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Coarse Woody Debris: Managing Benefits and Fire Hazard in the Recovering Forest

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Abstract

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Management of coarse woody debris following fire requires consideration of its positive and negative values. The ecological benefits of coarse woody debris and fire hazard considerations are summarized. This paper presents recommendations for desired ranges of coarse woody debris. Example simulations illustrate changes in debris over time and with varying management.

Keywords: fuel, salvage, snags, reburn, Fire and Fuels Extension to the Forest Vegetation Simulator

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Coarse Woody Debris: Managing Benefits and Fire Hazard in the Recovering Forest

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The Management Concern

Large fires in the Inland West during the past decade and efforts to conduct salvage logging have intensified public debate on what is the proper harvest of dead trees. Harvesting fire-killed trees as soon as possible following fire is often called salvage. The objectives of salvage can be to provide economic value, improve forest health by thinning, and reduce fire hazard by removing fuel (Gorte 1996; SAF 1995). In this report, harvesting and salvage refer to cutting of trees for their product value and for reducing fire hazard. Positive values of salvage harvest are generally perceived as economic benefits from jobs and forest products, site rehabilitation, fuel hazard reduction, and lessening the buildup of insect pests. Negative values include lost recreational opportunities, damaged soils through erosion and reduced nutrient processes, reduced wildlife habitat, and spread of weeds (McIver and Starr 2001). A quandary faced by managers is deciding where and how to manage fire-killed trees in the new developing forest. Their decisions about taking action come down to two questions: Where on the landscape should cutting and fuel treatment be undertaken, and how much of what sized material should be removed?

An important goal in dealing with these concerns is to manage toward quantities of accumulated downed woody material such that the risk of damage from a reburn is acceptable and benefits derived from coarse woody debris (CWD) can be realized. Considerable uncertainty exists over the effects of a possible reburn on soil productivity and vegetation succession. Although repeated fires have occurred as long as vegetation covered the landscape (Pyne 1982), the term "reburn" has specific meaning. Reburn results when falldown of the old burned forest contributes significantly to the fire behavior and fire effects of the next fire.

The purposes of this report are (1) to identify a range of CWD quantities that provides for positive values and avoids excessive fire hazard, and (2) to illustrate how simulation of the effects of various management alternatives on CWD over long periods can assist in planning. We examined the knowledge of the ecology of CWD, its contribution to potential fire behavior, historical stand structures and large fuel accumulations, and potential reburn severity as a basis for identifying optimum quantities of CWD. The fires of 2000 on the Bitterroot National Forest served as a case study to illustrate the way in which simulation modeling can be used in conjunction with these general concepts to aid in planning. Example simulations use data from the Bitterroot Forest. The general discussion of coarse woody debris is meant to be broadly applicable and not limited to a particular forest.

A note on terminology: low soil heating severity or burn severity as reported in the Bitterroot Post Fire Assessment (Bitterroot National Forest 2000) and as used in this paper is typical of understory and mixed fire regime types. Moderate severity is typical of mixed and stand-replacement fire regime types, and high severity is typical of the stand-replacement fire regime type. Fire regime type refers to historical effects of fire (Brown 2000).

- Understory fire regime—fires are generally nonlethal to the overstory (approximately 80 percent or more of the dominant vegetation survives).
- Stand-replacement fire regime—fires are lethal to most aboveground dominant vegetation (approximately 80 percent or more of the dominant vegetation is killed).
- Mixed severity fire regime—fire severity varies between understory and stand-replacement regimes.

Ecology of Coarse Woody Debris

Coarse woody debris is typically defined as dead standing and downed pieces larger than 3 inches in diameter (Harmon and others 1986), which corresponds to the size class that defines large woody fuel. Some ecologists include woody material larger than 1 inch in diameter as CWD. Coarse woody debris is an important component in the structure and functioning of ecosystems. A dead tree, from the time it dies until it is fully decomposed, contributes to many ecological processes as a standing snag and fallen woody material lying on and in the soil. Fire, insects, pathogens, and weather are responsible for the decomposition of dead organic matter and the recycling of nutrients (Olson 1963; Stoszek 1988). Fire directly recycles the carbon of living and dead vegetation. The relative importance of fire and biological decomposition depends on site and climate (Harvey 1994). In cold or dry environments, biological decay is limited, which allows accumulation of plant debris. Fire plays a major role in recycling organic matter in these environments. Without fire in these ecosystems, nutrients are tied up in dead woody material for a long period. Fire, insects, and diseases perform similar roles in that they both create and consume CWD and smaller dead woody material.

Importance to Wildlife

Coarse woody debris plays many roles in the forest. Animal life processes, site productivity, site protection, and fire are probably the ones that managers most often deliberate. Coarse woody debris contributes to biodiversity by being part of the life cycle of soil mites, insects, reptiles, amphibians, mammals, and birds (Brown 2000). Invertebrates such as bark beetles, wood borers, carpenter ants, and wasps utilize CWD for food and protection. Mammals, reptiles, and amphibians mostly utilize downed logs for purposes such as feeding, reproduction, and shelter (Harmon and others 1986). As more downed CWD accumulates in the forest, activity of small mammals such as voles increases (Ucitel 1999). A 15 to 20 percent coverage of downed CWD was recommended by Carey and Johnson (1995) for favoring small animal communities. A 15 percent coverage of CWD is equivalent to 32 tons per acre of 6-inch diameter pieces or 64 tons per acre of 12-inch pieces, assuming wood densities typical of ponderosa pine and lodgepole pine.

Woody debris incorporated in streams creates habitat diversity that improves rearing habitat for anadromous fish (Everest and Harr 1982) and provides survival cover. Woody debris also provides a source of nutrients for aquatic life that increases abundance of macroinvertebrates (Smock and others 1989). However, excessive accumulations can block fish passage, cover important spawning sites, and damage aquatic habitat during postfire flood events (Gresswell 1999). Desirable quantities of CWD to leave following salvage logging for recruitment into streams to benefit aquatic life are only generally known. However, the origin of CWD that eventually becomes incorporated in streams is known. In small streams in Washington and Oregon, McDade and others (1990) found that 70 percent of debris pieces were rooted within 60 ft of the streambank, and 50 percent came within a 30-ft wide strip on each side of the stream. In Alaska, Murphy and Koski (1989) observed that 95 percent of the CWD came from within 60 ft of the stream. They also observed that the larger the stream, the larger the CWD needed to form a stable accumulation. These studies suggest that leaving an uncut strip 60 to 100 ft from each streambank would maintain CWD in aquatic habitat.

A range of desirable snag densities depending on bird species has been suggested for forests in the Northern Rocky Mountains. About 25 percent of the bird species in the Northern Rocky Mountains are cavity nesters (Bull and others 1997). Cavity nesting birds and bats mostly utilize standing snags especially those of large diameters (Fischer and McClelland 1983). Smaller snags can be important for foraging. Salvage logging can enhance habitat for some species but diminish it for others, resulting in a shift in diversity but not in richness (McIver and Starr 2001). For Pileated Woodpeckers (*Dryocopus pileatus*), Bull and Holthausen (1993) showed that viable populations were maintained with an average of four snags per acre (10-inch and greater diameter at breast height, d.b.h.). Following high intensity wildfire Saab and Dudley (1998) found that the Lewis' Woodpecker (*Melanerpes lewis*) and Kestrel (*Falco sparverius*) preferred salvage logged areas that retained about 25 snags per acre (more than 9-inch d.b.h.). The Black-backed Woodpecker (*Picoides arcticus*) and Northern Flicker (*Colaptes auratus*) preferred the unlogged areas having about 50 snags per acre (more than 9-inch d.b.h.). Bull (1994) suggested leaving 40 standing or fallen snags per acre (preferably more than 15-inch d.b.h.) to retain as much wildlife as possible in stands to be salvage logged following fire. The CWD loadings represented by these snag densities range from about 1 to 25 tons per acre depending on diameter of trees (table 1, 2).

