for management, make the topic of decaying wood a priority for future research and adaptive management.[78, 149, 164] Effective approaches to managing decaying wood require that dead wood components of wildlife habitats be viewed within the context of the larger interacting ecosystem. To help managers achieve the goal of effective management of decaying wood, this chapter seeks to provide a focus on the ecological context for wood decay and associated wildlife in forests of the Pacific Northwest. Emphasis on

Wood Legacies in Managed Forests

John Hayes

Legacies are structures or components of ecosystems that exist prior to a disturbance and are "inherited" by the post-disturbance community. Legacies can provide important temporal connectivity within a stand, allowing organisms present in a pre-disturbance community to persist in an area following disturbance. In addition, legacy wood can provide structural elements and complexity in a stand that would otherwise require very long periods of time to develop. In managed forests, wood legacies, including large diameter trees, snags, and down wood, are ecologically important structures that play central roles in diverse ecosystem processes and functions, such as geomorphic processes, hydrology, nutrient cycling, and habitat for fish and wildlife. The ecological value of wood legacies has begun to gain widespread recognition only within the past two decades.[122, 164]

As a result of a variety of operational, safety, and economic considerations, application of intensive forest management practices often results in removal of legacy structures from stands and minimal retention of future legacy structures. Growing replacement structures with similar characteristics (e.g., large diameter trees with large diameter branches, thick and deeply-furrowed bark, and complex crown structure) requires decades or longer. Moreover, unless special provisions are made, large diameter trees, snags, and logs with these characteristics may never be produced in forests managed intensively on short- to moderate-length rotations. Habitat quality for species that depend upon or are closely associated with these structures can be seriously diminished with their loss from forest stands. The ecological importance of wood legacies combined with the difficulties of creating replacement structures provide convincing reasons to conserve legacy structures during management activities.

Managing wood legacies through time in managed forests is a multi-staged process. Existing structures that will serve as legacy structures in the post-disturbance environment should be identified prior to a disturbance event, such as logging. In some cases, it may be adequate to rely on the timber sale administrator or loggers to identify appropriate structures and implement the management strategy in the field. Since one intent of legacy structures is to provide various functions through time, it will often be valuable to either individually mark important legacy structures, or to document their location and purpose so that future managers can take the structures into account. Of equal importance, plans for recruitment of future legacy structures should be prepared to ensure that legacy structures will be available in future stands. Innovative silvicultural practices can be employed to create conditions favorable to development of future legacy structures.

concepts of long-term productivity in this chapter reflects an underlying principle that habitat functions of decaying wood are inextricably linked to ecosystem processes. Careful attention to the whole ecosystem is a prerequisite to successful management of decaying wood for wildlife.

This chapter provides a synthesis of knowledge on processes and functions of wood decay in forest productivity and wildlife habitat, and summarizes available information on the current regional status of decaying wood. It then ofers managers a stepwise assessment process to set goals and objectives, and select silvicultural tools to manage wood decay for desired results. Although the primary emphasis is on upland forests, the chapter also highlights wood decay structures and functions in forested wetlands, riparian forests, and aquatic systems. The analysis addresses a wide range of woody plant structures, with emphasis on large down wood and snags that form 'legacy' structures linking successive generations of stands.

Ecological Significance of Decaying Wood

Wood Decay Processes

Decay processes in wood form the basis for understanding ecological roles and relationships among wildlife and decaying woodand. Familiarity with these relationships facilitates the translation of these concepts into successful management strategies. Down wood, snags, and other persistent wood structures (such as stumps, root wads, and coarse roots) occur in most forest ecosystems. In moist forests, biological activity is the primary determinant of wood decay rates.[164, 346, 404] In drier forest regions, fire is often the primary agent of wood breakdown. In forest ecosystems with infrequent fire, the principal mechanisms of wood breakdown include leaching, fragmentation, transport, collapse, settling, seasoning, respiration, and biological transformation.[164] Decay processes in wood can be divided into two groups depending on whether the mode of action is mechanical fragmentation, or chemical breakdown. In the following section, we describe biologically mediated chemical breakdown of wood, and that various physical and biological processes fragment wood structure.

Terminology of Decaying Wood

Decaying wood includes all portions of a tree, standing or down, that are dead and in the process of decay. This is a broad definition that seeks to address wildlife uses[56] and other ecological functions of decaying wood. It includes the following wood structures:

- living trees with decay (e.g., heart-rot, root-rot, broken or decaying tops, large decaying branches, broken branch stubs, bole wounds, loose bark, stem cavities, and old trees with deep, fissured bark and thick, bulky branches)
- living hollow trees (advanced heartwood decay)
- broomed trees (diseased branches)
- snags (dead trees or portions of trees that remain upright)
- down wood (decaying trees or portions of trees that have fallen to the forest floor; includes other commonly used terms, such as logs, coarse woody debris, and large woody debris)
- stumps and other tree parts (rootwads, bark piles, coarse roots, and fine litter)

Ecosystem Definition

Ecosystems can be described at a variety of spatial scales and the spatial hierarchy of ecosystems is helpful for understanding the ecological functions of wood decay. Therefore, we use the "macrosystem" definition of ecosystems,[382] which recognizes the functional continuum of terrestrial, stream, estuarine and coastal ocean environments. Functional linkages include both the physical and biological processes and the interactions between organisms and decaying wood that contribute to nutrient, energy, and material cycling this continuum.[233] Smaller subunits of ecological organization[273] are recognized within this macrosystem, such as the forest floor and riparian communities.

Knowledge of wood structure and composition is useful for understanding processes of wood decay. Wood tissues of tree stems include the outer bark, cork cambium, inner bark (phloem), vascular cambium, outer xylem (living sapwood), and the inner xylem (non-living heartwood). Outer bark is a non-living barrier between the inner tree and harmful factors in the environment, such as fire, insects, and diseases. The cork cambium (phellogen) produces bark cells. The vascular cambium produces both the phloem cells (principal food-conducting tissue) and xylem cells of the sapwood (the main water storage and conducting tissue) and heartwood. Wood properties are determined mainly by plant cell walls, consisting ofcellulose fibrils impregnated within a cement-like matrix of lignin and other organic polymers in the approximate proportions: cellulose (40-50%), hemicellulose (20-35%), and lignin (15-35%).

Wood Fragmentation

Mechanical disruption of wood structure may be initiated abiotically by natural events, such as heavy snows, rime ice, avalanches, mass soil movement, floods, and windstorms that uproot or break trees.[86, 230, 270, 301, 316] Thermal expansion and contraction of wood, and water in woody tissues also promotes the physical disruption of wood structure. These disturbance agents affect wood decay variously by: 1) directly or indirectly inducing mortality of wood tissues, 2) altering the microclimate surrounding the affected wood structure, 3) increasing the surface area of wood exposed to the environment, and 4) increasing wood accessibility to microbes.

Fragmentation of decaying wood during the early stages of decomposition is accomplished by wood-boring insects such as beetles, carpenter ants, and termites.[23, 89, 230] As fissures develop in wood, invertebrates from minute mites to centipedes, millipedes, slugs and snails find suitable habitat, and contribute to further fragmentation. In the soil, an abundance of soil animals (including nematodes, earthworms, and microarthropods) contribute to the fragmentation of decaying wood and increase the surface area for microbial attack.[186] Functions and interactions between these soil fauna are varied and complex.[230]

A variety of vertebrate species contribute to the fragmentation of decaying wood in both live and dead trees. Most notable are the primary cavity excavators, such as woodpeckers and nuthatches that break wood fibers in the process of cavity excavation[216] (Figure 1). Other animal activities that fragment wood include limb pruning or breakage, foraging, denning, and burrowing. As decaying wood softens, tunneling and burrowing by other vertebrates such as salamanders, shrew, shrew-moles, and voles continue the fragmentation process in rotten wood and bark, and promote favorable conditions for further decomposition by invertebrates, fungi, and bacteria.

Principal Biological Agents of Wood Decay

Biologically mediated chemical breakdown of wood can be grouped into two basic categories: primary decay that establishes on living trees, and secondary decay that commences after tree mortality caused by other factors. Of the biological agents of wood decay, insects and fungi are the principal players in coniferous forest ecosystems. Wood-boring insects contribute to the early stages of wood decomposition by consuming and chemically digesting wood and by the enzymatic action of microbes. Insects also serve as vectors for other decay organisms and increase wood surface area accessible to both microbial and fungal attack.[23, 47, 89, 118, 230] Fungi accomplish wood decay by enzymatically decomposing the cell wall. Wood decay fungi can be separated into two main groups—the pathogenic heart-rot and root-rot fungi that colonize primarily the heartwood or roots of living trees (primary decay), and the saprobic fungi that colonize decaying wood (secondary decay) (Figure 2).

Figure 1. The pileated woodpecker, a primary excavator. Photo: David H. Johnson.

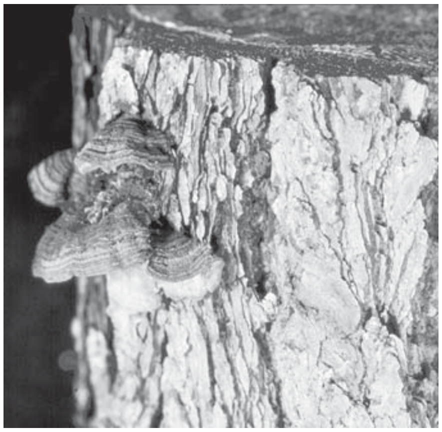

Figure 2. Conk of the fungus Fomes pini. Photo: Washington Department of Natural Resources.

On live trees, vulnerable locations for primary decay include heartwood, branch nodes, roots, dead and broken tops or branches, and wounds from fire, logging activities, windthrow, and lightning. Wounding is instrumental to primary decay because germinating fungal spores cannot penetrate intact bark or living sapwood, but must land directly on exposed dead wood connected to the heartwood. Generally, decay fungi located in the upper stems of living trees are heart-rot fungi.[220] Heart-rot fungi are not restricted to the heartwood, but usually infect through wounds in the sapwood of living trees. Every tree species is susceptible to at least one heart-rot fungus, but few fungi can cause heart-rot in living trees.[56, 175, 220]

Root rot is caused by a group of primary decay fungi that infect roots and spreads to other trees through root contact. These root pathogens act by causing nutrient deficiency after disrupting root tissue, altering root morphology, parasitizing the root cambium, or functioning as heart-rotters of the roots and lower tree bole.[220, 322] By weakening the root structure, root rot may directly kill trees, or indirectly contribute to mortality from windthrow and insects.

Processes of secondary decay are similar in both dead trees and in dead portions of live trees. Heart-rot fungi already present in a tree at the time of death usually contribute little to further decay of the dead tree. Instead they are replaced by other fungi termed saprobes, that are better adapted to degrade dead wood. Sapwood rotting fungi are quick to colonize a dead tree, particularly if tree mortality occurred without depletion of nutrient and carbohydrate stores. In general, once the sapwood is fully decayed, the sapwood fungi are replaced by saprobes that continue to degrade the sapwood and proceed into the heartwood. Saprobes may also invade larger patches of dead tissue on live trees, however.

Libe plant roots contribute to wood decay by producing enzymes and other exudates that accelerate cellulose decomposition and catalyze nutrient release from organic matter, and by forming symbioses with mycorrhizal fungi, N-fixing bacteria and actinomycete fungi to aid lignin decomposition.[1]

Stages and Structures of Decaying Wood

Various woody tissues in a tree have inherent differences in decay susceptibility. Decay normally begins at the exterior of a tree and progresses inward, though heart rot may degrade the interior of a tree with intact sapwood. The outer bark disappears mainly by fragmentation and sloughing from the top and sides of down trees. Despite a high concentration of nitrogen, decay of outer bark is inhibited by a high content of lignin and other anti-microbial compounds.[176, 203, 230] Inner bark rapidly decays due to its small volume and high nutritional quality (high digestibility and nutrient content). The outer ring of living sapwood is usually highly resistant to decay despite its high nutrient content, and may remain so even when adjacent tissues are extensively decayed. Dead sapwood decays rapidly, however. Compared to sapwood, heartwood decays slowly because of low nutrient quality and digestibility to microbes (high lignin and low nitrogen).[342]

All dead wood progresses through discreet stages of decay characterized by progressive changes in wood attributes, decomposition rates, and decomposer species. This chronology has been described in more detail for down wood than for snags, however. At each stage, decay is influenced by conditions in the physical environment, and by the structural and chemical composition of wood. As decomposition advances, changes in wood properties include decreased density and digestibility (higher ratio of lignin to cellulose), and increased water content and nutrient concentrations (including nitrogen, phosphorus, calcium, and magnesium in microbial tissue). Microbial decomposers vary in their nutrient requirements and in their inherent ability to degrade the structural matrix of wood (cellulose and lignin). Altered nutrient and structural attributes of wood with advancing decay thus creates sequential niches for different decomposer species.[220] Decay rates for dead wood are thus logarithmic rather than linear, because the more readily-decomposed fraction of wood is digested first, leaving the less digestible fraction,[184] and because nitrogen availability to microbes decreases over time.

Classification Systems For Decaying Wood

To facilitate the description and quantification of habitat attributes provided by decaying wood, several systems to classify decay conditions in conifers have been developed. New studies are needed to adapt such systems to hardwoods, which typically do not follow the same decay phases as conifers. A five-class system has been commonly used to describe the extent of decay in down wood.[28, 234, 339, 376] Decay classes are useful to ecological studies of wood decomposition because they describe functional and structural properties of wood, and eliminate the need to determine the date of tree mortality. The classes are based on a variety of tree characteristics, including the presence or absence of bark and fine twigs, bole shape, wood texture, and extent of log contact with soil. The decay status of a tree when it falls to the forest floor depends on its condition as a live tree or snag. For example, a live or recently dead tree that falls to the forest floor becomes a Class 1 log, however, a fallen snag may create a Class 1 to a Class 4 log.

A classification system for Douglas-fir snags describes a continuum of nine decay stages.[234, 370] The nine stages of snag decay correspond to the five decay classes for logs described above, with four additional stages: two earlier stages for live, but declining trees, and two later stages for progressive breakage and decay of the lower bole.[230] This nine-stage system was modified and refined[82, 263] into a five-stage system by eliminating Stages 1 and 2, and combining stages 7-9.

A simplified system of three structural classes each for conifer logs and snags has been developed based on the premise that fewer classes are sufficient to describe wildlife use and easier to apply in the field (Figure 3). Visual, chemical, and physical properties of conifer wood were evaluated in relation to degree of decay. Wood density, cellulose, and lignin content were found to be the best indicators of decay, whereas visual characteristics were relatively poor indicators.[182] Consequently, although the three class system of visually classifying wood decay may be satisfactory for assessing wood conditions important to many vertebrate wildlife species, the five-class system may better describe more subtle changes in wood properties (density, moisture) important to other organisms, and to ecosystem functions.

Ecological Functions of Decaying Wood

Wildlife Habitat Roles

Down wood, snags, and live trees with decay serve vital roles in meeting the life history needs of wildlife species in Oregon and Washington. Literature describing habitat relationships for wildlife and decaying wood in the Pacific Northwest are most comprehensive for vertebrate foraging ecology and cavity-nesting relations. Knowledge is more extensive for snags than for down wood, and for westside than for eastside ecosystems. Major regional ecosystem assessments recently completed in Oregon and Washington have examined the roles of decaying wood in habitat and in ecosystem biodiversity, productivity and sustainability.[114, 225, 302]

Recent significant advancements have defined wildlife species-specific relationships with particular characteristics and components of decaying trees, both standing and fallen,[56, 95, 185, 284, 351, 373, 386, 402] and implications for management.[13, 68, 223, 226, 250, 327] Much of this recent research has improved our understanding of poorly documented wildlife uses of microhabitats. Some of these are represented in the Habitat Element matrixes on the CD-ROM accompanying this book, and in the DecAID

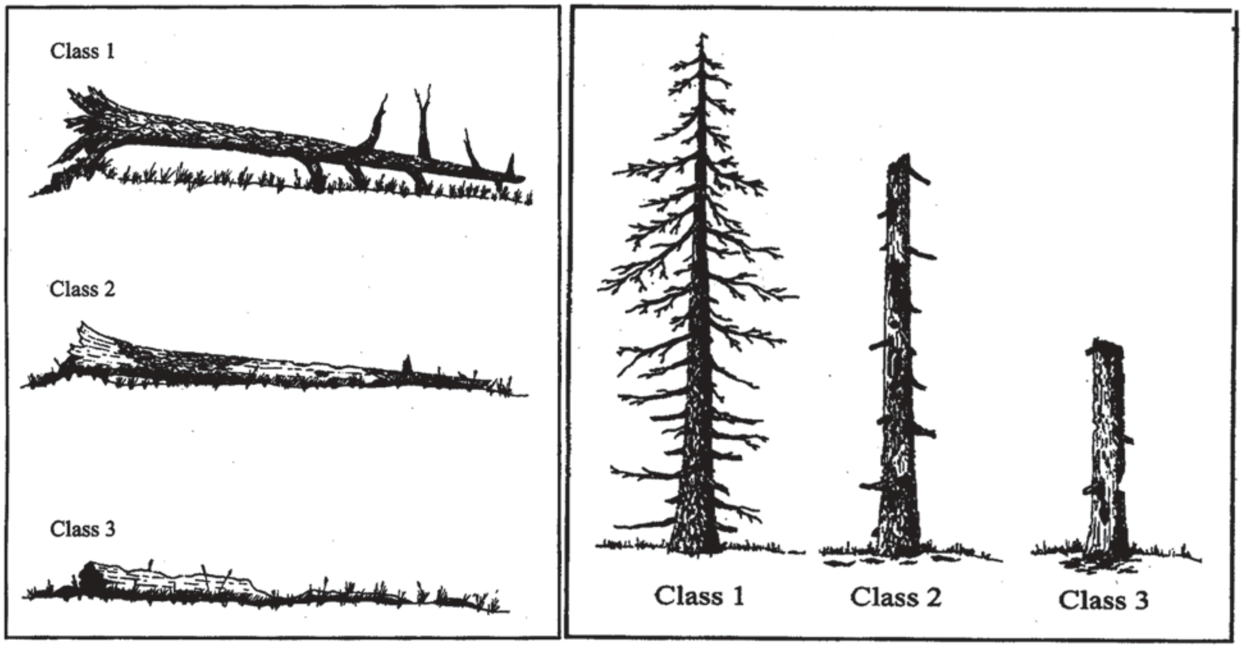

Figure 3. Structural classes of snags and down wood, from Bull et al.[56]

model.[226] For example, research on amphibians previously known to be generally associated with down wood, elucidated ways in which these species use distinctly different features of down wood.[22, 59a] For example, ensatinas occur primarily in bark piles at the base of snags, redback salamanders are found most often under moderately decayed logs, clouded salamanders prefer habitat under bark on logs, and Oregon slender salamanders inhabit the interior of logs.[22, 59a]

Up-to-date and specific information on species' habitat associations and key ecological functions is available in the matrixes on the CD-ROM accompanying this book and in the DecAID model.[226] The remainder of this section presents a sampling of new findings about resource partitioning among various wildlife communities in Pacific Northwest forests, with examples of current information available in the matrices and in the DecAID model.