Although an abundant literature shows the importance of standing and downed CWD to wildlife, few studies have quantified amounts needed to maintain specific populations much less whole faunal communities. One difficulty in interpreting and applying research results is that many studies deal with populations on specific sites and report conditions that enhance or maximize populations on those sites. Maintenance of metapopulations and a diversity of species, however, requires a landscape perspective and a strategy that provides a diversity of habitat structures (Hutto 1995; Lyon and others 2000; Tobalske and others 1991).

Importance to Soils

Maintaining soil productivity over the long term generally requires presence of soil organic material and fire effects characteristic of the natural fire regime. Most fires characteristic of the historic fire regime or moderate severity prescribed fires are likely

Table 1—Loading of standing dead ponderosa pine coarse woody debris (tons per acre) by number of snags per acre and d.b.h. (inches). Loadings computed from table 2.

	d.b.h.							
Number	**6**	**8**	**10**	**12**	**14**	**16**	**20**	**24**
4	0.2	0.4	0.8	1.3	2.0	2.9	5.3	8.6
6	.3	.6	1.2	2.0	3.1	4.4	8.0	12
8	.4	.9	1.6	2.7	4.1	5.9	11	17
10	.5	1.1	2.0	3.3	5.1	7.4	13	22
15	.7	1.6	2.9	5.0	7.7	11	20	32
20	1.0	2.1	3.9	6.6	10	15	27	43
25	1.2	2.7	4.9	8.3	13	18	33	54
30	1.4	3.2	5.9	10	15	22	40	64
40	1.9	4.3	7.8	13	20	29	53	86
50	2.4	5.4	9.8	17	26	37	67	
100	4.8	11	20	33	51	74		
200	9.6	21	39	66	102			
300	14	32	58	100				
400	19	43	78					
500	24	54	98					

Table 2—Total tree bole weight (tons) of wood and bark of individual trees based on whole tree volume equations[a], wood density, and bark-to-wood ratios for ponderosa pine (PP), Douglas-fir (DF), and lodgepole pine (LP)[b]. Data based on trees from stands of a variety of site indexes and densities.

d.b.h.	**PP**	**DF**	**LP**
4	0.017	0.021	0.026
5	.029	.037	.051
6	.048	.060	.081
7	.074	.088	.118
8	.107	.123	.162
9	.147	.166	.215
10	.196	.218	.275
11	.258	.274	.343
12	.332	.341	.420
13	.416	.416	.504
14	.511	.501	.597
15	.617	.595	.698
16	.736	.699	.807
18	1.009	.938	1.051
20	1.334	1.220	1.328
22	1.714	1.546	
24	2.151	1.921	
26	2.648	2.344	
28	3.208	2.819	
30	3.832	3.346	

[a] Equations for 4-inch d.b.h. from Faurot (1977) and for 5- to 30-inch d.b.h. from Brown and Johnston (1976) and Stage (1973).

[b] Wood density and bark ratios from Brown and others (1977).

to enhance soil development and fertility over the long term by periodic release of nutrients. However, extremely severe fires or large severely burned areas within fires, brought on by either rare natural events or humans, are likely to be highly detrimental to forest soils (Harvey and others1989).

Nitrogen is the most limiting nutrient in forest ecosystems. Its quantity and form in the soil is almost totally dependent on microbial action by way of two distinct processes, symbiotic and nonsymbiotic N fixation. Except where N-fixing plants such as alder (*Alnus* spp.) and ceanothus (*Ceanothus* spp.) are in good supply, most N acquisition in forests comes from nonsymbiotic fixation that depends on organic matter for energy (Harvey and others 1989). Another group of microorganisms that depend on soil organic matter and is important to a conifer's ability to acquire nutrients such as N is the ectomycorrhizal fungi associated with roots. Using ectomycorrhizae as a bioindicator of healthy, productive forest soils, Graham and others (1994) developed conservative recommendations for leaving CWD after timber harvesting to ensure enough organic matter was left to maintain long-term forest productivity. For Montana habitat types (Pfister and others 1977) they recommended 5 to 9 tons per acre (Douglas-fir/ninebark), 12 to 24 tons per acre (Douglas-fir/pinegrass), 7 to 14 tons per acre (grand fir/bear grass), 8 to 18 tons per acre (subalpine fir/bluehuckleberry, subalpine fir/grouse whortleberry), and 12 to 24 tons per acre (subalpine fir/bear grass, subalpine fir/twinflower). For ponderosa pine/fescue and Gambel oak (*Quercus gambelii*) habitat types in Arizona, they recommended 5 to 13 tons per acre. These recommendations were based on studies in undisturbed mature stands where ectomycorrhizae populations were used to determine optimum amounts of organic material. The upper limit of the recommended ranges or higher seems appropriate for stands recovering from high severity wildfire where much of the partially decomposed CWD and other forest floor organic matter was consumed.

The role of CWD in site protection can be significant or minor depending on site conditions. On steep slopes, CWD helps protect soils from erosion due to surface runoff. It disrupts flow near the ground, creates shade for seedlings, and reduces trampling by livestock, wildlife, and people.

Fire Hazard

Fire hazard generally refers to the difficulty of controlling potential wildfire. It is commonly determined by fire behavior characteristics such as rate-of-spread, intensity, torching, crowning, spotting, and fire persistence, and by resistance-to-control. In this paper we also consider fire severity to be an element of fire hazard. Fire severity refers to the effects of fire on the ecosystem. It depends on fuel consumption and heat flux into all living components. Downward heat transfer into the soil is an important determinant of fire severity (Ryan and Noste 1985). Fire intensity, largely a measure of upward heat transfer, is not a reliable indicator of fire severity because it can correlate poorly with downward heat transfer. Small and large downed woody fuels contribute differently to the various elements of fire hazard.

Fire Behavior

The influence of small woody fuels (3 inches and less in diameter) on spread rate and intensity of surface fires and associated torching and crowning is substantial and can be estimated using widely accepted fire behavior models (Andrews 1986; Finney 1998; Rothermel 1983; Scott and Reinhardt 2001). Large woody fuels have little influence on spread and intensity of the initiating surface fire in current fire behavior models; however, they can contribute to development of large fires and high fire severity. Fire persistence, resistance-to-control, and burnout time (which affects soil heating) are significantly influenced by loading, size, and decay state of large woody fuel. However, methods for estimating and interpreting these fire characteristics are not well established.

Accumulations of large dead woody fuel, especially containing larger diameter decayed pieces, can hold smoldering fire on a site for extended periods. When high winds occur, the sustained burning of persistent fire can be fanned into fast moving, dangerous fires (Chandler and others 1983). Historically, this was probably an important factor in development of large fires. The probability of a reburn is higher, to an unknown extent, in heavy accumulations of CWD because of the high fire persistence that characterizes decayed CWD. However, the probability of wildfire due to high fire persistence can be mitigated by effective fire detection and suppression actions.

Torching, crowning, and spotting, which contribute to large fire growth, are greater where large woody fuels have accumulated under a forest canopy and can contribute to surface fire heat release. Duration of flaming and energy release during flaming can be computed using a burnout model (Albini 1976) to indicate the potential for extreme fire behavior such as crowning and long-distance spotting. Compared to surface fuels with little CWD, Rothermel (1991) showed that 30 tons per acre of 6-inch sound pieces increases energy release of surface fuels in the flaming front and the associated crown fire, but not substantially. However, if the large woody fuel is decayed and broken up, its contribution is considerably greater, similar to fire in heavy slash. The contribution of large woody fuel to surface fire intensity is likely underestimated in fire behavior models that treat large woody pieces as smooth cylinders. An assumption of a smooth surface disregards the finely textured nature of bark-covered and weathered pieces.

Resistance-to-Control

Resistance-to-control is generally viewed as an estimate of the suppression force required for controlling a unit of fire perimeter. Ratings may be subjective as applied in the Photo Guide for Appraising Downed Woody Fuels in Montana Forests (Fischer 1981). For example, "high" resistance-to-control means "slow work for dozers, very difficult for hand crews; hand line holding will be difficult." Large woody fuel loadings in the Photo Guide ranged widely depending on size of downed pieces and undergrowth. Loading for a medium rating ranged from 14 to 50 tons per acre.

The USDA Forest Service Pacific Southwest Region (1976) developed a resistance-to-control rating scheme based on difficulty of hand line construction and an inventory of downed woody fuel loadings by size classes. High and extreme resistance-to-control ratings were reached for the following loadings (tons per acre):

0- to 3-inch diameter	3- to 10-inch diameter	
	High	Extreme
5	25	40
10	15	25
15	5	15

The above ratings were based on the assumption that few downed pieces greater than a 10-inch diameter were present. In computing the ratings, the number of large pieces (greater than 10 inch) by length class is more important than their loading in determining resistance-to-control. If the number of pieces greater than a 10-inch diameter exceeded 10 to 20 per acre, depending on length, less 3- to 10-inch diameter material would be required to reach the high and extreme resistance-to-control ratings.

Soil Heating

Soil heating is a complicated process that depends on burnout time of duff and woody material, removal of the insulating duff layer, and soil properties (Hungerford and others 1991). Under severe burning conditions, soil organic matter can be removed or destructively altered, nutrients volatilized, water-absorbing capacity decreased, and living plant parts and microorganisms killed. Loss of soil organic matter that is necessary for sustaining the biological activity of soils (DeBano and others 1998) is probably the most serious long-term concern.

Estimates of soil heating can be obtained using FOFEM (Reinhardt and others 1997). The model predicts a time-temperature profile at specified depths; depths at which critical temperatures occur can also be predicted. But to date little experience exists in interpreting the predicted soil temperature profiles across a large landscape. In addition to considering temperature, three other aspects of soil heating need to be evaluated: depth of undesirable heating, duration of heating (for example, 1 minute) that allows heat effects to unfold, and proportion of area that is impacted by undesirable soil temperatures. This last element is necessary because the model predicts a time-temperature profile based on an estimated unit average heat flux that expresses heating uniformly across a given area. In reality, however, excessive soil heating is concentrated beneath large woody fuel pieces particularly in the vicinity of piece intersections. For any predicted temperature it can be assumed that the temperature is considerably higher where the soil is overlaid with CWD, and elsewhere it is less than predicted.

To explore the effect of CWD on soil temperatures we exercised the soil heating model in FOFEM for a range of fuel loadings (fig.1a). We assumed absence of a duff layer, typical of a young forest developing after stand-replacement fire. One possible criterion for evaluating undesirable soil heating is the temperature at which organic matter is destructively distilled. This occurs at 200 to 300 °C (Hungerford and others 1991). Figure 1a indicates that high fuel loads (40 tons per acre) are necessary to cause soil to be excessively heated (at least 275 °C) from the surface to 2 cm depths. Figure 1b can be used to help with interpretation of soil heating

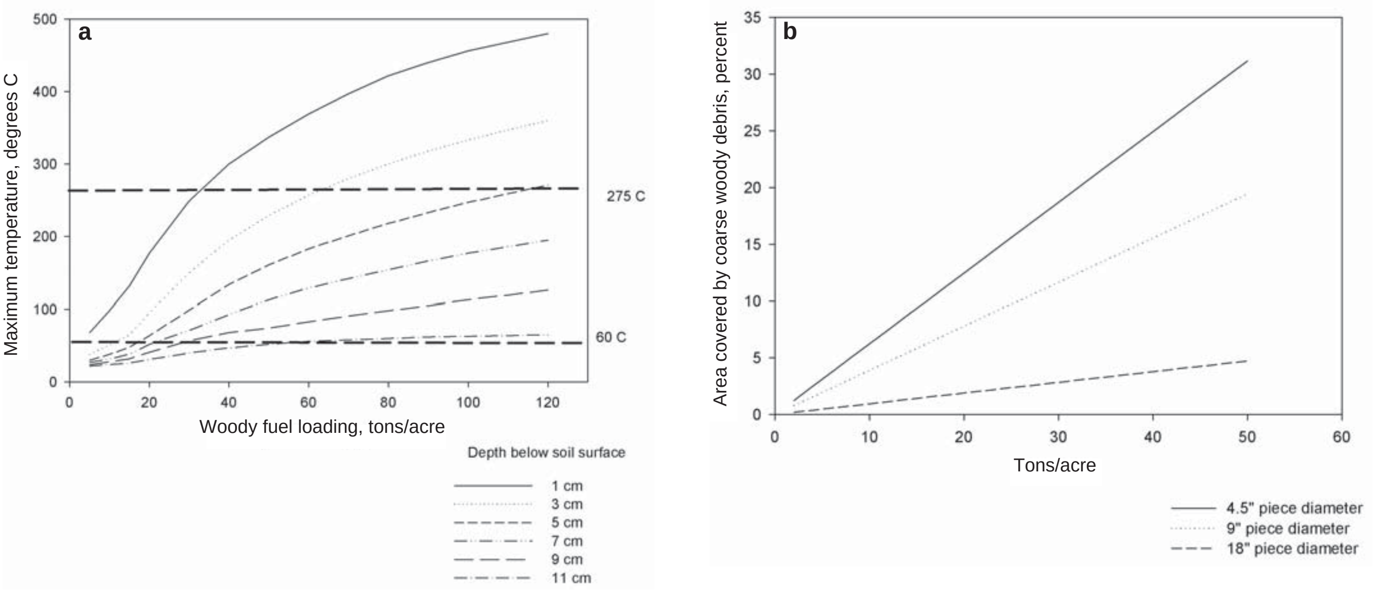

Figure 1—(a) Simulated soil heating. Curves show maximum temperatures reached at several soil depths for a range of woody fuel loadings. In these simulations, it was assumed the soils and fuels were dry, and that there was no duff to insulate the soil. (b) Percent of area covered by woody fuel for a range of piece diameters and woody fuel loadings, assuming the fuel is evenly spread. Actual area coverage would be reduced because of piece overlap, but area impacted by heating might be greater due to heating of soils adjacent to but not immediately below woody fuel.

results. It shows, for several piece sizes, the coverage of CWD over a range of fuel loads. Even at high fuel loads, a small portion of an area is covered with woody fuel. In areas that have no coverage, minimal soil heating can be expected.

A practical consideration for minimizing severe soil heating is to concentrate salvage activities in thickets of dead trees. If the thickets fall down naturally the CWD becomes concentrated. Burnout of large woody fuels is enhanced where the material is concentrated because of the interaction between adjacent burning pieces. Thus, salvage can be used to reduce and scatter the potential fuel concentrations.

Historical Conditions

Stand Structure

On dry sites occupied by ponderosa pine and mixed ponderosa pine and Douglas-fir, a structural mosaic probably existed due to variation in tree establishment, fire caused mortality, and other factors (Arno and others 1995). Research plots on the Bitterroot and Lolo National Forests showed that ponderosa pine existed in all-aged and even-aged stands that experienced similar fire histories. Although age-class structures varied substantially, most stands probably appeared open or parklike (Arno and others 1997). Long periods (50 to 100 years) without new pine establishment occurred presumably because the site was too stocked to allow recruitment of shade-intolerant species, or most of the regeneration was killed by fire.

After 1900, when occurrence of frequent, low intensity fires was significantly reduced in Western forests, understories changed with an increase in basal area and number of trees per acre. A shade-tolerant tree understory of Douglas-fir developed. We computed the increase in standing bolewood and crowns for trees up to an 8-inch diameter that accrued from 1900 to 1991 on the four Bitterroot National Forest study plots (Arno and others 1995). The increase in bolewood weight ranged from 1 to 11 tons per acre and crown weight from 0.5 to 6 tons per acre.