Tree Species. Few studies have demonstrated the causal relationship between tree species per se, and the habitat functions of decaying wood. However, some habitat functions of wood are provided primarily by certain tree species. Woodpeckers, sapsuckers, and nuthatches are highly specific in their selection of tree species for nesting and roosting, and this selectivity is attributed to the presence of decay fungi.[29, 56, 95, 351] Tree species also influences other life requisites, such as prey production. For example, carpenter ants, a primary prey species of pileated woodpeckers in northeastern Oregon, prefer down larch logs (Larix laricina).[373] Decay characteristics, size, and wood density may account for more variation in wildlife use of wood than tree species. These parameters are likely to be highly correlated; that is, some tree species are more readily decomposed by organisms creating suitable conditions for cavity excavators.[284, 323] Tree species may also be correlated with environmental conditions that influence habitat suitability, such as microclimate, canopy position, geographical location, etc.

Decaying Wood Habitat Structures. In a recent review, decaying wood structures were grouped into five categories representing key habitat elements for wildlife, including living trees with decay, hollow trees, trees with brooms, dead trees (snags), and down woody material (logs).[56] An overview of these habitat structures is provided below, with reference to the three-class systems for classifying wood decay in snags and logs.[56]

- Standing Trees. Living trees often have pockets of decay, dieback, wounds, or broken tops and limbs that serve as wildlife habitat. To be useful to most cavity excavators, live trees usually must contain wood in a Class 2 stage of decomposition.[56, 238] For example, strong excavators, such as Williamson's sapsuckers, pileated woodpeckers, and black-backed woodpeckers, select trees with a sound exterior sapwood shell and decaying heartwood to excavate their nest cavities.[238, 284, 307] Armillaria root rot and other saprophytic fungi produce softer exterior wood suitable for cavity construction byweaker excavators such as red-breasted nuthatch and chickadee.[216] Trees with decaying tops or large dead or deformed branches provide roosting and drumming habitat for birds, and nesting platforms for murrelets, owls, and raptors (Figure 4).[102, 114, 153, 269] In addition, localized wood decay resulting from tree wounding and scarring (particularly at the tree base) provides substrate for ants and other insects consumed by foraging birds.[53]

Figure 4. Spotted owl roost. Photo: Deborah Lindley.

Figure 5. Hollow snag of ponderosa pine. Photo: Deborah Lindley.

A hollow tree (live or dead) is formed when advanced heartwood decay (Class 3) causes the heartwood cylinder to detach from the sapwood, leaving a hollow core surrounded by a reinforcing band of sapwood. The softened heartwood of trees colonized by heart-rot fungi provides suitable conditions for excavating a nest chamber, and the living sapwood functions to maintain the tree's structural integrity (Figure 5).[56] The structural elements produced by advancing heartwood decay include hollow cavities from small patches to larger cylinders, to entire hollow trunks. These decay legacies and resulting habitat elements are described in detail by Bull et al.[56]

Hollow trees larger than 20 inches (51 cm) in diameter at breast height (dbh) are the most valuable for denning, shelter, roosting, and hunting by a wide range of animals.[7, 52, 55, 56, 265, 282] Hollow chambers are used as dens by black bears, as night roosts by woodpeckers, and as dens, shelter, roosts, and hunting sites by a variety of animals, including flying squirrels, wood rats, bats, American marten, northern flickers and Vaux's swift.[7, 51, 52, 55, 56, 265, 282] Hollow trees and down wood are formed from only a few tree species that can maintain bole structural integrity as the heartwood decays.[56] Western redcedar is especially valuable in providing hollow trees because the decay-resistant sapwood remains structurally sound for centuries. In the Interior Columbia Basin, grand fir and western larch form the best hollow trees for wildlife uses.

Broomed trees caused by mistletoe, rust, or needlecast fungi may remain alive for decades, and have attributes distinct from decay patches in live trees. Abundant forage is produced from mistletoe shoots and fruits. Regardless of the extent of decay, broom infections provide various habitat functions to wildlife depending on how and where they form along the bole.[371, 372] For example, mistletoe brooms form platforms used for nesting, roosting, and resting sites by owls, hawks, and song birds; roosting by grouse; and resting cover by squirrels, porcupines, and marten.[56, 114] Little information is published on the use of rust or needlecast brooms by wildlife, but it is likely they serve similar functions as dwarf mistletoe. Documented uses include rest sites for American marten and nest sites for squirrels and great horned owls.[50, 56, 256] Because the dieback of infected tree parts may occur over a protracted time frame, a single tree infected with these types of pathogens may contain discrete patches of dead wood in various stages of decay.[51, 256]

Recent studies have provided valuable insight on wildlife uses of snags (dead trees).[21, 56, 314, 402] Snags provide essential habitat features for many wildlife species (Figure 6). The abundance of cavity-using species is directly related to the presence or absence of suitable cavity trees. Habitat suitability for cavity-users is influenced by the size (diameter and height), abundance, density, distribution, species, and decay characteristics of snags.[307] In addition, the structural condition of surrounding vegetation determines foraging opportunities.[402]

The Habitat Elements matrix on the CD-ROM with this book lists a total of 96 wildlife species associated with snags in forest (93 species) or grassland /shrubland (47 species) environments. Most of these species use snags in both environments. In forests, this includes 4 amphibian, 63 bird, and 26 mammal species. Additionally, 51 wildlife species are associated with tree cavities, 45 with dead parts of live trees, 33 with remnant or legacy trees (which may have dead parts), 28 with hollow living trees, 21 with bark crevices, and 18 with trees having mistletoe or witch's brooms. Habitat uses include nesting, roosting, preening, foraging, perching, courtship, drumming, and hibernating (Figure 7).

Of the 93 wildlife species associated with snags in forest environments, 21 are associated with hard snags (Stages 1 and 2), 20 with moderately decayed snags (Stage 3), and 6 with soft snags (Stages 4-5) in the five-stage classification system. According to the matrixes,[188] most snag-using wildlife species are associated with snags >14.2 inches (36 cm) diameter at breast height (dbh), and about a third of these species use snags >29.1 inches (74 cm) dbh.

This query of the Habitat Elements matrix illustrates the breadth of updated information about wildlife and snag habitat relations. Research results have expanded the number and variety of decaying wood categories over what was previously presented in Thomas[366] and Brown.[48] For example, the portion of the query (above) about cavity-

Figure 6. Snags provide essential habitat for wildlife. Photo: Deborah Lindley.

Figure 7.Brown creeper nest in sloughing bark. Photo: Harry Hartwell.

nesters includes subsets of species associated with different types of cavities, such as bark crevices, hollow trees, cavities in dead trees (snags), and cavities in living trees. Further differences in matrix summaries of species' relations may result from changes in the taxonomic classification of species, updated species' range and geographic distribution data, as well as data limitations for some species' associations with specific habitat elements. It should be noted that the Habitat Elements matrix denotes wildlife species' associations with the various habitat elements, but does not distinguish species' uses of habitat elements for life history needs (eg., nesting, feeding, hibernating, etc.), nor does it indicate the degree of association or species' versatility. However, species' habitat use information is available in the DecAID advisory model.[226]

Stumps provide a variety of wildlife habitats. Stumps with sloughing bark (Class 2) provide sites for bat roosts,[387] and foraging sites for flickers, and downy, hairy and pileated woodpeckers. In openings, tall stumps with advanced decay (Class 3) provide nest sites for flickers, and subsequently for blue birds and other secondary cavity-nesters associated with openings. Squirrels and chipmunks also use stumps as lookouts and platforms for cone-shredding. The matrixes on the CD-ROM with this book do not include stumps as a habitat element.

- Down Woody Material (logs). Down wood affords a diversity of habitat functions for wildlife, including foraging sites, hiding and thermal cover, denning, nesting, travel corridors, and vantage points for predator avoidance.[56, 64, 230] Larger down wood (diameter and length) generally has more potential uses as wildlife habitat. Large diameter logs, especially hollow ones are used by vertebrates for hiding and denning structures.[214, 230] Bears forage for invertebrates in logs during summer and fall. Fishers use large logs to a limited degree as den sites.[297] Lynx select dense patches of downed trees for denning.[200] Jackstrawed piles of logs form a habitat matrix offering thermal cover, hiding cover, and hunting areas for species such as marten, mink, cougar, lynx, fishers, and small mammals[305, 313] (Figure 8). Smaller logs benefit amphibians, reptiles, and mammals that use wood as escape cover and shelter. Small mammals use logs extensively as runways[234] (Figure 9). California red-backed voles use Class 2-3 down logs for cover, and feed on fungi (especially truffles) and lichens growing in close association with down wood.[378] The orientation of down wood also influences wildlife habitat use.[56] Logs oriented along slope contours may be useful travel lanes for wildlife, whereas logs oriented across contours impede travel.

The moist environment beneath loose bark, bark piles and in termite channels of logs with advanced decay provides a protected area for foraging by salamanders.[22] The cool, moist environment of rotten wood may be required for some species of salamanders to survive heat stress during summer. Decaying wood also provides habitat for invertebrates on which salamanders and other foraging vertebrates feed (e.g., collembolans, isopods, millipedes, mites, earthworms, ants, beetles, flies, spiders and snails).[230] The folding-door spider constructs a silk tube within the cracks and crevices of wood with advanced decay.

Generalizations regarding decay classes of habitat structures must be made cautiously. Habitat functions may encompass several decay classes or be specific to particular patterns and classes of decay.[56, 233]

Habitat structures in upper layers of the forest floor (soil, litter, duff) result from processes involving organic material (litter, decaying roots, vertebrate and invertebrate carrion, and fecal matter) and a diverse community of organisms, including bacteria, fungi, algae, protozoa, nematodes, arthropods, earthworms, amphibians, reptiles,

Figure 8. Jackstrawed logs offer hunting areas and den sites for lynx. Photo: Gary Koehler.

Figure 9. Townsend's chipmunk, Photo: D. Anderson, National Museum.

and small mammals[167, 185, 207, 230, 249, 376] The complex trophic web supported by nutrient and moisture conditions within the litter and duff layers transforms plant material into a variety of degradation products, thereby storing and releasing nutrients within the ecosystem.

According to the Habitat Elements matrix on the CD-ROM with this book, in forest environments, 86 vertebrate wildlife species are associated with down wood, 38 with litter (undecomposed fine wood), and 14 with duff (decomposed litter and other vegetation matter underlying the litter layer). Of these species, 58 are associated exclusively with down wood, 10 exclusively with litter, and none exclusively with duff. Wildlife uses include reproduction, hibernation, feeding, resting, sunning, drumming, preening, dusting, lookout and travel. All decay stages of down wood are used by wildlife.

Decaying wood forms many habitat structures in riparian forests. Accumulations of large wood on stream banks provide habitat for small mammals and birds that feed on stream biota,[103, 104] and provide structural diversity in streamside forests.[233, 261, 262, 376] The matrices on the CD-ROM with this book list 27 wildlife species associated specifically with down wood in riparian areas.

The role of down wood in salmon habitat has received much attention over the past two decades. Large wood is a key component of salmonid habitat both as a structural element and as cover and refugia from high flows. Large wood serves key functions in channel morphology, as well as sediment and water routing.[33, 38, 262] The importance of wood to salmon habitat varies from headwater to stream mouth.[235] As stream order increases and gradient decreases in third- to fifth-order streams, down wood is a dominant channel-forming feature. Larger wood deflects water and increases hydraulic diversity, producing a range of pool conditions that serve as habitats for juvenile salmonids in summer.[37] Diverse channel margins are a primary aspect of rearing habitat. Flow obstructions created by large wood provide foraging areas for young salmonid fry that are not yet able to swim in fast currents,[40] and provide refugia to juvenile salmonids at high flow.[257] In higher order streams, flow deflections created by large wood trap sediments and nutrients, and enhance the quality of gravels for spawning. Down wood is less of a channel-forming feature along large rivers, but defines meander cutoffs and provides cover and increased invertebrate productivity for juvenile salmonids.[392]

Long-Term Productivity

Long-term productivity is technically founded on the concept of net primary productivity—the conversion of solar energy to plant biomass, expressed as grams of organic matter per unit area per year. At any point in time, ecosystem productivity may vary depending on the successional stage of vegetation, disturbances, and variation in climate and other environmental factors. In terms of present-day forest management objectives, long-term ecosystem productivity typically refers to the production, in perpetuity, of diverse resources, including timber, fish, wildlife, and other ecosystem services, such as air and water quality. Processes that sustain the long-term productivity of ecosystems have become the centerpiece of new directives in ecosystem management and sustainable forestry.[78, 229, 291, 320] Given the key role of decaying wood in long-term productivity of forest ecosystems in the Pacific Northwest,[122, 169, 261, 302] the topic should remain of keen interest to scientists and managers during the coming decade.[149] Below, we highlight functions of decaying wood directly linked to long-term productivity, including influences on the frequency and severity of disturbances such as fire, disease, and insect outbreaks.[5, 6, 133, 137]

Nutrient Cycling and Soil Fertility. Decaying wood has been likened to a savings account for nutrients and organic matter,[376] and has also been described as a short-term sink, but a long-term source of nutrients in forest ecosystems.[164] The total amount and distribution of nutrients in different woody tissues varies from region to region and among forest types. Coarse wood contains 0.3-4.4% of the total nitrogen and 4.2-10.6% of the total phosphorus in westside forests. Nutrient cycling via foliage and fine litter has been well-described.[1, 161, 388, 408] Substantial amounts of nitrogen are returned to the soil from coarse wood inputs, yet even where annual rates of wood input are high, 4 to 15 times more nitrogen is returned to the forest floor from foliage than from large wood.[164] This is a consequence of the higher nutrient concentrations and shorter turnover times of leaf litter compared to wood.[164, 300] The relative contribution of large wood to the total nutrient pool in an ecosystem depends to a large extent, on the size of other organic pools in the system.

The proportion of tree nutrition derived from large wood during normal stand development is unknown. The low nutrient content in wood, small mass of tree boles relative to foliar litterfall, and slow rates of wood decay suggest that large wood plays a minor role in forest nutrition.[18, 159, 162] After large scale disturbance such as fire and blowdown, however, the large nutrient pool stored in woody structures of trees (bole, branches, twigs, roots) becomes available to the regrowing forest. Large down wood may thus be an ample source of nutrients throughout secondary succession.[281]

The slow rate of nutrient release from decomposing wood may serve to synchronize nutrient release with nutritional demands in forests, and also to minimize nutrient losses via leaching to the ground water.[8, 34, 83, 174, 341] In addition to nitrogen bound chemically within wood, down wood reduces nutrient losses from ecosystems by intercepting nutrients in litterfall and throughfall. Favorable temperature and moisture conditions also makes large decaying wood sites of significant nitrogen inputs via N-fixation.

Chronosequence studies indicate that large decaying wood accumulates nitrogen, calcium, and magnesium over time, but loses phosphorus and potassium.[76, 117, 146, 164, 205, 340] The time frame for nutrient immobilization and release (mineralization), as well as the specific processes responsible for changes in nutrient content of down wood have not been fully elucidated. Mineralization of nitrogen has been associated with a critical carbon-to-nitrogen ratio of approximately 100. That is, nitrogen and other elements stored in microbial tissues are gradually released to plants as ratios decline below 100.[105, 340] Despite growing recognition of the roles of decaying wood in soil productivity, details of many processes are poorly understood.[125, 131, 164, 376] Harmon et al.[164] describe patterns in the accumulation and release of major nutrients in decaying wood through time.

Recent studies indicate that wood may release nutrients more rapidly than previously thought through a variety of decay mechanisms mediated by means other than microbial decomposers, i.e. fungal sporocarps, mycorrhizae and roots, leaching, fragmentation, and insects.[107, 158, 159, 162, 339, 405] Harmon et al.[162] found that during early stages of decomposition, fungal sporocarps concentrated nitrogen, potassium and phosphorus from down wood. Annual dieback of the sporocarps returned nutrients to the available soil nutrient pool.

Soil is the foundation of the forest ecosystem.[68, 348] Large wood is a major source of humus and soil organic matter that improves soil development.[164, 242] An estimated 9-68% of the forest floor in Douglas-fir/western hemlock (Tsuga heterophylla) clearcuts in the Pacific Northwest is derived from decaying wood.[213] On the H. J. Andrews Experimental Forest of western Oregon, 20-30% of the soil volume consists of decaying wood dispersed throughout a matrix of litter and duff.[294] Because wood is a relatively inert substance, it may help to stabilize pools of organic matter in forests by slowing soil processes and buffering against rapid changes in soil chemistry. Humus and soil organic matter are critical to site productivity on dry sites, and may limit site productivity on excessively wet and cold sites.[169, 377, 381]

Litter decomposition processes in the upper soil are the major locus of nutrient cycling within forests of the Pacific Northwest.[1] Soil organic matter and wood can abiotically (chemically) retain large amounts of nitrogen and other elements in forest ecosystems. A significant fraction of the nitrogen is believed to be in soil organic matter pools.[58, 189, 219, 266, 355, 385] Down wood and soil organic matter thus, may regulate productivity in some forest ecosytems by limiting nutrient availability.[106] Numerous studies have demonstrated that losses in soil productivity often are closely linked to losses in soil organic matter.[298]

Moisture Retention. Water stored in large decomposing wood accelerates microbial decay rates by stabilizing temperature and preventing dessication during the summer.[11, 160, 376] Moist conditions within the wood favor decay by attracting burrowing and tunneling mammals and invertebrates that improve aeration of wood, and by providing colonization substrate and moisture for mycorrhizae and other fungi.[88, 168, 206] Moist “nurse logs” also provide excellent sites for seedling establishment and production of sporocarps. These processes increase retention and cycling of nutrients within ecosystems and contribute to higher biodiversity and biomass production.

Mycorrhizae. Mycorrhiza, meaning “fungus-root”, is a symbiotic association of fungi with plant roots. The fungus improves nutrient and water availability to the host in exchange for energy derived from plant sugars. Mycorrhizae are necessary for the survival of numerous tree families, including pine, hemlock, spruce, true fir, Douglas-fir, larch, oak, and alder. Mycorrhizal associations are a source of nutrients to promote wood decay. By the time a log reaches more advanced stages of decomposition (Class 3) fungal colonization leads to the accumulation of nutrients in hyphae, rhizomorphs and sporocarps,[23, 87] especially for ectomycorrhizal fungi, where >90% of the fungal activity is associated with organic material.[119, 168, 310] Ectomycorrhizal fungi decrease the ratio of carbon to nitrogen in decomposing wood, and mediate nutrient availability to plants while improving nutrient retention by forest ecosystems.[13, 206, 251]

Mass Wasting and Surface Erosion. In the Pacific Northwest, combined effects of steep slopes, high rainfall, a history of tectonic uplift, and rapid weathering of weak rocks make unstable slopes a dominant erosion process. Large wood helps to anchor snowpacks, limit the extent of snow avalanches, and may even stabilize debris flows, depending on the depth of the unstable area.[125, 356, 358] The energy derived from falling or flowing water is the driving force behind erosion processes in Pacific Northwest forests. By covering soil surfaces and dissipating energy in flowing and splashing water, logs and other forms of coarse wood significantly reduce erosion.[357] Large trees lying along contours reduce erosion by forming a barrier to creeping and raveling soils, especially on steep terrain. Material deposited on the upslope side of fallen logs absorbs moisture and creates favorable substrates for plants that stabilize soil and reduce runoff.[230]

Stand Regeneration and Ecosystem Succession. Decomposing wood serves as a superior seed bed for some plants because of accumulated nutrients and water, accelerated soil development, reduced erosion, and lower competition from mosses and herbs.[160, 376] In the Pacific Northwest, decaying wood influences forest succession by serving as nursery sites for shade-tolerant species such as western hemlock, the climax species in moist Douglas-fir habitat.[80, 123, 160, 163, 244] Wood that covers the forest floor also modifies plant establishment by inhibiting plant growth, and by altering physical, microclimatic, and biological properties of the underlying soil. For example, elevated levels of nitrogen fixation in Ceanothus velutinus and red alder[35, 88] have been reported under old logs.

Streams and Riparian Forests. Long-term productivity in streams and riparian areas is closely linked to nutrient inputs, to attributes of channel morphology, and to flow dynamics created by decaying wood.[144, 233, 360] Small wood contributes to nutrient dynamics within streams and provides substrates to support biological activity by microorganisms, as well as invertebrates and other aquatic organisms.[145, 262] Much of the organic matter processed by the aquatic community originates in riparian forests and is stored as logs.[90, 259] Down wood also helps to retain nutrients in streams, by trapping carcasses of dead salmon and increasing carcass availability to terrestrial scavengers.[72]

Large wood is the principal factor determining the productivity of aquatic habitats in low- and mid-order forested streams.[262] Large wood stabilizes small streams by dissipating energy, protecting streambanks, regulating the distribution and temporal stability of fast-water erosional areas and slow-water depositional sites, shaping channel morphology by routing sediment and water, and by providing substrate for biological activity.[361] The influence of large wood on energy dissipation in streams influences virtually all aspects of ecological processes in aquatic environments, and is responsible for much of the habitat diversity in stream and riparian ecosystems.[262, 376] The stair-step gradients produced by wood in small stream basins supports higher productivity and greater habitat diversity than that found in even-gradient streams lacking wood structure.[32, 40, 142, 173, 254, 357]

Key Ecological Functions of Wildlife Species Associated With Decaying Wood

As previously described, decaying wood provides habitat elements for many wildlife species. Beyond this, the associated wildlife species play diverse ecological roles in their ecosystems, which in turn can influence other species. These roles are termed "key ecological functions" or KEFs, which are categorized and denoted for each species in the Key Ecological Functions matrix on the CD-ROM with this book.[224]

Detailed descriptions of the patterns of KEFs of wildlife species associated with wood decay have been summed from the Key Ecological Functions matrix.[223] An associated "functional web" summarizing the ecological roles of wildlife associated with down wood included 86 wildlife species in Washington and Oregon and traced various functional categories.

Similarly, a functional web can be described here for the 96 vertebrate species associated with snags in forest or grassland/shrubland environments, as denoted by the Habitat Elements matrix on the CD-ROM with this book. For example, a query of the KEF matrix for these species shows that 40% of snag-associated species are primary consumers, 95% are secondary consumers, and 8% are carrion feeders. The remaining >5% are tertiary consumers, cannibalistic feeders, coprophages (feed on fecal matter), or feed on human refuse. The primary consumers include spermivores or seed-eaters (63% of all primary consumers associated with snags), frugivores or fruit-eaters (50%), sap feeders (18%). The others include (each <15%) fungivores or fungus-eaters, foliovores or leaf-eaters, grazers, and feeders on flowers or buds, aquatic plants, bark or cambium, and roots. Secondary consumers associated with snags include insectivores (90% of all secondary consumers associated with down wood), vertebrate predators (36%), ovivores or egg-eaters (13%), and piscivores or fish-eaters (8%). Percentages may sum to >100% because some species have multiple roles.

Various symbiotic relations can be described for the 96 snag-associated species. Sixteen species are primary cavity excavators and 35 are secondary cavity users; 8 are primary burrow excavators and 11 are secondary burrow users; 5 are primary terrestrial runway excavators and 6 are secondary runway users. Nine snag-associated species create nesting or denning structures and 8 use created structures. Sixteen species might influence vertebrate population dynamics and 22 might influence invertebrate population dynamics. Snag-associated species also contribute to dispersal of other organisms including seeds and fruits (21 snag-associated wildlife species perform this function), invertebrates (8 species), plants (8 species), fungi (2 species), and lichens (1 species). Six snag-associated species can improve soil structure and aeration through digging, 2 species fragment standing wood, and 2 species fragment down wood. One snag-associated species creates snags, and at least 1 can alter vegetation structure and succession through herbivory.

The ecological roles of wildlife associated with various decaying wood structures have both many similarities and salient differences. For example, both snag- and down wood-associated wildlife more or less equally participate in dispersal of seeds and fruits (although the particular species they disperse may differ); however, snag-associated wildlife play a greater role in dispersal of invertebrates and plants, and down wood-associated wildlife play a greater role in dispersal of fungi and lichens. Down wood-associated species might contribute more to improving soil structure and aeration through digging, and to fragmenting wood.

This is one example of the far greater differentiating power afforded by a well-constructed set of matrixes than was previously available in Thomas[366] and Brown.[48] That is, a combined query of the Habitat Elements matrix and the Key Ecological Functions matrix can produce a list of species with unique combinations of habitat element associations and particular ecological functions. For example, other decaying wood elements, such as hollow live trees, cavities in dead trees, dead parts of live trees, bark crevices and bark piles, support different arrays of wildlife species; their ecological roles (KEFs) may also differ from those discussed here.

It should be recognized, too, that invertebrates play critical major roles in wood decay ecology in both standing and down wood.[327] The full array of ecological roles of invertebrates associated with wood decay and related soil formation processes has been little studied, but is likely to be substantial. Included in 11 functional invertebrate groups described by FEMAT,[114] based on ecological roles, were coarse wood chewers, litter and soil dwellers, understory and forest gap herbivores, canopy herbivores, epizootic forest species, pollinators, riparian herbivores, and riparian predators. A 1 square meter of undisturbed forest soil is estimated to contain from 200 to 250 species of arthropods, including up to 75 species of fungivorous mites reaching densities of 200,000 individuals.[249]

Current Regional Patterns of Decaying Wood

Factors Influencing Regional Abundance of Decaying Wood

Quantities and characteristics of decaying wood in an ecosystem represent a balance between additions through tree death, breakage, transport, and losses through processes of decomposition and fire consumption, all of which can be influenced by forest management activities.[164] Management effects on the abundance of decaying wood can be accurately assessed only within the context of underlying natural patterns of wood dynamics. The following section describes predominant influences on accumulations of decaying wood in forests of the Pacific Northwest, including inputs (primary productivity and mortality), and outputs (decay and combustion), and interactions with various disturbances of natural and human origin.

Wood Input Rates

Primary Productivity. Regionally, ecosystem accumulations of decaying wood are closely related to gradients in net primary productivity as a result of moisture and temperature limitations. Consequently, dead wood abundance in the Pacific Northwest declines along an easterly gradient from the highly productive Douglas-fir zone[120] to the high desert. A summary of existing studies in Washington and Oregon[164] showed greater input rates of decaying wood biomass in mature and old-growth Douglas-fir and Sitka spruce/western hemlock forests (0.20 - 12.14 Mg/ac/yr) than in higher elevation Pacific silver fir (0.12 Mg/ac/yr). No data were available for eastside forests; however, lower accumulations of dead wood in juniper forests are closely tied to low biomass productivity, as well as fire. Detailed discussions of regional patterns in forest productivity have been provided elsewhere.[138, 148, 208, 274, 315, 396, 398, 399]

Successional Development. Pulses in tree mortality occur normally in stand regeneration and development. Self thinning from competition-induced suppression, for example, reduces stand density during the course of even-aged stand development in western Oregon and Washington.[277, 343] Suppressed trees are also more susceptible to insects and diseases. Suppressed trees are typically of small diameter and often remain standing until blown down by wind. Compared to young regenerating stands, natural mortality in old-growth stands usually affects a smaller number of trees, usually older and larger trees with slower inherent rates of decay and longer residence times compared to small trees. Natural aging processes may directly cause tree mortality by impairing tree physiological and hydraulic functioning, or indirectly by predisposing trees to other agents of mortality, such as insects, diseases, and windthrow.[194, 317, 318 393, 394, 400] Consequently, older trees with a higher ratio of heartwood to sapwood are more susceptible to heart-rot fungi, root-rotting fungi, sapwood fungi, and insects such as bark beetles.[79, 108, 237, 400]

The input rates and average piece size of dead wood generally increase with stand age,[164] although the amount of decaying wood can follow a U-shaped pattern if young forests inherit large amounts of decaying wood and live trees from preceding stands.[346] Age-related inputs and accumulation of wood throughout stands succession in the Pacific Northwest have been summarized.[71, 164, 277, 346] Information is lacking to describe natural patterns of decaying wood inputs and accumulation during stand development in forests east of the Cascade Range.

Fire. Prior to European settlement, natural disturbance regimes dominated by fire had a major influence on input rates and accumulations of dead wood in forests of the Pacific Northwest,[2, 5, 390] but other factors such as wind, pathogens, and insects also influenced forest development to varying degrees. Fire effects on ecosystem inputs of wood are varied and complex, depending on specific ecosystem attributes of soil, vegetation characteristics, and historic disturbance patterns.[1] Fire plays a major role in the dynamics of decaying wood by altering the rates and composition (size, species) of dead wood inputs, as well as combustions losses. The historic frequency and severity of fire events varies widely across the region. East of the Cascade Range, pre-settlement forests were subject to frequent low-intensity fires that killed only a small percentage of living trees, but consumed much of the decaying wood (85%), due to low moisture contents of fuel wood during late summer.[5, 24, 95] In moist forests west of the Cascade crest, by comparison, fire disturbances were infrequent, but of high intensity and magnitude, producing high inputs of wood from tree mortality.[2, 345, 346] For example, Agee and Huff[6] reported a 10-fold increase in snags and a 150% increase in down wood in old-growth hemlock-Douglas-fir forests after wildfire.

Insects and Pathogens. Insects and pathogens deserve special mention because they have had a major influence on historic inputs of dead wood in the Pacific Northwest. Although these disturbance agents are natural components of the ecosystems, their prevalence and degree of influence on ecosystem structure and function may be greatly modified by human activities. Insects and pathogens play a key role in maintaining diverse and productive forests by creating habitat and stimulating nutrient cycling. Catastrophic insect and pathogen infestations, though, may be symptomatic of imbalances causing reduced ecosystem productivity.

Insects and pathogens of Pacific Northwest forests are too numerous to describe in entirety here, but detailed information is available elsewhere.[133, 220, 322] Insects can be separated into general groups of defoliators, sap-suckers, bark beetles, wood borers, cone and seed insects, and excavators of seasoned wood. Insects may be primary agents of tree mortality or incidental agents that take advantage of trees weakened by other stresses. Bark beetle species represent both groups and may inhabit trees that are healthy, dying, or recently dead. Of the numerous varieties of tree pathogens, those that cause brooming in conifers induce substantial inputs of decaying wood in Pacific Northwest forests. These include the dwarf mistletoes (Arceuthobium spp.), rust fungi (Chrysomyxa spp. or Melampsorella spp.), or the needle cast fungus (Elytroderma deformans). Dwarf mistletoes are perennial parasitic plants that derive water and nutrition from their hosts, progressively killing branches, trees, and sometimes entire stands of vulnerable species.[171] Broom rusts are obligately parasitic pathogenic fungi that form witches' brooms on their coniferous hosts.[407] Needle cast fungus causes early needle drop in pines, and can form witches' brooms similar in appearance to dwarf mistletoe.[77]

Other Natural Disturbances. Flooding has diverse effects on ecosystems processes, thus specific effects on net accumulation of decaying wood may be difficult to discern. Streamside forests are often perturbed and even destroyed by flooding. Periodic flooding produces pulsed inputs of wood to forest ecosystems, but chronic flooding may eventually cause conversion to non-timber vegetation by impairing site productivity for trees. Reduced aeration in flooded soils can inhibit decay rates of wood in close contact with the soil, such as soil humus, small diameter wood, and large wood in advanced stages of decay. Poor aeration inhibits nitrogen mineralization and induces denitrification, reducing nitrogen supply to wood decomposers.[179] Prolonged flooding that eliminates beneficial populations of soil decomposer organisms thus, can also inhibit decay rates of wood.[353]

Wind is one of the most common disturbances to forests, with damage ranging from single trees to many hectares. In historic times, wind was the major disturbance factor controlling inputs of decaying wood to forests west of the Cascade crest in Washington and Oregon, and a primary influence in maintaining soil productivity.[46, 399] Wind produces pulsed inputs of decaying wood, often selecting for larger trees, though smaller trees in dense stands may also be highly vulnerable to wind, especially along natural topographic breaks, and on the windward side of harvest edges. Windthrow frequently also triggers outbreaks of bark beetles. Windthrow risk is difficult to predict, as it is is influenced by a complex interactions at scales ranging from individual trees to stands, to the surrounding landscape. Excellent discussions of windthrow processes in ecosystems have been presented elsewhere.[270, 335, 349] A recent study by Sinton et al.[337] is the first to evaluate the landscape context of forests as well as environmental factors contributing to historic windthrow patterns.

The Pacific Northwest is a region of active volcanic influence, most recently impacted by the explosion of Mt. St. Helens.[128, 129] Volcanic events variably contribute to large input, redistribution, and consumption of dead wood to ecosystems depending on proximity to the blast zone, pyroclastic flows, and debris flows. Thus, effects of volcanic activity on the subsequent abundance and decay rates of wood may be highly variable and difficult to predict. Mudflows from volcanic events can completely cover down wood and create a sanitized soil surface with reduced populations of decomposers.[101] However, plant succession after volcanic events may include many N-fixing species that serve to increase N availability and accelerate wood decomposition.

Landslides are a natural but infrequent occurrence (estimated interval of 500-1500 years) on steeper slopes within the region.[31, 190, 361] Altered slope hydrology and soil stability due to activities such as road building and logging, however, can increase the intensity, magnitude, and frequency of such events.[262] Landslides in the upper basins of steep mountainous terrain form debris flows that transport most of the sediment and wood in first- and second-order (i.e. low-order) channels.[359] Landslides and debris flows also contribute most of the sediment and coarse material into larger third to fifth-order channels (i.e. mid-order). These geomorphic events increase and redistribute large amounts of wood in Northwest ecosystems.

Wetlands Perpetuate Wood Legacies

Richard Bigley

Forested wetlands in the Pacific Northwest often contain a disproportionally high concentration of snags and down wood compared to most upland forests. Inundation promotes the accumulation of down wood by limiting decay and creating snags. Decaying wood contributes to many wetland functions and exerts considerable influence on water quality and flow routing in the forest.

Environmental conditions for wood decay in wetlands. Flooding often produces anaerobic soil conditions that curtail the decomposition of wood and other organic matter for many years. Buried wood thousands of years old has been recovered from deep peat and other anaerobic environments. Anaerobic conditions in wetlands inhibit wood decomposition rates by favoring facultative and obligate anaerobes that are less efficient dcomposers than areobic bacteria. Many fungal decomposers become dormant when water-saturated, and continue to grow only when oxygen is restored.