In restoring the dry site forest communities, a range of alternatives is possible because of the wide range in stand structures that probably existed historically. However, control of shade-tolerant species such as Douglas-fir will probably be necessary either using mechanical means or prescribed fire repeated periodically. Where prescribed fire is applied, probably after young pine can tolerate low intensity fire, woody fuels including CWD will be partially reduced.

Large Woody Fuel

Quantities of downed woody fuel, hence CWD, that fall within the presettlement era historical range of variability for the understory and mixed fire regime types can be inferred from existing inventory data and knowledge of fire history and fuel consumption. An indication of large downed woody fuel loadings that existed historically in the ponderosa pine, Douglas-fir, and lodgepole pine cover types is the summary of data gathered by forest inventory (stage I) and stand exams (stage II) during the 1970s (Brown and See 1981). The forest inventory was based on randomly located plots and is representative of forestwide conditions excluding classified wilderness. Stand exams were located where silvicultural activities were anticipated, such as timber sales that were often targeted for high risk stands. Thus, quantities of downed woody material might tend to be greater than found in the forest inventory over the whole forest as suggested in table 3. Results of inventories are summarized for the Bitterroot and Lolo National Forests, which have similar forests and fire histories (table 3). Considerable variability in quantities of downed woody material probably existed with many stands having little downed woody material and a few stands having excessive accumulations.

It seems reasonable to speculate that on average the quantities in table 3 would be less if understory fire had been allowed to occur at presettlement frequencies. This is supported by Habeck's (1976) study in the White Cap drainage of the Selway-Bitterroot Wilderness. In ponderosa pine stands having less than 0.5

Table 3—Average quantities of large woody fuel (tons per acre) by ponderosa pine (PP), Douglas-fir (DF), and lodgepole pine (LP) cover types on the Bitterroot and Lolo National Forests inventoried by the forest survey and stand exam programs (Brown and See 1981). Number of plots is shown in parentheses.

	Bitterroot			Lolo		
Program	**PP**	**DF**	**LP**	**PP**	**DF**	**LP**
Forest survey	5.3 (218)	9.2 (1,056)	12.2 (203)	4.8 (120)	11.5 (1,000)	13.3 (768)
Stand exam	11.3 (1,685)	21.1 (7,158)	25.9 (1,152)	10.4 (665)	11.9 (4,233)	15.8 (1,591)

inch (1 cm) of duff (averaged 2.4 tons per acre), large woody fuels averaged less than 1 ton per acre. The shallow duff indicated a fire history characteristic of the understory fire regime. In stands having more than a 0.5 inch of duff (averaged 11 tons per acre), indicating a long period without fire, large woody fuels averaged 23 tons per acre.

Snag densities on pre-European landscapes were estimated by Harrod and others (1998) as 6 to 14 snags per acre for dry forests east of the Cascades. This converts to approximately 4.5 to 7.0 tons per acre based on the wood density of ponderosa pine. He assumed stand structure to be open and parklike (basal area of 60 and 80 sq ft per acre) for forests of ponderosa pine, Douglas-fir, and dry associations of grand fir (*Abies grandis*). Lower densities favored larger tree diameters, which ranged from 7 to 35 inches. Snags were recruited with a life of up to 45 years under a regime of frequent, low intensity surface fires that created an uneven-aged structure with small even-aged groups. In a study of snag abundance in western Montana based on forest inventory data, Harris (1999) reported an average of 2.5, 9, and 12 snags per acre in uncut stands of the ponderosa pine, Douglas-fir, and lodgepole pine cover types. This is equivalent to about 2.2 to 6.0 tons per acre of snags. The spatial distribution of snags was highly variable, with many plots having none and some plots having many. The estimated snag densities from both studies over their modeled life span (Harrod and others 1998) seem to relate in a plausible way to the accumulated downed large woody fuels in table 3.

Optimum Coarse Woody Debris

The amount of CWD that provides desirable biological benefits, without creating an unacceptable fire hazard or potential for high fire severity reburn, is an optimum quantity that can be useful for guiding management actions. To arrive at this optimum, various sources of information about the roles of CWD in the forest and its historical dynamics should be considered. Most sources of technical knowledge about the benefits of CWD and fire characteristics deal with individual species or restricted segments of the ecosystem. We integrated the various sources of information to identify an optimum range of CWD that provides an acceptable risk of fire hazard while providing benefits to soil and wildlife (fig. 2). The optimum quantity for soil and fire considerations refers to downed CWD. For wildlife the optimum quantity involves both standing and downed CWD.

Although quantitative information is limited, we stress it here because it provides a good basis on which to plan. To summarize the positive values from earlier discussion, for maintaining soil productivity the upper limit of the following ranges is recommended: 5 to 10 tons per acre for warm, dry ponderosa pine and Douglas-fir types, 10 to 20 tons per acre for cool Douglas-fir types, and 8 to 24 tons per acre for cool lodgepole pine and lower subalpine fir types. Interestingly, these quantities coincide with the average amounts of large woody fuel inventoried by forest survey and stand exams (table 3) that may represent the high end of presettlement conditions because occurrence of fire

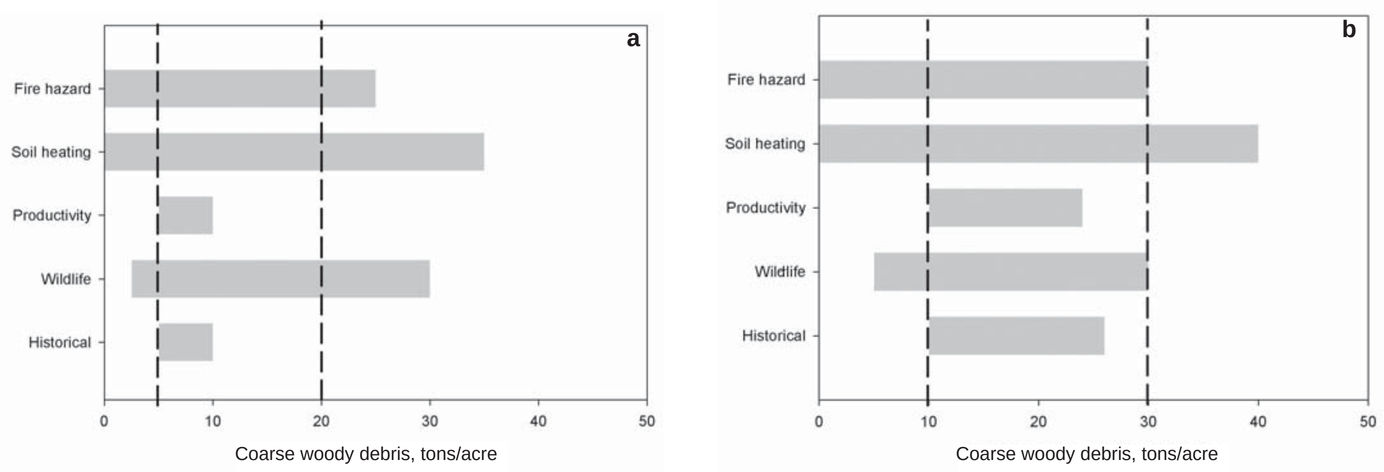

Figure 2—Optimum ranges of coarse woody debris for providing acceptable risks of fire hazard and fire severity while providing desirable quantities for soil productivity, soil protection, and wildlife needs for (a) warm dry forest types and (b) cool and lower subalpine forest types. Dotted lines show a range that seems to best meet most resource needs: 5 to 20 tons per acre for the warm dry types and 10 to 30 tons per acre for other types.

and associated fuel consumption had already been reduced compared to the historical fire regime. Although fire both creates and consumes fuel (Brown 1985), fuel depletion would tend to be greater than fuel accretion in high frequency fire regime types such as the warm, dry ponderosa pine and Douglas-fir types.