Clues as to the frequency, duration, and seasonality of wetland conditions can be inferred from soil features. Short periods of flooding may not be sufficient to inhibit wood decomposition in upland forests. Soils in areas without prolonged flooding usually have evenly-distributed red and yellow colors characteristic of oxidized iron. In contrast, forests with prolonged flooding often have deep organic surface horizons and underlying mineral soils lacking oxidized iron. Fluctuating water tables can usually be identified by the degree of "mottling" (red and yellow flecks) resulting from variable oxygen levels (and hence iron oxidation) in soils.

Wood structures contribute to wetland ecological function. Water storage in wetlands serves to reduce flooding at lower elevations, and to moderate seasonal variability in streamflow. Hydrological functions and surface runoff thus are major concerns in managing forests in and around wetlands. In forested wetlands where ground vegetation can be sparse, down wood is often a dominant influence in water routing and channel morphology.

Down wood significantly reduces erosion by dissipating flow energy and trapping sediments. Stable wood structures in wetlands create effective barriers to downslope transport of unconsolidated sediments, and facilitate vegetation establishment. Major fluvial erosion and deposition processes are influenced by overland flow resulting from heavy rainfall events and the limited infiltration capacity of some forest soils in the Pacific Northwest.

As with upland sites, down wood in wetlands provides sites for plant germination and establishment, protects vegetation from grazing, and serves as travel corridors for wildlife.

Wetland management and wood legacies. Forest management in and around wetlands is primarily concerned with soil disturbance and windthrow. Selective harvest and salvage of valuable western red cedar (*Thuja plicata*) has been the main impetus for management activities in forested wetlands of the Pacific Northwest. Management objectives to retain snags and down wood in forested wetlands require more detailed consideration of the different ecological functions of fast-growing hardwoods like popular (*Populus tremulodes*) and more decay-resistant but slower-growing species like western red cedar.

Wood Output Rates

Aside from wood removal in commercial harvesting, decay and combustion processes are the primary factors influencing the ouputs of decaying wood over time. Wood decay rates have been estimated for a number of forest types, but are highly sensitive to wood structure and chemistry as described earlier, and to climatic conditions, especially temperature, moisture, and aeration.[18, 105, 113, 146, 164, 300, 340] Decay rates of wood are most rapid under conditions of warm temperature and good aeration that limit the metabolic rates of decomposer organisms. Adequate moisture also is required to soften wood structure.[376]

Seasonal patterns of temperature and moisture in decaying wood have been reviewed in detail.[164, 230] In the western Cascades, decay is limited more by temperature during the winter and by moisture in the summer. Aeration may limit decay where poor drainage results in saturated soil and a perched water table. The brief warm season limits decay processes more in the eastern Cascades. Mesoscale atmospheric phenomena (e.g. orographic effects) that introduce finer-scale climate patterns also produce more variability in wood decay rates within ecosystems. Microclimatic variability at the scale of stands and individual trees is also affected by forest type, successional stage, aspect, slope, elevation, soil drainage, shading, and other factors.[131, 141, 146, 234] Wood size, shape, and placement affect decomposition rates by changing microclimates and wood exposure to decomposers.[56, 115, 205, 218, 341]

In addition to stimulating inputs of dead wood, fire eliminates dead wood via processes of decay and combustion. Decay rates are influenced by climatic and nutritional conditions for decay organisms in the post-fire environment.[193, 245, 379] Higher rates of wood decay in the warmer temperatures of forest openings created by fire, may be counterbalanced by moisture limitation. Similarly, changes in nutrient availablility after fire, may either stimulate or inhibit decay. Cool-burning fires consume less wood and produce a pulse of nutrients to decomposers.

Conversely, high intensity fires consume more wood and may cause nutrient losses via volatilization and leaching, or by depressing populations of beneficial microbial and invertebrate decomposer organisms in soil.[2, 5, 43] In addition, charring and case-hardening of wood surfaces by fire can retard decay processes.[218]

Effects of Human Disturbances on Wood Dynamics

Timber Management. Intensive forest management for timber objectives has been shown to simplify stand and landscape structure.[154] Harvest and burn cycles of 60-100 years in the western Cascades have been estimated to be equivalent to a 4- to 5 -fold increase in fire frequency compared to natural conditions, in terms stand structure.[368] Only two rotations of managed Douglas-fir have been estimated to reduce the abundance of dead wood by 90%, compared to levels in natural old-growth systems. In addition to removing wood, management activities also influence wood decay rates. For example, warmer microclimates after harvesting stimulate decay. Fertilization conducted to improve wood production in commercial forest lands[312] can accelerate decomposition rates of down wood by supplying decomposer organisms with limiting nutrients, particularly nitrogen. Conversely, intensive practices that deplete soil nitrogen, such as short-rotation, whole tree harvesting[198] may inhibit rates of wood decomposition over the longer term. Models estimate that between 50 to 100 years are required to replace nitrogen losses after timber harvest.[1]

Carbon Storage and Climate Change. Douglas-fir forests in low elevation temperate rain forests have the capacity to store more carbon in the form of biomass and dead wood than any forest ecosystem on earth.[197, 258] Consequently, these forests provide another benefit of global significance—the ability to sequester carbon from the atmosphere, and potentially to counteract global warming.[16] Intensive forestry practices that released large quantities of carbon stored as biomass and dead wood in Northwest forests during the 1980s have been implicated as a contributing factor in the rising atmospheric concentrations of carbon dioxide.[19, 161] The relative contribution of carbon storage in terrestrial forests to climatic warming remains equivocal, however.[16] The potential for warmer climates to accelerate decomposition of decaying wood in terrestrial systems remains an issue of concern.[294]

Furthermore, ecosystem accumulation of total wood (live and dead) has been postulated to increase in response to temporary stimulation of biomass productivity by higher temperatures, carbon dioxide, and nitrogen availability.[19, 308, 309] The increased rates of wood accumulation may level off, however, as nitrogen availability to forests stabilizes.[100] As a result of global warming, complex linkages between temperature, carbon dioxide, plant growth, decomposition, and nutrient cycling could alter the size and relative distributions of carbon and nutrient pools in forest soils and vegetation. Hence, wood accumulation and decay processes may exhibit considerable variation from one ecosystem to another.

Anthropogenic Pollution. Anthropogenic pollution can affect stand microclimates, soil chemistry, populations of decay organisms, and a variety of basic ecosystem processes, thus it is not surprising that pollutants alter processes of wood decay.[1, 280, 329] Ecological effects on forest ecosystems are highly specific to the source, type, and magnitude of the pollutants. Of the diverse pollutants affecting forest ecosystems, nitrogen pollution is the most widespread and has been thoroughly studied.[166, 219, 264, 288, 329] Nitrogen pollution is of concern because biomass production and storage in many forest ecosystems is tightly regulated by nitrogen availability. One of the most comprehensive studies of pollution impacts to date documented inhibited decomposition rates of organic material at a site receiving chronic inputs of nitrogen and sulfur.[166] Elevated nitrogen loading has been documented in coastal watersheds and estuarine environments;[380] consequently, wood dynamics may be altered in these environments, as well.

Fire Suppression. In the eastern Cascades and through much of the intermountain area, extensive forest insect and disease problems have resulted from decades of fire suppression in combination with selective harvesting of pines.[177, 194, 236, 401, 403] An analysis of landscape dynamics in the Interior Columbia River Basin[302, 379] revealed that fire suppression resulted in a decreased abundance of large-diameter trees, and caused fuel accumulations that predisposed forests to stand-replacement fires. As mentioned previously, more intense fires not only consume more wood, but can inhibit wood decay by reducing nitrogen availability (and other elements) through volatilization and leaching, especially for wood in close association with the soil.[245] Wood decay in post-fire regenerating forests also may be exacerbated by a decline in symbiotic nitrogen-fixing plant species in stands subject to prolonged fire suppression.[169]

Summary of Regional Patterns of Abundance for Snags and Down Wood

Regional variation in dead wood abundance reflects strong underlying gradients in physical environment, disturbance, and biological processes that affect community composition and structure, forest dynamics, and rates of dead wood input and output, as reviewed earlier in this chapter. These factors interact in complex ways in influencing abundance of dead wood on a given site. Basic information about regional ecological patterns of dead wood can provide context for management decisions at a variety of scales, and for analyzing forest policy at regional and national levels. A wealth of information on snags and down wood has recently become available from grids of field plots established by regional forest inventories across Washington and Oregon. This section summarizes findings of a recent analysis of these data by Ohmann and Waddell.[276]

Ohmann and Waddell[276] analyzed data on dead wood collected on 16,867 field plots in 9 forested wildlife habitat types.[188] The plots represent about 49 million ac (20 million ha) of forest within Washington and Oregon, about 54 percent of which is publicly owned, 24 percent is owned by timber industry, and 22 percent is owned by nonindustrial private landowners.[296] The field plots were measured from 1984-1997 as part of inventories conducted by the BLM (Natural Resource Inventory, NRI); the USDA Forest Service, National Forest System (Current Vegetation Survey, CVS); and the USDA Forest Service, Pacific Northwest Research Station (Forest Inventory and Analysis, FIA). Dead wood data were unavailable for national and state parks, and down wood data were unavailable for nonfederal lands in Oregon and western Washington. Snags on plots were sampled on fixed- and variable-radius circular plots, and down wood was sampled on line transects. See Ohmann and Waddell[276] for information about inventory design, field methods, and data summary.

Plots in upland forest were classified into 1 of 9 wildlife habitat types based on potential natural vegetation and ecoregion.[75] Each plot was also classified into 1 of the following 3 successional stages, which are groupings of the structural stages based on current vegetation structure[188]: early (tree stocking [sensu[217]] <10 percent, or tree stocking >=10 percent and quadratic mean diameter [QMD] 1.0-9.8 in [2.5-24.9 cm]), middle (tree stocking >=10 percent and QMD 9.8-19.6 in [25.0-49.9 cm]), late (tree stocking >=10 percent and QMD >=19.7 in [50.0 cm]). The QMD is the diameter of the tree of average cross-sectional area at breast height (4.5 ft; 1.37 m) on the plot.

Differences in Dead Wood Among Wildlife Habitat Types

The abundance of snags and down wood varied substantially across the region. The greatest differences in dead wood abundance were among the wildlife habitat types, although differences among successional stages within wildlife habitat types also were significant in many cases. Total snag densities were greatest at higher elevations: 15.1/ac (37.2/ha) in montane mixed-conifer forest and 14.6/ac (36.0/ha) in subalpine parks (Table 1). Snags were least dense in the drier wildlife habitat types on the eastside: 0.3/ac (0.8/ha) in western juniper woodland and 2.0/ac (5.0/ha) in eastside ponderosa pine (Table 1). Large snags were most abundant in montane mixed-conifer forest (3.8/ac; 9.6/ha) and in westside conifer-hardwood forest (2.2/ac; 5.5/ha), and least abundant in western juniper woodland (0.1/ac; 0.2/ha) and ponderosa pine (0.4/ac; 1.0/ha) (Table 1). The volumes of both total and large down wood were greatest in westside conifer-hardwood forest and lowest in western juniper woodland (Table 2, 3). Total down wood volume among wildlife habitat types ranged from 105.6 to 2,619.7 ft^3/ ac (7.4 to 183.3 m^3/ha), and large wood from 64.3 to 1,883.7 ft^3/ac (4.5 to 131.8 m^3/ha). Differences in total dead wood generally were more pronounced among wildlife habitat types on the west side of the Cascades than among the eastside types, and the amounts of total snags and down wood in montane mixed-conifer forests were significantly different from almost all other wildlife habitat types.

Much of the regional variation in dead wood abundance, expressed as differences among the wildlife habitat types, probably can be attributed to strong gradients in net primary productivity. For example, the large amount of dead wood in westside conifer-hardwood forests probably can be explained by high rates of input within these forests, which are the most productive of the wildlife habitat types.[120] In contrast, the large amount of dead wood in montane mixed-conifer forest also may be explained by slow rates of decomposition in the cold temperatures at high elevations. The high density of snags in the subalpine parkland and montane mixed-conifer types may be a function of high mortality rates and low fall rates in these habitats.

Successional Patterns of Dead Wood

Snag density generally increased with stand age. Within wildlife habitat types, total snag density always was lowest in the early successional stage and usually was highest in the late stage, although no differences were detected among stages of subalpine parkland, ponderosa pine, and western juniper (Table 1). Large snag abundance increased with successional development in all of the wildlife habitat types except western juniper woodland, where no trends were evident (Table 1).

The volume of total and large down wood also generally increased with forest development, but successional patterns differed somewhat among the wildlife habitat types (Table 2, 3). Late successional stages contained the largest concentrations of both total and large down wood in 7 of the 9 wildlife habitat types (Table 2, 3). In the westside wildlife habitats and in montane mixed-conifer forest, the volume of total and large down wood in the late stage usually was significantly different from the early and mid stages, but early and mid stages usually were not significantly different from one another (Table 2, 3). Large down wood volumes differed significantly between the early and middle successional stages in all of the eastside wildlife habitat types except western juniper woodland (Table 3).

No wildlife habitats exhibited a U-shaped pattern in snag abundance, which can occur if large amounts of wood is inherited from a preceding stand.[346] Down wood also most often increased with succession, but this pattern was less consistent than for snags, and some wildlife habitat types did exhibit a U-shaped pattern. The lack of a U-shaped successional pattern for snags is not surprising. Snags have much shorter lag times in the forest than down wood. Natural processes of fragmentation and decomposition begin much sooner, and they disappear as recognizable structures much faster.[164] In addition, much of the dead wood in westside forests is input directly as down wood rather than snags.[164] Snags also are much more likely than down wood to be damaged or intentionally removed by humans through the course of forest management and harvest activities. In a previous analysis of regional plot data, Hansen et al.[154] found that large snags

Table 1. Weighted mean (standard error) density of snags by wildlife habitat type, successional stage, and snag size, Oregon and Washington.[1]

	Successional Stage and Snag Size							
	Early		*Middle*		*Late*		*All stages*	
Wildlife habitat type	*Total*	*Large*	*Total*	*Large*	*Total*	*Large*	*Total*	*Large*
	Mean (SE) trees per acre							
Westside conifer-hardwood	2.1 [a]	0.8 [a]	7.2 [b]	2.4 [b]	12.7 [c]	5.8 [c]	5.8	2.2
	(0.1)	(0.0)	(0.2)	(0.1)	(0.4)	(0.2)	(0.1)	(0.1)
Westside white oak-Douglas-fir	2.5 [a]	0.6 [a]	4.6 [a]	1.1 [a]	6.9 [b]	2.4 [b]	4.1	1.0
	(0.4)	(0.2)	(0.4)	(0.1)	(1.0)	(0.4)	(0.3)	(0.1)
SW OR mixed conifer-hardwood	3.8 [a]	1.0 [a]	6.9 [b]	2.0 [b]	8.5 [b]	3.8 [c]	6.2	2.1
	(0.4)	(0.1)	(0.4)	(0.1)	(0.4)	(0.2)	(0.2)	(0.1)
Montane mixed-conifer	7.2 [a]	1.2 [a]	20.0 [b]	4.2 [b]	16.3 [c]	8.8 [c]	15.1	3.9
	(0.6)	(0.1)	(0.5)	(0.2)	(0.6)	(0.3)	(0.4)	(0.1)
Subalpine parkland	14.1	0.7 [a]	15.1	2.3 [b]	NA	NA	14.6	1.5
	(3.0)	(0.2)	(1.7)	(0.4)			(1.7)	(0.2)
Eastside mixed-conifer	6.0 [a]	0.8 [a]	8.7 [b]	1.7 [b]	8.4	3.2 [c]	7.9	1.5
	(0.4)	(0.1)	(0.2)	(0.0)	(0.2)	(0.2)	(0.2)	(0.0)
Lodgepole pine	6.7 [a]	0.3 [a]	11.2 [b]	0.9 [b]	NA	NA	8.0	0.5
	(0.6)	(0.0)	(1.1)	(0.1)			(0.5)	(0.0)
Ponderosa pine (eastside)	2.0	0.4	2.0	1.1	2.1	0.6	2.0	0.4
	(0.2)	(0.0)	(0.2)	(0.0)	(0.3)	(0.1)	(0.1)	(0.0)
Western juniper	0.3	0.1	0.6	0.2	0.3	0.1	0.3	0.1
	(0.1)	(0.0)	(0.2)	(0.1)	(0.2)	(0.1)	(0.1)	(0.0)
All wildlife habitat types	3.7 [a]	0.8 [a]	8.6 [b]	2.1 [b]	11.5 [c]	5.4 [c]	7.0	2.0
	(0.1)	(0.0)	(0.1)	(0.0)	(0.2)	(0.1)	(0.1)	(0.0)

[1] NA: Not applicable — sample size <10 plots.
Significantly different means (alpha=0.05) within rows (among successional stages for a given snag size-class) are indicated by different letter footnotes.
"Total" includes snags >= 10.0 in DBH, decay classes 1-5, and >=6.6 ft tall
"Large" includes snags >=19.7 in DBH, decay classes 1-5, and >=6.6 ft tall.
Table modified from Ohmann and Waddell (in press).

were 3-5 times more abundant in stands that had never been clearcut than in stands that had been clearcut at least once. These factors taken together suggest that snag levels would more closely track recent disturbance and forest succession, while down wood amounts would be more strongly influenced by the long-term history and productivity of the site.

Dead Wood in Wilderness Areas

Over all wildlife habitat types, large snags were more than twice as dense in wilderness areas than outside wilderness (Figure 10 a). The strongest differences were for westside conifer-hardwood forest (2.06/ac [5.1/ha] outside wilderness vs. 6.15/ac [15.2/ha] within wilderness), eastside mixed-conifer forest (1.30/ac [3.2/ha] vs. 3.84/ac [9.5/ha]), and lodgepole pine (0.3/ac [0.8/ha] vs. 1.1/ac [2.7/ha]). In contrast, large down wood was more abundant outside wilderness than within wilderness in all of the wildlife habitat types except eastside ponderosa pine (Figure10 b), although the differences usually were not significant. The most pronounced differences in down wood volume were in southwest Oregon mixed conifer-hardwood (918.9 ft^3 /ac [64.3 m^3/ha] outside wilderness vs. 323.1 ft^3/ac [22.6 m^3/ha] inside wilderness) and montane mixed-conifer (1,061.9 ft^3/ac [74.3 m^3/ha] vs. 502.9 ft^3/ac [35.2 m^3/ha]).

The wilderness stratification of the plots was intended to separate plots with different likelihoods of having been disturbed by timber harvest and management. However, comparisons of dead wood within and outside of wilderness areas must be interpreted with caution. Plots in wilderness are strongly biased towards higher elevations and lower productivities, which may account for much of the higher amounts of down wood outside wilderness. In addition, even though wilderness areas are off-limits to future timber harvesting, they have been affected by other human activities to some degree (e.g., roads, recreation, exotic species introduction, fire suppression). Furthermore, many plots outside wilderness areas sample old growth and younger natural forest.

Nevertheless, if snags are more strongly influenced by timber management activities than down wood, then wilderness areas would be more likely to contain greater amounts of snags than areas outside wilderness, as the data show. In fact, OSHA standards historically have

Table 2. Weighted mean (standard error) volume, percent cover, and density of total down wood by wildlife habitat type and successional stage, Oregon and Washington.[1]

	Successional Stage											
Wildlife habitat type	*Early*	*Middle*	*Late*	*All stages*	*Early*	*Middle*	*Late*	*All stages*	*Early*	*Middle*	*Late*	*All stages*
	Mean (SE) cubic feet per acre				*Mean (SE) percent cover*				*Mean (SE) pieces per acre*			
Westside conifer-hardwood	2,169 ^{a}	2,396 ^{a}	3,234 ^{b}	2,619	4.4 ^{a}	4.5 ^{a}	5.5 ^{b}	4.8	132.1 ^{a}	102.9 ^{a}	101.5 ^{b}	109.7
	(109)	(89)	(120)	(61)	(0.2)	(0.1)	(0.2)	(0.1)	(5.6)	(2.8)	(2.8)	(2.1)
Westside white oak-Douglas-fir	772	632	1,017	733	1.8	1.5	2.2	1.7	70.5	41.1	51.9	48.9
	(167)	(87)	(176)	(73)	(0.3)	(0.1)	(0.3)	(0.1)	(11.1)	(4.1)	(7.5)	(3.8)
SW OR mixed conifer-hardwood	1,213 ^{a}	983 ^{a}	1,695 ^{b}	1,227	2.5 ^{a}	2.2 ^{a}	3.2 ^{b}	2.5	64.3 ^{a}	59.7 ^{a}	69.7 ^{b}	63.5
	(123)	(66)	(114)	(54)	(0.2)	(0.1)	(0.2)	(0.1)	(5.9)	(3.2)	(3.8)	(2.3)
Montane mixed-conifer	1,459 ^{a}	1,608 ^{a}	2,837 ^{b}	1,769	3.8 ^{a}	4.3 ^{b}	5.1 ^{c}	4.3	102.8 ^{a}	101.3 ^{b}	90.0 ^{c}	99.8
	(91)	(47)	(151)	(46)	(0.2)	(0.1)	(0.2)	(0.1)	(4.1)	(2.6)	(3.8)	(1.9)
Subalpine parkland	502	789	NA	629	1.6	2.1	NA	1.8	45.8	52.2	NA	47.8
	(104)	(149)		(90)	(0.3)	(0.4)		(0.2)	(7.0)	(7.9)		(5.1)
Eastside mixed-conifer	672 ^{a}	780 ^{b}	840 ^{b}	753	2.0	2.2 ^{a}	1.9 ^{b}	2.1	63.9	57.8 ^{a}	41.3 ^{b}	58.5
	(31)	(19)	(70)	(16)	(0.1)	(0.0)	(0.1)	(0.0)	(2.0)	(1.1)	(2.7)	(0.9)
Lodgepole pine	714	792	NA	734	2.9	2.8	NA	2.9	81.6	65.2	NA	77.3
	(36)	(60)		(31)	(0.1)	(0.2)		(0.1)	(3.4)	(5.0)		(2.8)
Ponderosa pine (eastside)	304 ^{a}	406 ^{b}	282	362	0.8 ^{a}	1.0 ^{b}	0.7 ^{a}	0.9	28.4 ^{a}	31.9 ^{b}	18.1 ^{a}	29.7
	(19)	(20)	(43)	(14)	(0.0)	(0.0)	(0.1)	(0.0)	(1.6)	(1.2)	(2.8)	(0.9)
Western juniper	107	104	107	106	0.2	0.3	0.3	0.2	6.6	9.3	10.9	7.8
	(44)	(27)	(67)	(27)	(0.1)	(0.1)	(0.2)	(0.0)	(1.7)	(2.5)	(6.6)	(1.4)
All wildlife habitat types	1,000 ^{a}	1,109 ^{b}	2,306 ^{c}	1,255	2.6 ^{a}	2.7 ^{b}	4.1 ^{c}	2.9	74.0 ^{a}	67.7 ^{b}	77.4 ^{c}	71.0
	(27)	(19)	(64)	(17)	(0.1)	(0.0)	(0.1)	(0.0)	(1.4)	(0.8)	(1.6)	(0.7)

[1] NA: Not applicable — sample size <10 plots.

Total down wood includes pieces >=4.9 in large end diameter, decay classes 1-4, and >=6.6 ft long.

Significantly different means (alpha = 0.05) among successional stages are indicated by different letter footnotes.

Table modified from Ohmann and Waddell (in press).

Table 3. Weighted mean (standard error) volume, percent cover, and density of large down wood by wildlife habitat type and successional stage, Oregon and Washington.[1]

	Successional Stage											
Wildlife habitat type	*Early*	*Middle*	*Late*	*All stages*	*Early*	*Middle*	*Late*	*All stages*	*Early*	*Middle*	*Late*	*All stages*
	Mean (SE) cubic feet per acre				*Mean (SE) percent cover*				*Mean (SE) pieces per acre*			
Westside conifer-hardwood	1,408 [a]	1,709 [a]	2,459 [b]	1,883	1.9 [a]	2.2 [a]	3.1 [b]	2.4	23.9 [a]	19.7 [a]	24.1 [b]	22.3
	(97)	(81)	(114)	(57)	(0.1)	(0.1)	(0.1)	(0.1)	(1.6)	(0.9)	(1.1)	(0.7)
Westside white oak-Douglas-fir	442	373	609	432	0.6	0.6	0.9	0.6	9.0	5.9	6.5	6.6
	(147)	(79)	(154)	(64)	(0.2)	(0.1)	(0.2)	(0.1)	(2.4)	(1.1)	(1.8)	(0.9)
SW OR mixed conifer-hardwood	766 [a]	609 [a]	1,197 [b]	803	0.9 [a]	0.9 [a]	1.6 [b]	1.1	7.9 [a]	7.4 [a]	12.0 [b]	8.9
	(107)	(57)	(106)	(49)	(0.1)	(0.1)	(0.1)	(0.1)	(1.2)	(0.8)	(1.2)	(0.6)
Montane mixed-conifer	699 [a]	660 [a]	2,071 [b]	906	1.0 [a]	1.0 [a]	2.9 [b]	1.3	10.3 [a]	8.7 [a]	23.4 [b]	11.6
	(80)	(34)	(137)	(40)	(0.1)	(0.0)	(0.2)	(0.1)	(0.9)	(0.4)	(1.5)	(0.4)
Subalpine parkland	104	319	NA	207	0.2	0.5	NA	0.4	2.6	4.4	NA	3.4
	(47)	(91)		(54)	(0.1)	(0.1)		(0.1)	(1.2)	(1.4)		(0.9)
Eastside mixed-conifer	247 [a]	329 [b]	513 [c]	317	0.4 [a]	0.5 [b]	0.7 [c]	0.5	3.6 [a]	4.2 [b]	6.4 [c]	4.2
	(26)	(14)	(60)	(13)	(0.0)	(0.0)	(0.1)	(0.0)	(0.2)	(0.2)	(0.7)	(0.1)
Lodgepole pine	80 [a]	209 [b]	NA	116	0.2 [a]	0.3 [b]	NA	0.2	1.7 [a]	3.2 [b]	NA	2.1
	(13)	(40)		(14)	(0.0)	(0.1)		(0.0)	(0.3)	(0.7)		(0.3)
Ponderosa pine (eastside)	147 [a]	221 [b]	160	191	0.2 [a]	0.3 [b]	0.3	0.3	2.3 [a]	2.9 [b]	2.5	2.7
	(16)	(17)	(34)	(11)	(0.0)	(0.0)	(0.1)	(0.0)	(0.2)	(0.2)	(0.6)	(0.2)
Western juniper	71	50	89	64	0.1	0.1	0.2	0.1	0.4	0.8	4.5	0.7
	(40)	(23)	(66)	(24)	(0.0)	(0.0)	(0.2)	(0.0)	(0.2)	(0.4)	(3.3)	(0.2)
All wildlife habitat types	496 [a]	579 [b]	1,695 [c]	720	0.7 [a]	0.8 [b]	2.2 [c]	1.0	7.1 [a]	6.9 [b]	17.5 [c]	8.5
	(23)	(16)	(59)	(14)	(0.0)	(0.0)	(0.1)	(0.0)	(0.3)	(0.2)	(0.6)	(0.2)

[1] NA: Not applicable — sample size <10 plots.

Large down wood includes pieces >=19.7 in large end diameter, decay classes 1-4, and >=6.6 ft long.

Significantly different means (alpha = 0.05) among successional stages are indicated by different letter footnotes.

Table modified from Ohmann and Waddell (in press).

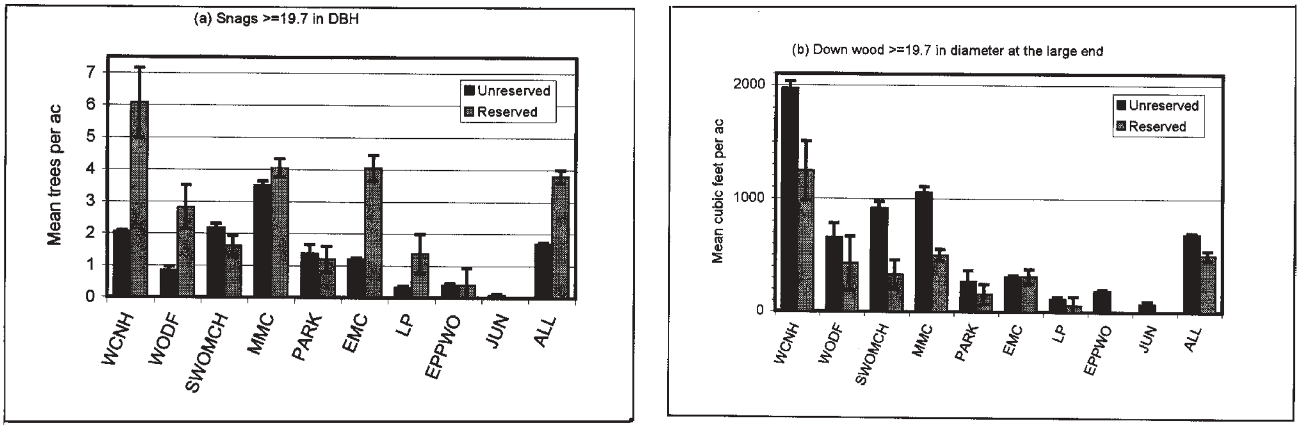

Figure 10. Abundance of dead wood by habitat type and reserved status, Oregon and Washington. (a) Weighted mean density of snags >=19.7 in DBH, decay classes 1-5, and >=6.6 ft tall. (b) Weighted mean volume of down wood >=19.7 in diameter at the large end, decay classes 1-4, and >=6.6 ft long. Error bars indicate one standard error of the mean. WCNH=westside conifer—hardwood, WODF=white oak—Douglas-fir, SWOMCH=southwest Oregon mixed conifer-hardwood, MMC=montane mixed-conifer, PARK=subalpine parkland, EMC=eastside mixed-conifer, LP=lodgepole pine, EPPWO=eastside ponderosa pine—white oak, JUN=western juniper, ALL=all habitats. There were <10 plots in reserved western juniper.

required the removal of most snags from harvest units for worker safety. Therefore, fewer snags were expected in managed stands outside wilderness. If snags are cut and left on site, this would contribute to the larger amount of down wood we observed outside wilderness areas. High snag densities in the high elevation habitats (subalpine parkland and montane mixed conifer) also result from inaccessibility for timber and firewood cutting.

Distribution of Dead Wood Abundance

Estimates of wood abundance in Ohmann and Wadell[276] are regional averages within wildlife habitats. The standard errors of these estimates were fairly low because of the very large sample sizes for most of the wildlife habitat types and successional stages. In reality, the plot-level amounts of dead wood within the wildlife habitat types were extremely variable. This variability reflects the high spatial and temporal variability in the many interacting environmental and disturbance factors that influence dead wood on a site. All of the wildlife habitat types examined had similar patterns: distributions were non-normally distributed and strongly skewed to the right. A large proportion of the plots contained no snags or down wood, and a very small proportion of the plots contained extremely large accumulations of dead wood. Mean values for these skewed distributions must be interpreted with caution. The distribution of snags for the conifer alliance of westside conifer-hardwood forest (Figure 11) illustrate this pattern. In this wildlife habitat type, 39 percent of the area sampled had no snags.

Comparisons with Other Studies

Very few estimates of dead wood abundance at broad geographic scales are available for comparison with results from Ohmann and Waddell.[276] Direct comparisons with published studies are extremely difficult to make because of differences in geographic location; the vegetation types, stand ages, and disturbance histories sampled; sampling design; definitions (e.g., dead wood sizes and decay classes); and units of measure (numbers of trees, volume, density, cover, or linear meters). Other regional studies of dead wood in Washington and Oregon have been restricted either to federal or to nonfederal lands, which usually represent very different ecological conditions.[274] A study by Ohmann et al.[275] was limited to snags on nonfederal lands, because data were unavailable for dead wood on federal lands and down wood on nonfederal lands at that time. The study by Spies et al.[346] was confined to natural Douglas-fir forests >40 years old on federal lands on the westside. Published information for eastside forests is not available,[111] or consists of summaries of a few local studies.[56] Scientists for the Interior Columbia River Basin Ecosystem Management Project relied on expert opinion and local studies to estimate current and historical amounts of decaying wood.[202] Harmon et al.[164] did not include any studies from eastern Washington or eastern Oregon.

Estimates of down wood volume presented by Ohmann and Waddell[276] are somewhat lower than other published numbers, but this is expected for several reasons: the minimum diameters are larger than in many other studies; the data describe both managed and natural forests of all ages, not just older natural forests originating after fire; down wood of decay class 5 is excluded; the values represent means across many stands, including stands where no dead wood was observed, and maximum values are not presented. Estimates of percent cover of down wood also may be lower than in other studies that used plot sampling or total tallies, as percent cover calculated from line intersect sampling has been shown to underestimate true values.[27]

Although estimates of mean total down wood volume in successional stages of westside conifer-hardwood forest ranged from 2,169.2 to 3,233.8 ft^3/ac (151.8 to 226.3 m^3/ha) (Table 2), the maximum value on a plot was 30,625.9 ft^3/ac (2,142.9 m^3/ha). This compares to a range of 4,416

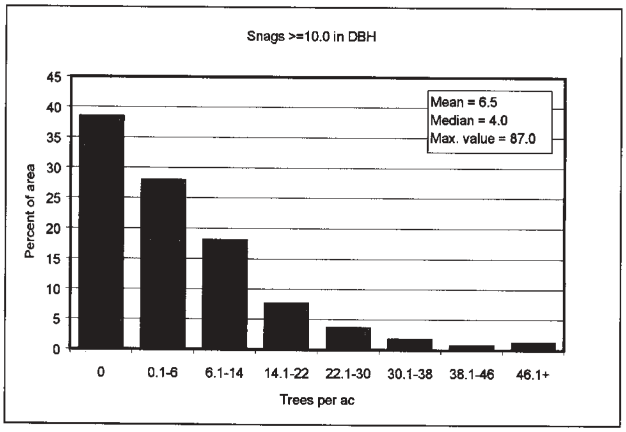

Figure 11. Density of snags >=10.0 in DBH, decay classes 1-5, and >=6.6 ft tall across plots in the conifer alliance of westside conifer-hardwood forest, Oregon and Washington, displayed as a percent of the sampled area.

to 20,306 ft^3/ac (309 to 1,421 m^3/ha) in various studies in westside Douglas-fir-western hemlock summarized by Harmon et al.,[164] and to 2,115 to 4,473 ft^3/ac (148 to 313 m^3/ha) reported by Spies et al.[346] The large snag densities in westside conifer-hardwood forest (Table 1) were substantially less than those reported by Spies et al.;[346] the estimate of 0.9 large snags/ac (2.1 large snags/ha) in early stages probably represent stands younger than the 40 yr minimum sampled by Spies et al.;[346] the estimate for middle-successional stages of 2.4/ac (6.0/ha) compares to 10.9/ac (27/ha) in their young stands; and the estimate for late stages of 5.70/ac (14.3/ha) compares to their mature 6.48/ac (16/ha) and old growth 10.9/ac (27/ha) classes.