For cavity-nesting birds, up to 25 tons per acre may be desirable depending on species (see tables 1 or 2 for converting tons per acre to number of snags per acre). For small mammals, more than 30 tons per acre is best. Needs of riparian systems for CWD can be met by leaving all or most of the trees in a 60- to 100-ft wide strip on each side of streams. A wide range in CWD is indicated for wildlife (fig. 2) because desirable quantities vary greatly by species. However, insufficient knowledge exists to define the upper limit of CWD beneficial to wildlife. To encourage a diversity of wildlife species, a worthy objective may be to manage for a wide range of CWD across the landscape. There is considerable latitude within the optimum range for managing CWD to achieve benefits and avoid excessive wildfire threats.

To summarize the negative values, fire hazard including resistance-to-control and fire behavior reach high ratings when large fuels exceed about 25 to 30 tons per acre in combination with small woody fuels of 5 tons per acre or less. Excessive soil heating is likely at approximately 40 tons per acre and higher. Thus, generally high to extreme fire hazard potential exists when downed CWD exceeds 30 to 40 tons per acre.

Consideration of these positive and negative aspects indicates that the optimum quantity of CWD is about 5 to 20 tons per acre for warm dry ponderosa pine and Douglas-fir types and 10 to 30 tons per acre for cool Douglas-fir and lodgepole pine types and lower subalpine fir types. The recommended optimum ranges of CWD quantities (fig. 2) should be modified by consideration of other factors such as quantity of small woody fuel, diameter of CWD, landscape level needs, and ecosystem restoration objectives. The CWD optimum quantities for acceptable fire hazard are appropriate when accompanied by small dead fuel loadings of about 5 tons per acre or less. Acceptable CWD quantities are less at higher small fuel loadings (greater than 8 to 10 tons per acre). Acceptable CWD for fire hazard (fig.2) is slightly less for the warm, dry sites because they occur in a more flammable fire environment where generally less soil organic materials are necessary for maintaining soil productivity.

Higher loadings of CWD are acceptable where larger piece sizes predominate, for example in accumulated falldown of old growth trees. Larger piece sizes also are desirable because, faced with decomposition and fire, they persist longer to benefit wildlife and soil productivity. Unfortunately, the relationship between quantity and size of CWD and the various measures of fire hazard is largely undefined. Thus, it is a matter of judgment to consider that the larger the diameter of downed CWD the greater the loading that could be allowed without undesirable fire effects. A graph of CWD surface area by piece diameter and vertical projection of piece areas by piece diameter (fig. 3) can provide some guidance for adjusting the optimum range. The curves flatten at about a 5-inch diameter for the vertical projection and at an 8-inch diameter for surface area. This suggests that where CWD comprises predominately 3- to 6-inch material, the optimum quantity is less, perhaps by 5 tons per acre or more, than for larger sized material. With this in mind, it seems reasonable to assume that high fire hazard ratings apply when 25 to 30 tons per acre of CWD largely comprises 3- to 6-inch material. If quantities of CWD, comprising mostly smaller diameter pieces (3 to 6 inches), were at the upper end of the optimum range, adverse soil heating might occur at low fuel moisture contents, especially if substantial quantities of small woody fuels were also present (8 to 10 tons per acre or more).

Severity of Reburn

A question often asked by managers is if a reburn occurs, what fire effects can be expected? The interest is primarily in recovery of vegetation and possible impairment to soil productivity. The purpose of this section is to suggest in general terms how burn severity and postfire succession might be affected by recurrence of fire at varying periods following the previous fire. The probability of a reburn occurrence, which is small for a particular site but high over a large area such as a Ranger District, is not dealt with here.

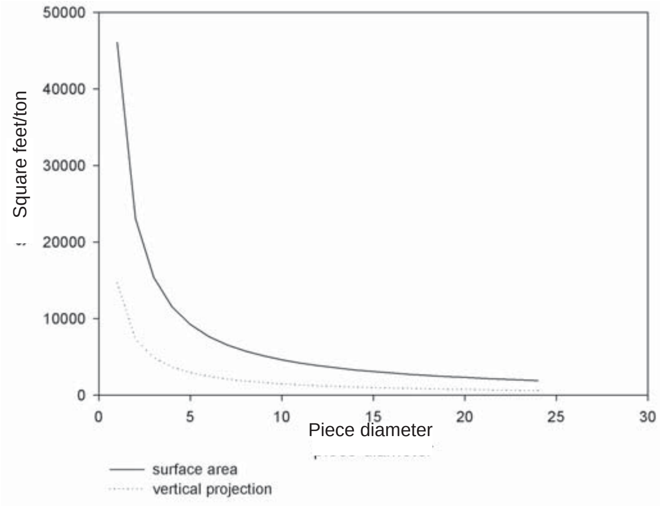

Figure 3—Surface area and vertical projection per ton of woody material as they vary by size class.

Vegetative succession following forest fire including reburns depends on a number of interacting factors including fire severity, prefire vegetation, species adaptations to fire, environmental conditions, and chance (Brown 2000; Lyon and Stickney 1976; Miller 2000; Morgan and Neuenschwander 1988). Although succession depends on many variables, the following principles can provide a general description of plant community development after a reburn.

1. The course of succession is set by the prefire composition of species that survive fire onsite by protected sprouting plant parts and seeds (Stickney 1990). In Northern Rocky Mountain wildfires, which are mostly of moderate to high severity, there is a tendency to get back most of the species that were present before fire (Lyon and Stickney 1976).
2. Many herb and shrub species have sprouting parts such as rhizomes, bulbs, and root crowns that are buried in mineral soil to varying depths.
3. The more severe the fire the higher the mortality and the less the survivor component in both species and number of plants (Stickney 1990). Only deeply buried sprouting parts survive. Resilient species such as pinegrass (*Calamagrostis rubescens*) and Douglas spirea (*Spiraea betulifolia*) usually retain surviving plant components. Further additions must come from offsite plants. Offsite colonizers that have light, easily wind-disseminated seeds are favored. Thus, both desired native plant and weed species fitting this category are favored.
4. The pattern of burn severity within a fire relates to the pattern of fuel consumption (Miller 2000). Duration of fire over uninsulated soil largely determines severity.
5. A future influence of unknown consequences on postfire succession is global warming, which may affect fire severity and plant establishment, growth, and mortality (Ryan 2000).

With these principles in mind, some general statements about the effects of a reburn during high to extreme burning conditions with low fuel moistures can be made:

0 to 10 Years After First Fire—High severity fire is unlikely because duff and downed woody fuels that support prolonged burning would be absent. Large woody fuels would still be accumulating through falldown, and they would not have decayed enough to support smoldering combustion, which can extend the period of downward heating. If salvage operations leave concentrations of small woody fuels, high severity burning could occur where the fuels are concentrated. This situation would be aggravated where stand-replacement fire did not consume foliage, thus allowing a layer of scorched needles to accumulate as surface fuel. Surviving onsite herbs and shrubs should dominate the recovering vegetation. Newly established trees that regenerate by producing seeds could be lost. Even seedlings of species having sprouting capability could die if their root systems are not well established.

10 to 30 Years After First Fire—Downed CWD would exhibit some decay and support a longer period of burning. A duff layer, however, would not be well established and would be unable to contribute to soil heating. Thus, high burn severity would primarily occur where large woody material was lying on or near the soil surface. High severity fire could be substantial where a large proportion of the soil surface was directly overlain by large woody material, which could accumulate from falldown of a large amount of tree basal area. A limited amount of conifer regeneration might be possible from young cone-bearing trees established onsite after the previous fire. Onsite herbs and shrubs would dominate the recovery vegetation except where burnout of large woody pieces caused deep soil heating, which would occur particularly in the near vicinity of overlapping pieces.