Estimates of dead wood presented by Ohmann and Waddell[276] are not directly comparable to those reported in most wildlife studies.[226] Wildlife studies typically describe dead wood around nest sites, where dead wood abundance may be substantially higher than in surrounding stands because many wildlife species select nest sites within clumps of snags.[226] Limited evidence suggests that dead wood is most often distributed randomly within stands, but sometimes is clumped,[82, 215] (Marcot et al. in prep., unpublished data). Twenty-five percent of stands sampled in the Oregon Coast Range were found to contain patches of 5-10 trees that died simultaneously.[82]

Management Considerations

Management Ramifications of Snag and Down Wood Abundance

Wildlife Species

By querying the CD-ROM matrixes, some generalizations can be drawn about the implications to wildlife of the current status of decaying wood as detailed above. Unfortunately, such inventory data are not available for historic conditions, so little can be quantified about potential changes in wildlife communities.

It is clear that wilderness and parks generally provide substantial standing dead wood habitat, but this provides for wildlife associated more with montane through alpine environments than with lower elevation environments. This would favor such species as black-backed and northern three-toed woodpeckers. The apparent dearth of large snags in Ponderosa pine may mean lower suitability for the 54 wildlife species associated with large snags (20+ in or 51+ cm dbh) in that wildlife habitat.

Intensive forest management activities that have decreased the density of large snags in early forest successional stages (sapling/pole and small tree stages) may have had adverse impacts on the 61 associated wildlife species (Figure 12). Similarly, the lesser amount of large down wood in early forest successional stages may not provide as well for the 24 associated wildlife species. Such results suggest the continuing need for specific management guidelines to provide large standing and down dead wood in all successional stages.

Ecological Processes

Natural patterns of wood distribution and legacy retention are characterized by high variability through space and time. The lack of data on historical conditions of snag and down wood abundance, combined with highly altered disturbance regimes, limits conclusions that may be drawn regarding temporal changes in decaying wood across the region.[164, 178] The interpretation of inventory data will be improved in future years only as more detailed background information on stand conditions and disturbance histories becomes available. Until then, it may be more productive for managers to assess future trends in dead wood abundance and composition using new models that evaluate effects of specific management practices on wood habitat functions, such as DecAID.[223, 226] To assist with the assessment process, the following section examines evidence regarding impacts of past silvicultural practices on wood dynamics in the Pacific Northwest.

During the past century, management practices in the Douglas-fir region have favored even-aged stands, although there was some selective cutting prior to the 1950s (see reviews[94, 365]) Clear-cut harvesting on short rotations was the dominant silvicultural system, depending on site productivity, market preferences, and accessibility. To facilitate site preparation, reserved trees were usually absent and standing snags were felled and slash was burned. Management priorities emphasized a shift in stand composition from species mixtures to monocultures of the most valuable and fast-growing species, such as Douglas-fir. The economic rotation age varied from 40 years to over 100 years.[59] In addition to fire suppression, forest management east of the Cascade crest emphasized even-aged silviculture via clear-cutting, and uneven-aged silviculture using selective removal of overstory dominants.[59, 137] Piling and burning of slash was common in even-aged management regimes. These silvicultural practices clearly altered the abundance and recruitment of large down wood and snags in managed forests of the Pacific Northwest,[1, 2, 5, 59, 94, 112, 122, 130, 154, 198, 228, 230, 261, 262, 275, 276, 279, 302, 330, 344, 346, 357, 376] including:

1. Lower abundance of large diameter snags and down wood "legacies" in managed forests (and streams); e.g. lack of the U-shaped pattern; higher accumulation of smaller-diameter fuels in eastside forests.
2. Reduced recruitment and retention of large trees to provide future "legacies"
3. Shorter mean residence time for down wood (i.e. faster decomposition as a function of reduced log diameter).
4. Altered species composition of forests (westside: more Douglas-fir, less western red cedar; eastside: less pine, more true fir species).

Depletion of Large Wood. The loss of large wood structures has numerous potential impacts on ecological functions of forests, although available information is inadequate for a definitive assessment. The lack of large logs on steep slopes can decrease water percolation into soil, impair slope stability, accelerate soil erosion and sediment input to streams, and increase nutrient losses in litter.[164, 358, 359, 360, 361] Some data support a linkage between intensive management (especially depletion of decaying wood) and reduced forest biomass productivity, particularly on less productive sites. Lower productivity is attributed to nutrient losses from managed forests, reduced nutrient availability in older stands, and decreased nutrient storage, particularly in the soil.[272, 383, 384] Depletion of soil organic matter has been cited as a primary factor contributing to declining forest productivity and biodiversity in the Pacific Northwest and elsewhere.[17, 137, 198, 199, 228, 292, 293, 298, 299]

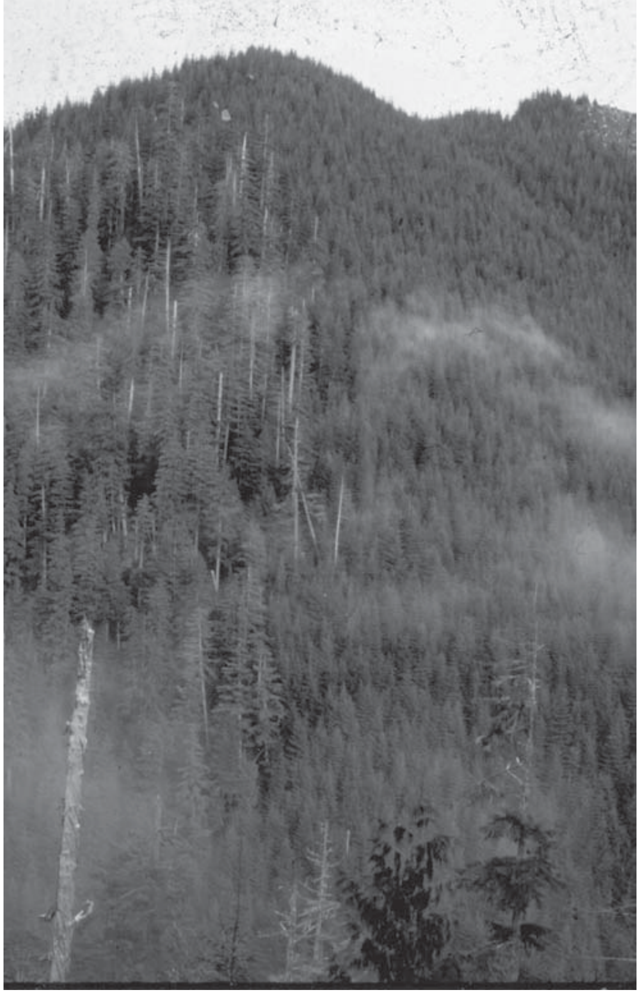

Figure 12. Management practices of the past have simplified forest structure. Note the lack of snags in this regenerating forest on the right side of this hillslope near Satsop, Washington. Photo: Deborah Lindley.

One study of a western hemlock stand in Oregon determined that after 150 years of intensive utilization and short rotations (Forcyte-10 model), reduced timber yields were linked to depleted soil organic matter and lower nutrient availability.[319] Such imbalances frequently reduce tree growth in early stages, and impair ecosystem resilience to disturbance in later stages.[9, 291, 292, 293] In contrast, Curtis et al.[94] review evidence that forest management does not degrade site productivity in moist temperate forests. Management effects on site productivity are likely to be highly variable, depending on site-specific attributes of climate, soil, and vegetation.

Small Wood Accumulation. In eastside forests subject to fire suppression, large accumulations of small wood fuels have been shown to improve site productivity due to increased soil organic matter and nutrient retention. These nutritional benefits to tree growth may be short-lived, however, as the forests are predisposed to high intensity fires that consume wood and accelerate nutrient losses.[137, 170]

Riparian Forests. Human alteration of riparian and aquatic ecosystems in the Pacific Northwest over the past century has proceeded with limited understanding of the ecosystems and the effects of human disturbances. The few studies that have examined streams as ecological systems (see review in Naiman et al.[262]) highlight the spatial and temporal complexity of riparian ecosystems, and the importance of connectivity to diverse ecosystem functioning. A balanced ecosystem is one in which biodiversity, productivity, biogeochemical cycles are in balance with the geological and climatic conditions of the region.[191, 192] The delivery of woody material to stream channels has been identified as a key process determining the ecological functioning of watersheds in the Pacific Northwest coastal ecoregion.[33, 40, 260, 262] This statement may be extended to most areas west of the Cascade crest in Oregon and Washington. Far-reaching effects of the absence of large wood structures in streams include: 1) simplification of channel morphology, 2) increased bank erosion, 3) increased sediment export and decreased nutrient retention, 4) loss of habitats associated with diversity in cover, hydrologic patterns, and sediment retention.[33, 144, 262] In coastal environments and estuaries, the loss of large wood may disrupt trophic webs and alter coastal sediment dynamics.[233]

Other Management Effects. In forests throughout the region, multiple stand entries and stump residues have spread diseases, particularly root pathogens. Root diseases initiate changes in stand composition, structure, and growth that alter nutrient and biomass dynamics of ecosystems.[137, 220, 237] Root diseases also predispose trees to windthrow. Injury to residual trees during partial cutting contributes to the spread of stem decays that influence input rates of dead wood and provide wood structures for wildlife habitat. Silvicultural practices that produce multi-layered stands of susceptible species may also affect ecosystem processes by favoring the spread of mistletoe. In general, it is important to recognize that stresses imposed by management have the potential to alter the abundance and dynamics of decaying wood by altering ecosystem energy and nutrient cycles, stand microclimates, and forest susceptibility to disturbance.

Lessons Learned During the Last Fifteen Years

What new developments have ensued since publication of Thomas[366] and Brown [48] in our applied knowledge of wildlife-wood decay relations? Much basic research has been conducted on terrestrial vertebrates associated with snags, although much remains to be learned of wildlife associated with the other forms of decaying wood. Major research initiatives such as the Demonstration of Ecosystem Management Options (DEMO) study by USDA Forest Service is helping to quantify relations of wildlife presence to down wood. Nothing can replace field zoology and ecology in providing such basic understanding of wildlife relations with decaying wood.

Several models have been introduced that help track the demography of snags,[60, 183, 221, 286, 306] and several other unpublished models provide further evidence. More recently, limited capabilities for handling snag dynamics have been incorporated into the Forest Service's Forest Vegetation Simulator (FVS) model. Some of these models track numbers of snags over time by dbh and decay class, and variously incorporate creation, decay, and fall rates of snags. The only available down wood dynamics model to date is the Coarse Wood Dynamics Model for the western Cascade Mountains of Oregon and Washington.[247]

No model, however, had been advanced to replace the "biological potential" models[263, 369] until the DecAID model was developed for this book[188] and USDA Forest Service (see next section). Several major lessons have been learned in the period 1979-1999 that have tested critical assumptions of these earlier management advisory models:

- Calculations of numbers of snags required by woodpeckers based on assessing their "biological potential" (that is, summing numbers of snags used per pair, accounting for unused snags, and extrapolating snag numbers based on population density) is a flawed technique. Empirical studies are suggesting that snag numbers in areas used and selected by some wildlife species are far higher than those calculated by this technique.[226]
- Setting a goal of 40% of habitat capability for primary excavators, mainly woodpeckers,[369] is likely to be insufficient for maintaining viable populations.
- Numbers and sizes (dbh) of snags used and selected by secondary cavity-nesters often exceed those of primary cavity excavators.
- Clumping of snags and down wood may be a natural pattern, and clumps may be selected by some species, so that providing only even distributions may be insufficient to meet all species needs.
- Other forms of decaying wood, including hollow trees, natural tree cavities, peeling bark, and dead parts of live trees, as well as fungi and mistletoe associated with wood decay, all provide resources for wildlife, and should be considered along with snags and down wood in management guidelines.
- The ecological roles played by wildlife associated with decaying wood extend well beyond those structures per se, and can be significant factors influencing community diversity and ecosystem processes.

We have also learned that managing forests with decay processes should be done as part of a broader management approach to stand development, with attention paid to retaining legacies of large trees and decaying wood from original or prior stands. Further lessons have been learned in the area of technical and operational developments; some of these are discussed below.

Habitat Assessment

Regional summaries of the current abundance of snags and down wood presented by Ohmann and Waddell[276] have several potential applications to forest management, planning, and policy. One use is in broad-scale assessments of wildlife habitat. Managers and planners can compare the inventory information on current dead wood resources to characteristics selected and used by wildlife and other organisms in developing management guidelines for federal lands, or in evaluating forest practice regulations or incentive programs for state and private lands. Such guidelines currently are based on very limited scientific data.

Comparisons of inventory estimates to those reported in most wildlife studies are complicated, however, by the fact that inventory estimates represent average conditions within a wildlife habitat type at the regional level rather than around nest sites (see earlier discussion), and few wildlife studies report both values (nest site and stand average) for comparison.[226] Furthermore, although the analysis of inventory data presents data on dead wood abundance, management actions at the local level may best be focused on the ecological processes that lead to development of these forest structures rather than on the abundance of structures themselves. Management decisions also may require information on the spatial distribution (landscape pattern) of dead wood, which cannot be estimated from sample-based inventories.

Information on regional patterns of dead wood is currently being incorporated into the DecAID model[248] depicting the range of natural conditions. This information is intended to help guide managers in considering dead wood and processes of decomposition in forest management. The regional inventory database contains information on occurrence of pathogens such as stem decays and root diseases that contribute dead wood. In addition, the data contain new information about the range of variability in dead wood—both historically and in the current landscape. The range of variability in dead wood abundance among plots in the region can help guide management decisions regarding the desired distribution of dead wood within a large landscape or watershed being managed, but not spatial variation within stands.

Caution must be exercised in using the regional plot data to describe the historical range of conditions in dead wood. The regional plot data sample only current conditions and lack data on site history, as discussed earlier. Even if plots in "natural" forest could be identified, current levels of dead wood have been altered to an unknown degree by fire suppression and other human influences. On the eastside in particular, current levels of dead wood may be elevated above historical conditions due to fire suppression and increased mortality, and may be depleted below historical levels in local areas burned by intense fire or subjected to repeated salvage and firewood cutting. Plot data from natural forests on the westside, where fire return intervals are longer,[5] may provide a reasonable approximation of historical conditions.

Template for a Stepwise Assessment Process

The following template presents a stepwise process for habitat assessment and management planning to achieve objectives for down wood and snags. These recommendations are based on existing knowledge of wood dynamics and decay processes in ecosystems, and insights developed by the inventory analysis of Ohmann and Waddell.[276] This process also can be applied in managing for other elements of forms of decaying wood or wood legacies.

Set Quantitative Objectives. To develop effective management plans for down wood and snags, it is imperative to evaluate: 1) land ownership and desired biodiversity, in terms of wildlife species to be supported, 2) specific land allocation, 3) site capability and history, and 4) management scale. Consideration of these factors assists in identifying a range of target values as guideposts for management activities.

Evaluate Current and Historical Status of Decaying Wood. Information on the current and historical status of dead wood is helpful in determining how the existing patterns in abundance, composition, and distribution of down wood and snags relate to objectives identified for the area of interest. If detailed data on the current and historical range of natural conditions is lacking (which is likely), it may be preferable to substitute functional target values for specific wildlife species. For example, to provide maximum habitat elements for specific cavity-nesting species, a designated quantity and distribution of snags of a given size and decay class may be the identified objective. The functional objectives should be determined to be within the productive capability of the ecosystem. Productive capability may be evaluated by examining information on primary productivity for the ecoregion and forest type (described earlier) and if available, data summaries on the historical range of natural conditions of dead wood status.

Wood status may include various descriptors of the amount (volume or weight), size class, decay class, and perhaps species of wood structures. Current inventory methods for quantifying the status of dead wood, including plot design and sampling techniques, have been reviewed.[56, 71, 164, 165, 276, 285] Field inventories should be conducted at the scale at which management guidelines are intended to be developed and implemented, such as among watersheds within basins.

Incorporate Wood Dynamics Into Planning. The extended residence time for dead wood legacies necessitates that snag and log dynamics models be incorporated into the process of long-term management planning. New and existing wood dynamics models are reviewed below. It is important to remember that such models typically operate at the stand level, whereas management guidelines for snags and down wood are directed at broader scales. Thus, model output should be averaged across stands within watersheds, or management guidelines should address stand- (meaning successional stage) specific conditions.

Monitor Management Effects on Wood Dynamics. Due to the general lack of information guiding management of decaying wood, wood dynamics and associated wildlife response is a priority topic for monitoring and adaptive ecosystem management.[149] Approaches for monitoring natural resources and for modifying management activities must be carefully planned and evaluated, with consideration of appropriate landscape scale.

How To Set Quantitative Objectives Using DecAID

How should the manager determine appropriate objectives for managing decaying wood? This chapter is not intended to prescribe standards for wood decay management. Instead, we offer the following set of questions that the land manager could use to develop overall objectives and specific guidelines for wood decay management.

What is the land ownership and overall expectation for biodiversity conservation? It may be socially acceptable to have different levels of expectation for conservation and maintenance of biological diversity, including decaying wood and associated wildlife, on different land ownerships and land use allocations. Land ownerships are subject to different sets of laws and regulations regarding biodiversity and habitat conservation. For example, commercial forestry landowners may be regulated by the appropriate state forest practices act, as well as any habitat conservation plans, but are not subject to the more stringent wildlife habitat regulations found in the National Forest Management Act that regulate national forests. Consequently, commercial tree farms and commercial forestry lands may call for conservation of decaying wood and associated wildlife at moderate statistical levels presented in the cumulative species curves of the DecAID advisory model, whereas some Federal lands such as national forests and national parks may strive for the high statistical levels.

What is the specific land use allocation? For a given land ownership, specific land use allocations may guide objectives for the abundance of decaying wood. For example, on commercial forestry lands, intensive timber-use zones on upland slopes may provide for lower levels of decaying wood than in riparian buffer zones, and on some Federal lands, old-forest conservation areas (such as Managed Late-Successional Reserves) may warrant even higher levels.