30 to 60 Years After First Fire—Large woody pieces would probably exhibit considerable decay, and a forest floor of litter and duff would be established to a variable extent depending on the density of overstory conifers. Burnout of large woody pieces and duff is assisted by the interaction of these two components (Brown and others 1991). Higher severity burning than would typically occur during earlier periods is possible depending on extent of soil coverage by large woody pieces. If a conifer overstory exists, crowning coupled with burnout of duff could amplify the burn severity. Offsite colonizers would be an important component of the recovery in the more severely burned locations. Prescribed fire during this period could greatly reduce the severity of a reburn wildfire. However, a reburn involving optimum quantities of CWD should not lead to unusually severe fire effects. Historically, fires probably often occurred in the understory and mixed fire regime types when large downed woody fuels were in the optimum range.

To predict succession more specifically following a reburn, managers would need an inventory of plant species onsite and offsite and an inventory of fuels.

Planning Retention of Coarse Woody Debris

The environmental effects of postfire salvage and fuel treatment activities may be due to the activity of removing trees or due to the altered stand structure (McIver and Starr 2001). Deciding whether to remove fire-killed or damaged trees and how much CWD should be retained on various sites could be viewed as passing through a series of decision gates or addressing questions that evaluate the environmental effects. For example, consider the following questions:

1. Where will salvage activities cause unacceptable soil compaction, erosion, and sedimentation? Roads have the greatest potential for exacerbating erosion. Also consider the need for site rehabilitation and that a reburn in heavy accumulations of CWD could encourage erosion.
2. Where will expected falldown of fire-killed trees together with existing downed woody fuels exceed the optimum CWD? Consider mortality to surviving trees that may die during the next 5 to 10 years due to fire injury, insects, and windfall.
3. Where should landscape scale considerations influence retention of CWD? For example, salvage may be desirable in the wildland-urban interface zone and elsewhere to break up large blocks of high fuel loadings and create areas having low to moderate fire behavior potential and resistance-to-control. Salvage may be undesirable where large diameter snags needed by wildlife are in short supply in adjoining areas.

The Bitterroot National Forest: An Example

Following the wildfires of 2000 on the Bitterroot National Forest, managers were particularly concerned with:

1. Potential for large, severe fires in the future that are of high risk to firefighters and public safety
2. Creating a fire-defensible wildland-urban interface
3. Recovery of the dry site forest types to fit with the historical fire regime
4. Effects of a possible reburn on soil productivity and vegetation succession
5. Providing wildlife values and forest products
6. Avoiding soil erosion and sedimentation and invasion of weeds

Of primary concern were three ecosystems identified as vegetation response units (VRU) in the Bitterroot Fires 2000 Assessment of Post-fire Conditions with Recovery Recommendations (Bitterroot National Forest 2000):

1. VRU 2—warm, dry ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) habitat types
2. VRU 3—cool, dry, and moist Douglas-fir habitat types
3. VRU 4—cool lodgepole pine (*Pinus contorta*) and lower subalpine fir (*Abies lasiocarpa*) habitat types.

Approximately 126,000 acres in VRU 2 and VRU 3 were burned with 60 percent of VRU 2 and 49 percent of VRU 3 experiencing moderate to high soil heating severity (Bitterroot National Forest 2000). Understory and mixed fire regime types characterize VRU 2 and VRU 3. Management direction for these vegetation response units was to keep wildfire hazard in the wildland-urban interface at acceptable levels by reducing fuels and to return the vegetation and fuels to conditions falling within the historical range of variability (Brown 2000) for these fire regime types. Approximately 86,000 acres burned in VRU 4, with 51 percent of the area experiencing moderate and high soil heating severity, which fits with the mixed and stand-replacement fire regime types that characterize VRU 4. In all, 356,000 acres were burned on the Bitterroot National Forest and adjacent State and private lands.

Modeling Predictions

Management of CWD should consider how much of it is desired onsite in the future. This requires predictions of falldown of fire-killed trees, continued tree mortality and falldown, and loss of dead woody material through deterioration and decay. The time interval chosen for predicting CWD should be long enough for a new immature or mature forest to develop. Keep in mind that the further in time the projection, the more uncertainty exists about the predicted values. Reasonable predictions of CWD can probably be provided over a period of 50 to 100 years.

To project future trends of CWD we used The Fire and Fuels Extension (FFE) (Beukema and others 2000) to the Forest Vegetation Simulator (FVS) (Stage 1973) to simulate the effects of alternative management strategies on future quantities of CWD and small woody fuels. The FVS simulates tree growth, tree mortality and regeneration, and the impacts of a wide range of silvicultural treatments. The FFE simulates additions to fuel pools from stand dynamics and management activities, and the removal of fuels through decay, mechanical treatments, and prescribed or wildfires. Various types of fuels are represented, including canopy fuels and surface fuels by diameter classes. Fire behavior of the propagating fire front and fire effects, such as fuel consumption, tree mortality, and smoke production, are modeled. Model outputs include fuel characteristics, stand structure, snag density, and potential fire behavior that provide a basis for comparing proposed stand and fuel treatments.

We selected three stands representing different vegetation types on the Bitterroot National Forest to illustrate how FVS and FFE could be used to simulate the effects of no treatment, salvage, and fuel treatment on CWD. The selected stands were considered typical of forest conditions occurring commonly on the Bitterroot National Forest (table 4). The VRU 2 stand contained a few old growth ponderosa pine and Douglas-fir trees with a dense understory of Douglas-fir, a condition that has developed extensively in the absence of repeated low intensity fire. The VRU 3 stand is a pure Douglas-fir stand with trees mostly ranging from 4 to 20 inches d.b.h. The VRU 4 stand consisted of a dominant lodgepole pine overstory with a dense understory of small subalpine fir and Englemann spruce (*Picea engelmannii*). The salvage treatment called for removing merchantable quality dead trees greater than 12 inches d.b.h. Approximately the same proportion of trees in each size class was removed. Fuel treatment called for removing dead trees 6 inches and less in d.b.h. by slashing, piling, and burning. Figure 4a shows an untreated stand typical of VRU 2 following high severity fire, while figure 4b shows a similar stand following partial salvage and surface fuel treatment. Figure 4c shows a VRU 2 stand following low severity fire, partial salvage, and surface fuel treatment.

For the simulation of high fire severity (100 percent tree mortality) in VRU 2, untreated CWD accumulated well beyond the optimum range for the next 100 years (fig. 5). The large quantity of CWD together with 8 to 10 tons per acre of small woody fuel (fig. 6) presented a high fire hazard over many years. Salvage of 50 percent or more of the merchantable dead trees accompanied by treatment of fuel left an acceptable quantity of CWD (fig. 7). The number of snags greater than 12 inches d.b.h. per acre (snags per acre, SPA) initially ranged from 4 for the 100 percent salvage treatment to 17 for 50 percent salvage (table 5). After 20 years SPA falls to 0.8 for 100 percent salvage and 1.5 for 50 percent salvage. Many years elapse in high fire severity burns before newly grown large diameter snags can replace the fallen snags, so leaving an ample density of snags following fire can help maintain a minimal snag resource during the 20 to 40 year postfire period when many snags have already fallen. Leaving a high density of snags would require constraints on harvesting.

Living stand structure and CWD varied considerably between simulations of low and high fire severity (fig. 5). Under low severity fire (80 percent tree mortality),

Table 4—Number of trees per acre by d.b.h. class (inches) for the representative vegetation response unit stands used in the FFE simulation of postfire recovery.