What is the site capable of producing overall and given its particular site history? For a given site, such as a particular forest stand, the manager may wish to determine what the site is capable of producing in terms of sizes and densities of decaying wood structures such as snags, hollow live trees, and down wood. Then, considering current stand conditions and recent site history, the manager can craft reasonable management direction to provide for appropriate levels of decaying wood as integrated into other site management activities such as tree pruning, precommercial thinning, final tree harvests, etc.

What is the appropriate spatial scale for managing decaying wood? The tools discussed in this chapter pertain to helping prescribe or predict effects of the abundance of decaying wood at the scale watersheds or larger, rather than for particular sites such as individual forest stands. However, this does not mean that attending to individual stands is unimportant. Studies suggest that wood habitat structures function best for wildlife when they are broadly distributed as well as occurring in locally-dense clumps, such as with scattered snag or down wood patches. The manager might use some of the concepts, suggestions, and tools in this chapter at stand levels but would need to validate them at broader geographic scales.

Even broader geographic areas such as subbasins might need to be evaluated when considering or projecting natural and human-caused disturbance regimes. Disturbances can radically change local conditions. Borrowing from landscape ecology, one rule of thumb that the manager might follow is to evaluate, as analysis units, a land area large enough to fully encompass the occurrence and full extent of the infrequent (e.g., 50-year) disturbance event such as a major wildfire or harvest schedule rotation period. Planning should be targeted for average levels of decaying wood across the analysis unit realizing that individual sites within the unit might be subject to greater uncertainty of specific conditions at various times.

The manager can use tools such as the DecAID model and matrixes on the CD-ROM to perform a risk analysis of the likelihood of providing for wildlife species and ecosystem functions associated with particular amounts and sizes of snags and down wood and other decaying wood, in specific wildlife habitats, over time, and at several statistical levels. Using such tools, the manager may consider alternative scenarios for retention, recruitment, and restoration of decaying wood for wildlife and ecosystem function. Uncertainty in wildlife response, expected levels of decaying wood on site, likelihoods of fire, insect, and disease conditions, and future disturbances, may factor into specific management guidelines, as well as into monitoring programs to help evaluate efficacy of the guidelines and objectives.

How To Evaluate The Current And Historical Status of Decaying Wood

To determine a quantitative objective for dead wood, it is necessary to evaluate the functional target for wood relative to the historic range of natural consditions and current status of dead wood in the area of interest. A new modeling tool named DecAID is available to assist with this task. DecAID (as in "decayed" or "decay aid") is a new Decayed Wood Advisory Model being developed to address some of the recent lessons learned.[226, 247] DecAID is based on a thorough review of literature, available research and inventory data, and expert judgement. It broadens the paradigm for wildlife species and habitat assessment by considering the key ecological functions of wildlife (see below) as well as the ecosystem context of wood decay in terms of secondary effects on forest productivity, fire, pest insects, and diseases.

DecAID has four components:

(1) Species-habitat associations, specifically, the use and selection by terrestrial wildlife species of snag dbh, snag density (number per unit area), down wood diameter, and down wood percent cover (percent of forest floor covered by down wood or wood litter). This information is based on a synthesis of empirical data, and interpretations made by the authors and experts.[226] DecAID presents cumulative species curves for combinations of wildlife habitats and habitat structures, showing the size and density of snags (or diameter and percent cover of down wood) corresponding with each species as reported in field studies. Where data permit, these curves are shown for low (30% tolerance interval), moderate (mean), and high (80% tolerance interval) statistical levels. Some studies pertain to snag (or down wood) densities averaged across study stands, whereas others pertain to locally high densities in snag (or down wood) clumps centered on nest/breeding, den/roost, or foraging sites.

(2) Key ecological functions of wildlife species associated with decaying wood, and full lists of wildlife species associated with decaying wood. This information is based on the species functions database of the matrices on the CD-ROM with additional information from the literature and other databases.[223, 224]

(3) Range of natural conditions. This information is an analysis of current and recent past inventory data on snags and fallen trees.[276] The inventory data are taken from several sources, including the Forest Inventory and Analysis of USDA Forest Service, Pacific Northwest Research Station; the Current Vegetation Survey of USDA Forest Service, National Forest System; and the Natural Resource Inventory of USDI Bureau of Land Management. Collectively, these inventory data cover all national forests and BLM lands, and all other non-reserved lands. Use of inventory data is limited for eastside, fire-dominated systems.

(4) Ecosystem processes and productivity. This information is based on a synthesis of publications and research identifying how wood decay provides for ecosystem productivity.

The manager will be able to use DecAID for advice on the following topics by first specifying wildlife habitat, structural stage, and statistical (confidence) level: 1) wildlife species associated with particular sizes and densities of snags and down wood, or, conversely, the sizes and densities required to meet specified wildlife management objectives, at three levels of confidence; 2) the array of key ecological functions of wildlife associated with decaying wood; 3) the recent-historic and current range of natural conditions of snags and fallen trees; 4) advice on fire risk assessment and mitigation; 5) advice on the roles of insects and diseases associated with various amounts of decaying wood; 6) and the influence of the abundance of decaying wood on ecosystem processes and productivity.

As an example of using Component 1 and 2 of DecAID, a manager might be interested in the role of snags in the Upland Aspen Forest wildlife habitat type. A query of the CD-ROM portion of DecAID reveals that 30 bird and 10 mammal species are coded as being associated with snags in this forest type. DecAID has compiled all available empirical data on aspen-related species, which totals 9 birds (8 primary and 1 secondary cavity-nester) for snag density data, and 23 bird (16 primary and 6 secondary cavity-nesters, the primaries including 4 sapsucker hybrids) and 1 mammal species for snag dbh data. For Upland Aspen Forest, the cumulative species curves suggest that providing for all nesting or breeding species as found in field studies entails locally dense clumps of snags averaging 32.4 snags per acre larger than 33 in (80 snags per ha) with at least some snags 20.3 in (52 cm) or greater in dbh.

If the manager had a known or expected condition different from this, the expected associated species could also be determined. An example is an Upland Aspen Forest stand with locally dense snag clumps averaging 20.3 snags per ac (60 snags per ha) of 15.7 in (40 cm) dbh. In this case, the snag density corresponds to providing for 6 of the 9 studied bird species, and the snag dbh corresponds to providing for all of the 21 species (100%) at low statistical levels, 14 species (67%) at average, and 6 species (35%) at high statistical levels; DecAID also lists the specific species in each case. The manager can use the information on statistical levels as a risk analysis and also as a means of setting objectives, where the high statistical level might correspond with highly conservatory objectives such as for Late-Successional Reserves.

DecAID also ties into the CD-ROM matrix on wildlife species and their key ecological functions. The 30 bird and 10 mammal species associated with snags in Upland Aspen Forest collectively perform some 60 categories of key ecological functions. These include primary consumers or herbivores (16 species), secondary consumers or primary carnivores (38 species), and tertiary consumers or secondary carnivores (3 species). Other ecological functions performed by this set of species include potential control of insect populations (10 species) or vertebrate populations (7 species); dispersal of fungi, lichens, insects and other invertebrates, seeds, fruits, or vascular plants (11 species); creating sapwells (2 species), creating nesting structures (4 species), excavating cavities (11 species), digging burrows (3 species), and creating terrestrial runways (2 species) potentially used by other species, some of which are also associated with snags in Upland Aspen Forest. Other ecological functions of snag-associated wildlife in Upland Aspen Forest are potential improvement of soil structure and aeration through digging and tunneling (2 species), physically fragmenting standing or down wood (2 species), creating snags (1 species), and potentially altering vegetation structure or succession through herbivory (1 species). Using the CD-ROM, the manager also can determine the specific ecological roles of just those species expected to be provided at given sizes and amounts of snags and down wood, and trade-offs with other functions. Overall, through such lists, DecAID provides the manager with insights into the array of ecological roles performed by wildlife species associated with decaying wood structures in specific wildlife habitats. The model also indicates how those functions might respond to changing attributes of decaying wood. Thus, the model offers an indication of how different management practices affect the relative "functionality" of ecosystems.

How To Incorporate Wood Dynamics Models Into Planning

Once an appropriate objective is determined with quantitative targets, the next step is to integrate wood dynamics into the planning process. This is a critical step because of the extended time frames required to replace large wood structures. Dynamics models predict the general rate of fall of snags and decay of snag and logs on a site to determine the amount of decaying wood occurring through time (e.g. a rotation). These models can also be used to estimate the number of green replacement trees to leave on a site and when to convert them to snags or logs. Mortality estimates from growth and yield models (Forest Vegetation Simulator, Organon, DFSIM, etc.) can be input into all the models reviewed here to track snag and log recruitment in forest stands. The following are three dynamics models available for Washington and Oregon.

Snag Recruitment Simulator (SRS)—Marcot. [221] SRS is based on the snag life-table approach.[263] The model was built to generalize snag decay and falling rates, and can be parameterized with any such rates. Data limitations, however, necessitated that the westside version of the model (i.e., Oregon and Washington west of the Cascades crest) predict fall and decay of Douglas-fir snags based on data from the Oregon Coast Range,[82] and the eastside version predict fall rates of ponderosa pine snags from the Blue Mountains of Oregon and decay rates from the Coast Range Douglas-fir data. SRS consists of a series of compiled Lotus spreadsheets and runs in DOS on a PC. It is the easiest of the three models to use. Several people have parameterized SRS for specific geographic areas. A similar model based on a Leslie Matrix was later published.[253]

Snag Dynamics Projection Model (SDPM)—McComb and Ohmann.[240] SDPM uses logistic regression analysis to predict the probability of a snag falling over a 10-year period. A straight rate is used for the probability of a snag changing from hard to soft over the same period. Forest Inventory and Analysis (FIA) remeasurement data from western Washington was used to develop the model. SDPM models Douglas-fir, western hemlock and western redcedar snags. SDPM incorporates site factors such as climate, slope, and aspect which affect snag fall and decay rates. The model is an executable DOS-based program written in C language.

Coarse Wood Dynamics Model (CWDM)—Mellen and Ager,[246] Mellen and Ager,[247] Mellen et al.[248] CWDM analyzes the dynamics of both snags and down logs in forests on the westside of the Cascade Mountains. The model assesses snag fall, height loss and decay, and log decay for Douglas-fir and western hemlock. Snag fall and height loss rates are from FIA remeasurement data from western Oregon and Washington. Decay rates are based on work in the western Oregon Cascades.[140] A single-exponential equation[164] was used to model the dynamics of snags and logs. CWDM is available in both DOS and Windows versions. An east-side version of CWDM will be developed as data on decay rates of snags and logs in eastern Washington and Oregon become available.

Management Tools and Opportunities

Silvicultural Methods

Traditional forestry practices in the Pacific Northwest[94] have been based on the simplification and homogenization of forests to achieve economical wood fiber production.[122, 228, 289] As a result, the amount of old-growth forests has declined over 50% in the last 60 years,[41] and remaining stands are highly fragmented.[347] Such practices have been at the center of intense controversy over the past three decades.[271, 272] Concerns center on the loss of biological "legacies" resulting from natural disturbances—surviving organisms and wood structures that contribute to resilient ecosystems with structural, compositional, and functional diversity.[291]

New management paradigms, originally coined "New Forestry,"[121] have shifted the emphasis from maximized fiber production over the short-term to diverse forest values and maintenance of long-term forest productivity (see also [201]). Alternative forest management systems are required to meet these new objectives, particularly the goal to produce and retain legacies of decaying wood.[122, 228, 292] Management goals for dead wood, thus, are inextricably embedded within the broader goals for diverse forest resources. To accomodate multiple objectives, Franklin[122] has suggested that new management should do the following:

1. Emphasize adding new silvicultural tools to the old.
2. Address stand and landscape-level objectives.
3. Maintain stands that are structurally and compositionally diverse (practices will differ from stand to stand, depending on forest type, condition, environment and specific objectives).

New silvicultural practices are a high priority in regenerating stands where one or more harvest cycles have simplified stand structure and composition and removed wood legacies. In young stands, Franklin[122] recommends that management should:

1. Aggressively create stands of mixed composition to maintain habitat for a broad array of species (and to achieve diversity in quality and timing of nutrient inputs to streams).
2. Delay the process of early canopy closure (wide spacings, pre-commercial thinning etc.).
3. Provide for adequate amounts and a continuous supply of large wood, including snags and down logs, for maintaining structural divesity in forests and streams and maintaining all other ecosystem processes associated with wood.

The basic theme of these revisions of intensive forestry practices is to retain the higher levels of complexity found in natural forests, and in so doing, to protect processes and structures that retain future options for ecosystem management. Effective management of decaying wood must do more than simply provide for inputs of dead trees. Rather, management should strive to provide for diversity of tree species and size classes, in various stages of decay and in different locations and orientations within the stand and landscape.[122, 233] Examples of new practices include retention of large woody structures at the time of harvest, long rotations, and creation of snags and logs from green trees. An overview of different silvicultural practices to regain (i.e. retain and create) wood legacies in managed stands is provided below. Detailed discussions of alternative silvicultural practices are available.[94, 132] Through the integrated application of silvicultural practices described below, it becomes possible to conserve biodiversity in managed forests by retaining legacy structures and accelerating the development of structural complexity.[61, 69a]

Structural Retention. Structural retention refers to any practice that retains significant structural elements from a harvested stand for incorporation into a new stand. The focus of this practice has been on harvesting in old and mature stands. Objectives in structural retention include maintenance of organisms and processes on harvested areas, structural enrichment of the regenerating forest, and enhanced connectivity across managed landscapes. To a limited degree, structural retention mimics the effects of variable disturbance patterns to create legacy structures. Retention of wood structures from a harvested stand for carryover into a new stand offers an infinite array of alternatives to clearcutting and other regeneration harvest systems.[132, 364] Variables in structural retention include the type, size, number of structures, and spatial distribution of the retention. Large, old, and decadent trees, standing dead trees (snags), and down wood are examples of structures selected for retention (Figure 13).

Retention of snags and large logs is a particularly effective practice in maintaining large wood when harvesting stands that already contain significant wood legacies—such as young and mature stands of natural origin and old-growth forests. Practices including the removal or burning of unmerchantable trees and down wood in forests and near stream channels should be minimized or eliminated. Retention of snags provides numerous habitat benefits.[154, 239, 402] However, safety and liability issues associated with snag retention have posed an operational barrier to management objectives for structural retention. Two approaches useful in reducing hazards associated with snags are: 1) to cluster snags in patches rather than wide dispersal, and 2) to create snags from green trees after cutting.[122]

Many questions remain regarding the most desirable density and spatial distribution of snags and down wood for wildlife.[94] New information suggests that snags and down wood may follow a naturally "clumped" distribution. Therefore, managers can take opportunistic advantage of site-specific occurrences of snags and down wood without having to match a particular spatial distribution pattern of clumps. This offers managers broad flexibility to provide varying local densities of snags and down wood across the ground, within and among stands. Managers must also consider the temporal dimension to decaying wood, to ensure that sufficient sufficient snag and down wood densities are provided through time. Franklin et al.[132] review information on the type, amount, and distribution of structural retention for various objectives. Additional examples of wildlife benefits from structural retention have been described.[20, 21, 63, 64, 69, 152, 154, 210, 314, 326]

Live (Green) Tree Retention. Retention of living trees on cutover areas is one form of structural retention that can provide for future recruitment of snags and down wood (created artificially or through natural processes).[122] Other terms commonly used for this method include partial cutting or partial retention to distinguish it from selection cutting. Green tree retention involves reserving a significant percentage (10-40%) of living trees, including dominants through the next rotation. The density, composition, condition, size classes, and spatial distribution of the retained trees varies according to management objectives, stand and site conditions, and other constraints. The objective is to maintain a more structurally diverse stand than could be achieved through even-aged management.

Green trees function as a refugium of biodiversity in forests. For example, many species of invertebrate fauna in soil, stem, and canopy habitats of old-growth forests do not disperse well, and thus, do not readily recolonize clear-cut areas.[207, 326] The same concept holds for many mycorrhizae-forming fungal species.[293] Added benefits of green tree retention include moderated microclimates of the cutover area, which may increase seedling survival, reduce additional losses of biodiversity on stressed sites,[293] and facilitate movement of organisms through cutover patches of the landscape. Green trees retained across harvest cycles can also be used to grow very large trees for either ecologic or economic goals**.** This may be an especially valuable practice in providing large wood to riparian forests subject to harvest: green tree retention can be implemented to favor species such as Douglas-fir and redcedar that produce larger and more persistent wood. Other benefits of green tree retention include reduced hazards of landslides via maintenance of root strength and reduced potential for rain-on-snow flood events.

Green tree retention offers many benefits to wildlife. For example, the higher structural diversity in young stands that contain legacy trees from previous stands provides much improved habitat values to late successional species such as the northern spotted owl, as well as other vertebrates that use late-successional stands for some elements of their life history.[69, 122, 314] Such stands may provide wildlife habitat as early as age 70-80 years rather than 200-300 years, the approximate time interval required for old-growth conditions to develop after secondary succession. Green tree retention on a harvest cycle of 120 years has been proposed as a method to provide habitat for late successinal species in only 40-50 years.[278] Different scenarios for green tree retention have been offered.[122, 278] To meet needs of all species likely to occur in area, it is critical to identify tree species for retention. Updates on wildlife and vegetation response to

Figure 13. Retention of old-growth "legacy" snags in a commercial thinning unit in western Washington. Photo: Deborah Lindley.

green tree retention are recently available for the DEMO program in Oregon and Washington, and other silvicultural trials.[20, 30, 152, 155, 156, 210, 268, 311, 406]

Variable Retention Harvest Systems. Franklin et al.[132] recommended the term "variable retention harvest systems" to refer to harvesting practices that allow a continuous spectrum of removal and retention in mature and older stands, depending on objectives. The development and maintenance of structurally complex managed forests is the primary rationale for retaining structural elements of the harvested stand. Retention of various decaying wood structures through variable retention harvest provide many benefits to many wildlife species and functions,[20, 26, 64, 70, 73, 156, 326] as well as other forest resource commodities.[12]

More recently, there has been increasing interest in aggregated or "patch" retention—the maintenance of small forest patches, instead of dispersion of retained structures.[64] These patches can provide refugia, while also providing microclimatic gradients for more sensitive species and functions.[151] By providing for the maintenance of refugia, tree and patch retention may benefit species limited by slow dispersal rates, rather than by particular habitat structures.[13, 239, 343] Franklin et al.[132] review major issues in developing harvest prescriptions based on the variable retention harvest concept, including the type, amount, and distribution of structural retention for various objectives. Franklin[122] described several alternative management approaches for maintaining wood production and complex forest structure suggested by fire history research. In a multi-aged management strategy, selective cutting practices can be used to sustain complex stand structure and composition for long periods. It may be beneficial that the management system mimic the natural disturbance regime to the extent possible, so that the site can accomodate future natural disturbances as they interact with managed stands.

Long Rotations. Long rotations involve the use of rotation ages that are significantly longer than that defined by the culmination of mean annual increment.[91, 92, 93, 94] Long rotations provide for the recruitment of larger and more complex wood structures by allowing tree to grow to a larger size and by eliminating logging disturbances that damage or remove wood legacies. When coupled with a series of silvicultural treatments, long rotations can produce complex managed forests, increase commodity yields, and address cumulative issues where too much of the landscape is in a recently-harvested condition. Long rotations also may be applied to patches of trees at a scale smaller than individual stands. As an added benefit, extended rotations can reduce the need for permanent transportation systems.[196]

Long rotations may not provide adequate protection for all structural elements, processes, and organisms, particularly those most sensitive to disturbance, or with more rapid turnover rates. For example, large-diameter, moderately-decayed snags removed at the time of harvesting (via clearcutting) may not be replaced within the rotation cycle. Rather, retention of snags at harvest, combined with long rotations would be necessary to provide for present and future recruitment of such snags. Long rotations are unlikely to provide forests with structural, functional, and compositional features comparable to late-successional reserves.[12, 132, 156]

Thinning. Thinning in plantations can be used to decrease the time required to develop larger trees and multiple-canopy forests for species associated with late-successional forests, while producing ecomonic benefits from thinnings and shorter rotations.[94, 364] It may not produce desired amounts of down wood or heavy-limbed tree crowns. However, benefits of accelerating the rate of stand development must be weighed against the detrimental effects of logging disturbances on species, particularly those with limited dispersal capabilities.[343] Variable density thinning is a variant of the traditional unifrom spacing that shows promise for accelerating structural and compositional diversity.[66] In general, thinning is beneficial to the development of more structural diversity in young stands, and to a variety of wildlife species, particularly in more complex and patchy stand structures, with legacy structures.[26, 70, 73, 150, 155]

Restoration Techniques

Restoration with respect to decaying wood involves silvicultural manipulations to develop and create wood legacies in stands lacking suitable existing structures. In addition to retention of existing snags and down wood at the time of harvest, and young stand management to favor structural complexity (retain green trees), intentional methods have been developed and tested to create snags, down wood, cavities and other habitat niches.[96, 132] Techniques include girdling, injection with herbicide, topping, explosives, fungal innoculation, and use of pheromones to attract beetles.[25, 54, 57, 84, 212, 284] Various techniques for creating artifical cavities have been tested, including creation of cavities by den routing,[63, 65] or by cutting a hole with a chainsaw and covering with a faceplate.[62]

Many of these techniques have produced favorable habitat for wildlife. However, characteristics of artificially created snags may not always be comparable to natural snags. Additional research and monitoring is needed to better evaluate the attributes and habitat uses of snags and down wood created by artificial methods. Costs for creating artificial snags and down wood are important management considerations, thus it is desirable to retain existing legacy structures, as well as trees for future snag recruitment. In addition, it may be both biologically and operationally beneficial to create and preserve snags within patches of uncut trees, rather than to distribute them uniformly across stands.

Few long-term data are available to assess the effectiveness of different methods of snag creation. Results of a recent study[328] monitoring natural and artificially created snags on the Siuslaw National Forest in the Oregon Coast Range provide useful guidance to managers. The study tracked longevity and wildife use in 150 green leave trees, 91 natural (Class 1) snags, 27 intentionally-topped Douglas-fir trees, and 23 hardwood leave trees (big-leaf maple and alder) and snags in variable retention harvest units from 1987 to 1998 (Figure 14).

The study identified several interesting facts about topped leave trees and residual snags:

1. Topped leave trees (blasted or cut) are far more windfirm than natural snags or green leave trees (Figures 15, 16). Greater windfirmness of topped trees (0.7% rate of windthrow) compared to natural snags (11%) or green leave trees (17%) is attributed to both lower rates of root failure and stem breakage. Windthrow of green leave trees can be substantial, particularly in wind-prone areas. Numerous cavities and other defects in the lower bole indicate that bole breakage could increase in the future. Thus, long-term cavity habitat requires periodic topping, rather than a single entry, especially for small-diameter trees that decay more rapidly.
2. Live leave trees experience high rates of windthrow and breakage due to increased exposure in clearcuts. Thus, live green trees may not provide for snag recruitment for an extended period post-harvest.
3. Degradation and loss of natural snags is high due to root throw, but more significantly to bole breakage. Breakage is most frequent near cavities, areas of advanced decay, and structural deformities. The longevity of Class 1 snags is limited. Continued recruitment of new snags requires snags to be created periodically from green trees during the course of stand development.
4. Trees topped above two branch whorls survive and develop new tops. Continued diameter growth in these trees provide higher values as wildlife snags. Large crooks formed in these trees also provide platform nest sites and create future breaking points to form a tall snag. The greater longevity of these live-topped trees should reduce the need to cause intentional mortality in leave trees in the future.
5. Methods for topping trees by either blasting or chainsawing produce similar results for both snags and live-topped trees. Blasting provides a more natural look, but the chainsaw method allows for directional felling if the salvage of tops is planned.
6. Natural and created snags show high levels of use by cavity-nesting birds. Topped trees rapidly develop cavities throughout the bole. Live-topped trees develop cavities ten years after topping, with cavities forming first near the upper bole. The creation of live trees with cavity habitat is highly desirable, as it allows cavity habitat to be maintained over longer periods.
7. Big-leaf maple has relatively high survival and provides a high density of cavity sites. The rapid diameter growth of big-leaf maple allows a tree size suitable for cavity production to be developed within thirty years.

Figure 14. Stand treated to restore wildlife snags. Treatments included topping with and without retention of live branch whorls. Photo: Barry Schreiber.

Topped trees present fewer conflicts with harvest and silvicultural activities than snags, and if trees are topped prior to harvest, some of the tops may be salvaged to offset the cost of topping. In planning for the desired density of leave trees, managers need to consider the vulnerability of green leave trees to wind and fire, and degree of competition to living topped trees by the regenerating forest. Thinning may be desirable to extend the lifespan of green trees or live-topped trees. Tree defects will affect the quality and longevity of leave trees as snag habitat. For example, bole crooks are weak points that can determine where stem breakage will occur, hence this feature can be selected to provide future snag habitat of desired height. Trees with butt rot, hollow stems, large bole sweeps, forks at the lower bole, or leaning trees are less suitable for retention, as they are less stable, and succumb more rapidly to wind and gravity. Live-topping of green trees has been found to have great potential to provide long-term cavity habitat in managed stands. This possibility should be more thoroughly investigated.[328] Additional considerations for active management of decaying wood are available in a recent review.[69a]

Management of Wood in Streams. In riparian areas, the development and maintenance of large trees is required to provide inputs of large wood to streams and rivers[33, 143] The forest adjacent to channels is particularly critical in small streams, since wood inputs from other sources may be negligible.[241] Natural stable wood in streams should be undisturbed[376] and supplementary wood recruited through management of riparian forests to the maximum extent possible. The delivery and routing of wood to streams is important to the vitality of watersheds and their component drainages in the Pacific Northwest.[262] Integrity of the lateral, longitudinal and vertical components, as well as the temporal and spatial characteristics of wood cycling within basins must be maintained. Thus, managers must pay attention to geomorphic considerations and connectivity between parts of the larger system when planning for inputs of large wood in riparian areas.

Figure 15. Snag created by blasting. Photo: Barry Schreiber.

Figure 16. Snag created by topping with a saw. Photo: Barry Schreiber.

Aquatic functions dependent upon connectivity include: 1) requirements for habitat access during discrete life history stages of fish and wildlife,[304, 321] 2) synchronization of emergence and migration of aquatic organisms to stream temperature,[303, 362] 3) regulation of nutrient and material exchanges between forests and streams,[295, 361] 4) and maintenance of hydraulic regimes within boundaries of evolutionary adaptation for specific organisms.[350] For example, in coastal Oregon, debris flows from tributaries provide most of the large wood inputs.[39] However, in southeastern Alaska, floodplain forests adjacent to the stream are the primary source of wood to the stream system.[233]

New silvicultural methods being developed and tested in riparian forests[143] include re-establishing conifer species, retaining snags, down logs, and green trees, and avoiding salvage. Underburning may be used to re-establish conifers, if necessary, to reduce competition with understory shrubs. Thinning and underplanting may also be used to create snags and provide large wood. In heavily degraded riparian areas, forest complexity can be improved by retaining large, and broken trees in the adjacent harvest unit. Where harvesting is allowed, group selection or single tree selection is preferred to clear-cutting.[3] Thinning should strive to leave trees dispersed in irregular patches.

Summary of Management Recommendations

The information presented in this chapter emphasizes several properties of decaying wood in forest ecosystems: (1) each structure formed by decaying wood helps support a different functional web in the ecosystem; (2) no one decaying wood structure supports all functions equally; and (3) all decaying wood habitats together support the widest array of ecological functions and associated wildlife species. The CD-ROM with this book in combination with the DecAid model provides managers with a powerful tool that makes it possible to assess the degree of "full functionality" of ecosystems as supported by the various decaying wood structures, and which functions are strengthened, diminished, or lost through alternative silvicultural management practices.

Lessons for managers are:

1. Examine forestry practices for how they influence the distribution and abundance of down wood and snags in relation to forest landscape patterns. In situations where forest management objectives extend beyond wood production to broader biological and human values, intensive forestry practices by themselves may inadequately maintain or restore biodiversity, especially in early and late successional forest development phases. Species, processes, and values associated with older stages of stand development (transition and and shifting gap stages)[277] are likely impaired or absent from intensively managed stands.[343] Species and processes associated with the early establishment phase also have shorter duration than may occur naturally. This does not mean that intensive forest management practices are incompatible with multiple forest objectives at a landscape scale, but rather that species and processes associated with early and late stages of forest development should be assessed over large areas such as landscapes, subregions, and regions.[291, 343] Management for certain species must consider habitat requirements at different spatial and temporal scales.[181] It may then be possible to modify silvicultural practices at the stand scale to meet multiple objectives at landscape and larger scales. The landscape perspective also is pertinent to managing riparian systems,[143] where the role of wood decay in riparian environments varies according to the type and geography of the associated water body.

2. Emphasize retention of wood legacies, and secondarily promote restoration where legacies are deficient to meet stated objectives. The decline of species associated with late-successional forest structures, as well as the prolonged time needed to produce wood legacies, suggests that it is both ecologically and economically advantageous to retain legacy structures across harvest cycles wherever possible, rather than attempt to restore structures that have been depleted. This is especially obvious for slow-growing tree species and very large wood structures. Retention of old-growth structural legacies has been identified as critical to conservation of biodiversity between large reserves and conservation areas.[222, 267]

3. Use an adaptive management approach to assess management options where possible. Our ability to sustain forest ecosystem values while producing commodities is uncertain. Given the imperfect state of our knowledge regarding management effects on biodiversity and long-term productivity of forests, prudence calls for an adaptive management approach that spreads environmental risk across a range of management strategies. Management must seek a blend of practices to meet biological and social objectives.[343] Guidance on approaches to adaptive management is available in several publications.[45, 110, 157, 338, 391]

4. Address management objectives and data needs to protect functions of dead wood in basic processes of forest ecosystems, not solely to fish and wildlife habitat. At the forest policy level, broad-scale assessments of down wood are needed to address Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests, developed through the Montreal Process. Although dead wood was not considered in the first national-level assessment, dead wood abundance will be addressed in the first assessment of forest sustainability to be conducted by any state in the U.S., by the Oregon Department of Forestry.[36]

Operational Considerations

Management for decaying wood will require new and innovative operational approaches. Structural retention and restoration pose many new challenges to forest operations, both in current and future harvest activities. To be successful, any plan for provision of wood decay elements should address operational aspects of implementation. This includes scoping operational approaches for plan implementation, and identifying strategies for resolving potential conflicts ahead of time. Two common sources of operational difficulties include safety concerns and associated administrative costs.

Worker safety

From 1980-1989, the average annual fatality rate for workers in the logging industry was more than 23 times that for all U.S. workers. More than half of these fatalities occurred when workers were struck by falling or flying objects or were caught in or between objects; most of these fatalities involved trees, logs, snags or limbs.[264a] An analysis of claims data from 1990-1997, ranked workers in the logging industry as having the highest risk of traumatic head and brain injuries in Washington state.[401b]

In recognition of the need for tree retention in harvests, OSHA revised the federal Logging Standard (29 CFR 1910.266) in 1995, to clarify its intent that danger trees may be avoided, rather than being removed or felled.[72a] A danger tree is any standing tree (live or dead) that poses a hazard to workers, from unstable conditions such as deterioration, damage, or lean. The revised rule allows some discretion in determining the hazard area around a danger tree, by "...allowing work to commence within two tree lengths of a marked danger tree, provided that the employer demonstrates that a shorter distance will not create a hazard for an employee."(OSHA Logging Preamble, Section V). Determining a safe working distance requires a case-by-case "...evaluation of various factors such as, but not limited to, the size of the danger tree, how secure it is, its condition, the slope of the work area, and the presence of other employees in the area." The employer is responsible for marking hazard trees and making this determination. Washington State guidelines for reserve tree selection provide definitions of hazard areas and examples of operational techniques that are compatible with safe work practices.[401a]

Oregon (Chapter 437, Oregon Administrative Rules) and Washington (Chapter 296-54, Washington Administrative Code) state safety regulations require employers to have a site-specific safety plan before logging activities begin. The operator can include strategies for safe retention of reserve trees in the safety plan. A safety consultation program, completely separate from OSHA's inspection program, is available through state safety agencies. The operator may request free, confidential, on-site assistance with safety planning, without risk of citations or penalties. State safety plan requirements and OSHA consultation services are two key mechanisms to resolve operational safety issues associated with structural retention and restoration. Reserve tree requirements are best implemented through descriptive criteria in contract or application conditions, rather than marking individual trees and snags. Because the employer is responsible for identifying hazards and preventing worker exposure, pre-marked trees could reduce the operator's flexibility to deal with unforeseen hazards which arise in the course of logging activities. If a tree marked by a timber sale administrator or forest practices officer turned out to be a danger tree, confusion over safety compliance authority also might result.

Potential safety conflicts can be addressed in advance by requiring a pre-work conference with the operator and a state safety consultant to review the operator's site-specific strategies for meeting reserve tree objectives in compliance with safety regulations. At this time, the types, locations, and distributions of leave trees can be specified, considering the logging system to be used, and site-specific topography, unit layout and decay conditions. Once landings and tail holds are identified, reserve trees may be mapped; as an example, clumps of reserve trees may be left between cable roads. For the variety of situations that may be encountered during operations, it is important to devise alternative strategies. This is a good way for managers to improve operational knowledge and expedite administrative compliance time.

Concerns frequently arise where high public use creates a risk of third party liability. Considerations include the proximity of reserve trees to roads, trails, campgrounds, ski areas, and other recreation areas and public access points. Methods for addressing these concerns include signage and clear delineation of potential hazard areas, fencing and other barriers to discourage public access, snag height reduction and use of setbacks to minimize exposure.

Costs and Forest Management Complexity

Legacy retention generally results in higher logging costs than clearcutting and may require alternative logging technology. Compared to clearcutting, logging costs have been estimated to be significantly greater for dispersed retention, but only slightly higher for aggregated retention.[201,406a] Aggregated retention has also been recommended to minimize interference with aerial application of pesticides, fertilizers, and herbicides.[201] Other concern regarding tree retention are effects on stocking density and genetic composition of the regenerating forest. Compared to live trees, the retention of snags, decadent trees, and down wood within a harvest unit have little influence on future stand genetics or stocking density. Retention of live trees and decaying wood may reduce wood yields due to volume in wood structures permanently retained on a site, or reduced growth in the regenerating stand due to shading.[1b, 311, 311a,401c, 406] Conversely, decaying wood may increase future wood yields by improving seedling survival and growth, and site productivity.[164]

Long Range Planning Considerations

Long-range plans should provide criteria for tree selection and distribution that are flexible enough to account for ongoing tree decay processes, and changes in harvest plans. For instance, a time lag between unit layout and harvest may result in changes in reserve tree decay classes. It is also important to consider how reserve trees will fit into plans for other forest practices after harvest, such as thinning operations, fertilization, vegetation management, and fire control. This is particularly important in uneven-age management schemes where multiple entries are planned. When developing conceptual long range plans and site-specific plans, it is thus important to consider whether a hazard would exist by the time future activities take place.

New Approaches

Few studies have analyzed operational challenges to managing for decaying wood. However, a variety of forest managers are currently testing various methods to retain and restore decaying wood in various forms as snags, decadent trees, and down wood. Recent publications offer useful discussions of concepts and silvicultural approaches to managing for structurally complex forest stands, including operational considerations; they also discuss recent lessons from experimental forestry operations.[31a, 69a, 201, 288a, 328, 406a]

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