	VRU2		VRU 3		VRU 4	
d.b.h.	**DF**	**PP**	**DF**	**LP**	**ES**	**AF**
0–1	409		112	191	464	5345
1–4	436		0	27		246
4–8	142		153	130		16
8–12	56		141	108		13
12–16	18		50	12		2
16–20	10	1	13			
20–24	1		2			
24–28	2					
28–32		3				
32+		2				

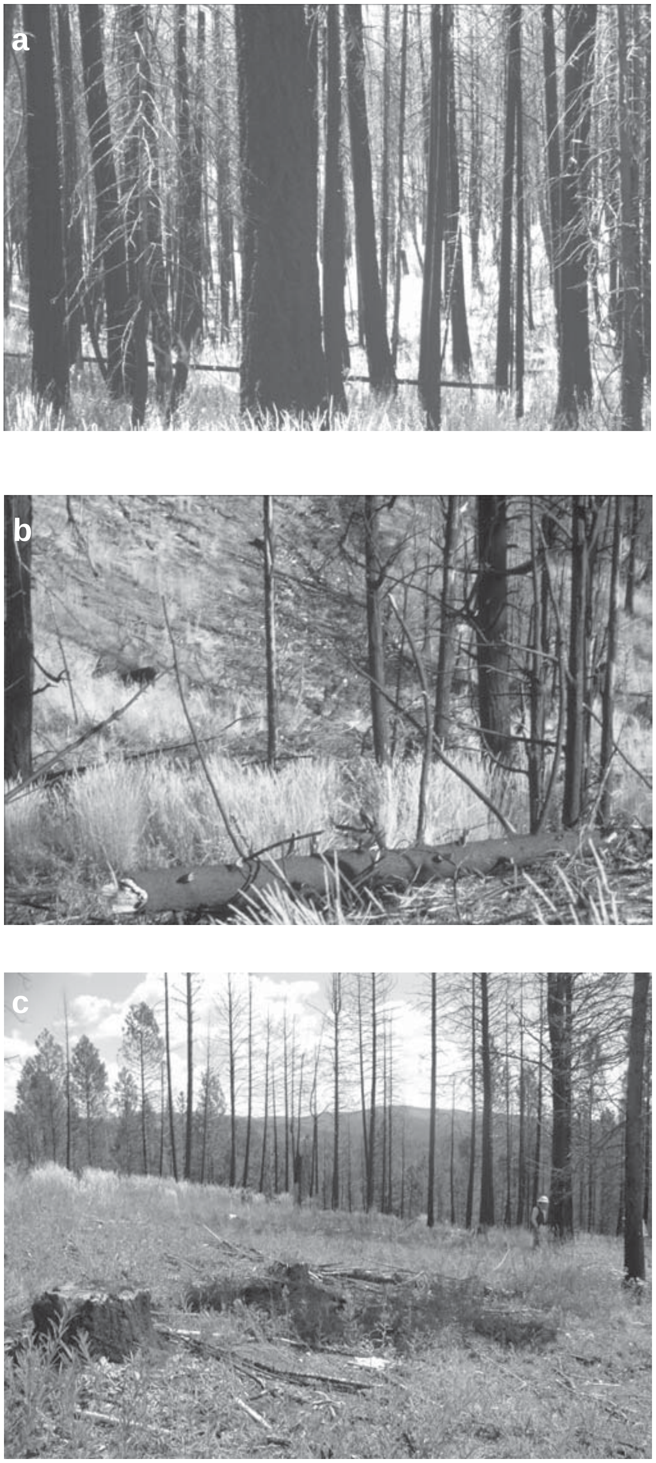

Figure 4—(a) Untreated stand following high severity fire, Bitterroot National Forest, 2002. (b) Treated stand following high severity fire, Bitterroot National Forest, 2002. Note the reduced density of standing dead trees and the presence of coarse woody debris on the forest floor. (c) Treated stand following low severity fire, Bitterroot National Forest, 2002. Note the standing live and dead trees, as well as the residual coarse woody debris.

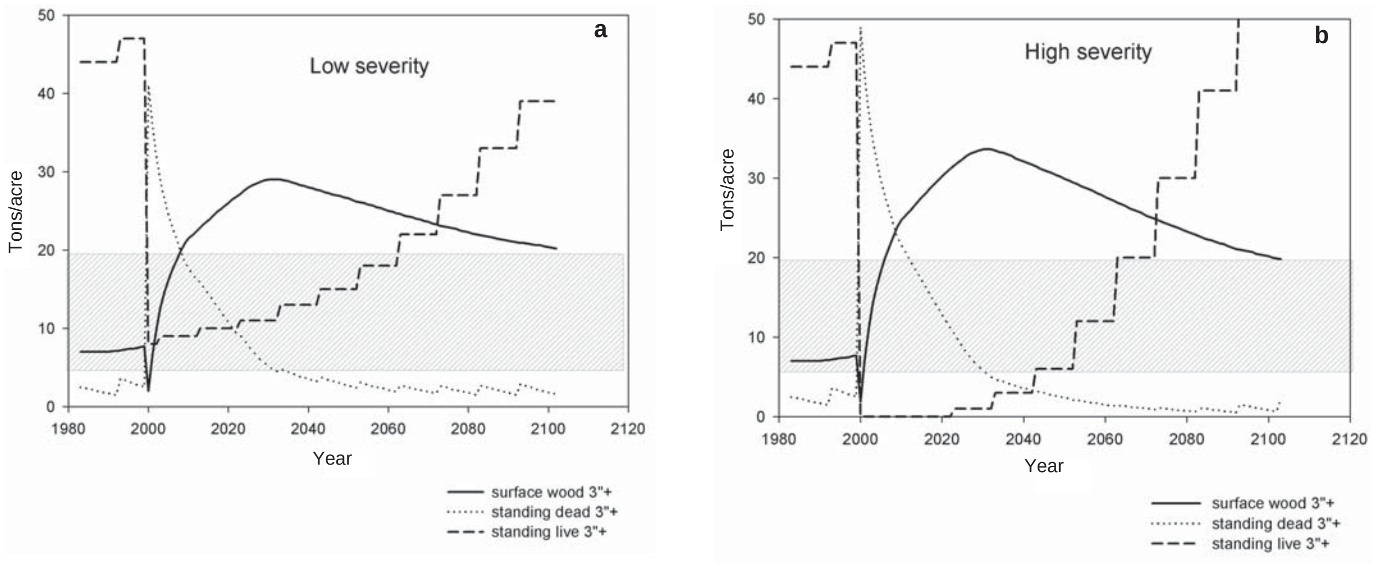

Figure 5—Simulated quantities of standing and surface coarse woody debris and live 3+ inch biomass for vegetation response unit 2 with no salvage and no fuel treatments under (a) low (80 percent tree mortality) and (b) high (100 percent tree mortality) fire severity conditions. Shaded bands indicate desired ranges.

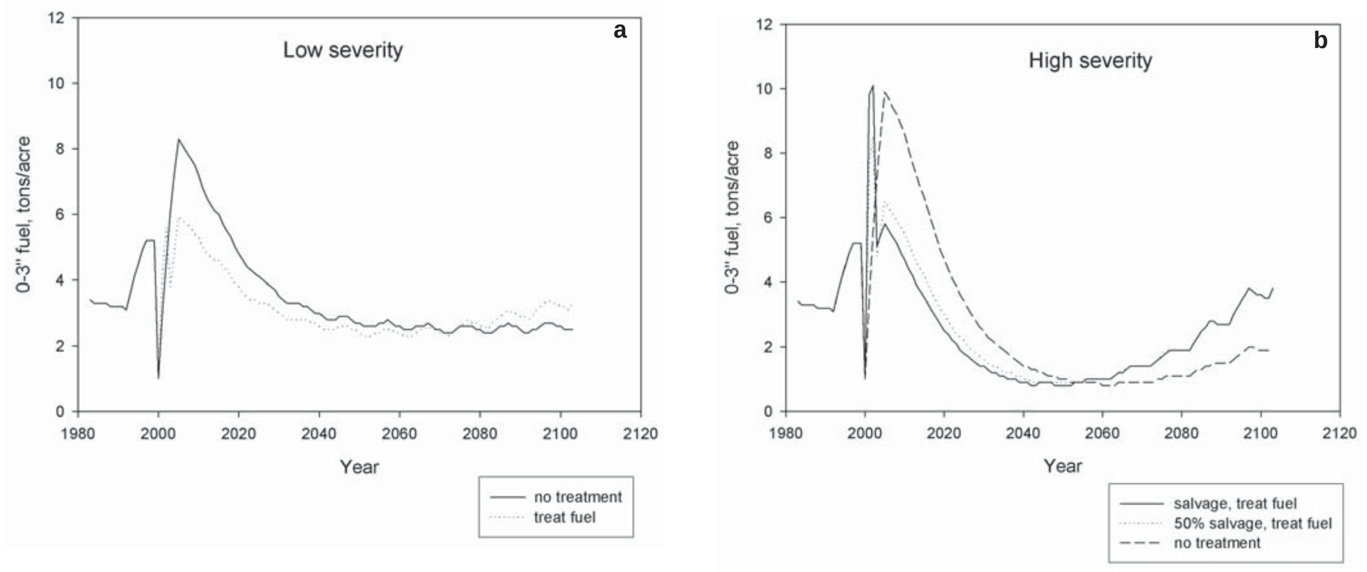

Figure 6—Simulated quantities of surface small woody fuel (0- to 3-inch diameter) for vegetation response unit 2 for combinations of 100 percent salvage, 50 percent salvage and no salvage with treated and untreated fuels under (a) low (80 percent tree mortality) and (b) high (100 percent tree mortality) fire severity conditions.

untreated CWD peaked at 24 tons per acre but remained slightly higher than the 20-tons per acre upper limit of optimum for next the 100 or more years due to contributions from growth and mortality of the surviving forest. Fuel treatment without salvage removed about 4 tons per acre of CWD and 2 tons per acre of small woody fuel. This kept CWD within the optimum range and lowered fire hazard.

For the VRU 3 stand, assuming high fire severity, untreated CWD peaked at 53 tons per acre and remained greater than the 30-tons per acre upper limit of optimum for the next 100 years (fig. 8). Salvage accompanied by fuel treatment lowered CWD into the optimum range (fig. 9). The simulations for salvage of all dead merchantable trees without fuel treatment and 50 percent salvage accompanied by fuel treatment produced nearly the same amount of CWD over the

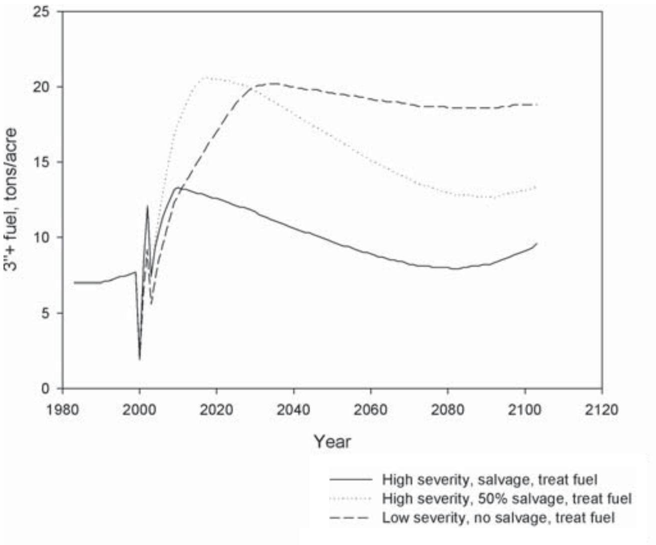

Figure 7—Simulated quantities of surface coarse woody debris for vegetation response unit 2 for high severity-100 percent salvage-treat fuels, high severity-50 percent salvage-treat fuels and low severity-no salvage-treat fuels.

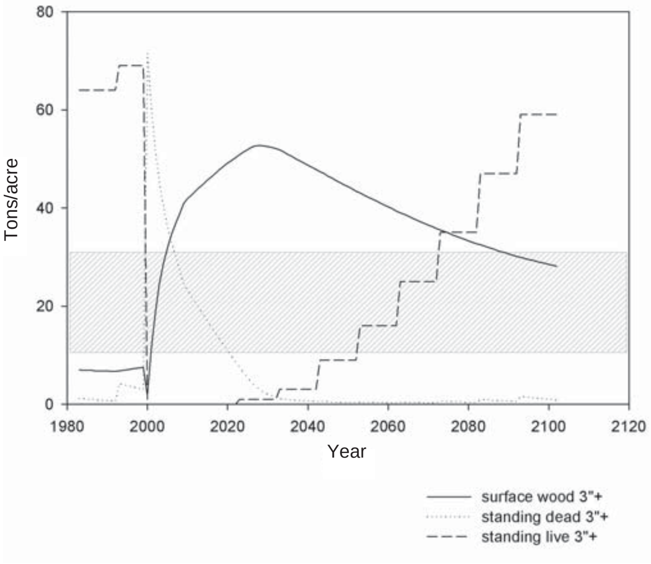

Figure 8—Simulated quantities of standing and surface coarse woody debris and live 3+ inch biomass for vegetation response unit 3 with no salvage and no fuel treatments under high (100 percent tree mortality) fire severity conditions. The shaded band indicates desired ranges.

simulation period. The CWD exceeded the 30-tons per acre upper limit of optimum for 18 years, making these treatments marginally acceptable. Regardless of the level of salvage prescribed, fuel treatment was necessary to keep CWD within the optimum range. Immediately after fire, SPA were 33 for 50 percent salvage and 7 for complete salvage. Most snags fell within about 20 years. After that the difference in SPA between salvage treatments was slight. However, for about 20 years in this simulation, the level of salvage affected snag density significantly. Depending on species and d.b.h., the time snags remain standing generally ranges from 15 to 40 or more years. In planning for retention of a given amount of CWD, treatment of fuel that reduces small-sized CWD (trees up to 6 inches d.b.h.) makes it possible to retain more large-diameter dead snags.

Table 5—Number of dead snags per acre in vegetation response unit 2 simulated by FFE for varying treatments and periods following fire.

	Years following fire				
Treatments	**3**	**20**	**40**	**60**	**80**
All snags (>0 inch d.b.h.)					
80% M, no S, no T[a]	482	26	32	39	39
100% M, no S, no T	532	14	11	18	26
100% M, 50% S, yes T	154	3.9	28	34	45
100% M, 100% S, yes T	140	3.1	28	34	45
Snags >12 inch d.b.h.					
80% M, no S, no T	22	8.2	3.2	3.0	3.4
100% M, no S, no T	34	11	1.7	.1	.7
100% M, 50% S, yes T	17	1.5	.3	.2	2.3
100% M, 100% S, yes T	3.7	.8	.1	.2	2.3

[a] M is mortality, S is salvage of dead merchantable trees, T is slash, pile, and burn trees < 6 inches d.b.h.

For the VRU 4 lodgepole pine stand, the salvage prescription had little effect on CWD (fig. 10) because few merchantable trees were present. Without salvage or fuel treatment, the CWD exceeded the optimum range by 1 to 5 tons per acre for about 20 years then fell within the optimum range. This simulation suggests that fuel treatment and salvage would be unnecessary unless landscape considerations such as maintaining low fire hazard in the wildland interface zone or in a strategically placed fuel break are important.

In stand-replacement fires, the CWD from the fire-killed trees is all that exists for a long time, until the new forest undergoes mortality and falldown. Some allowance for decay should be considered in the planning. For example, if 20 tons per acre was considered desirable in the 40 to 60 year old immature forest, 25 tons per acre or possibly more should be retained from the fire-killed trees. In low severity fire where an overstory survived, recruitment of CWD will probably occur regularly over time as trees continue to die from various causes such as insects, blowdown, and fire injury. Meeting a target of 20 tons per acre in 40 years

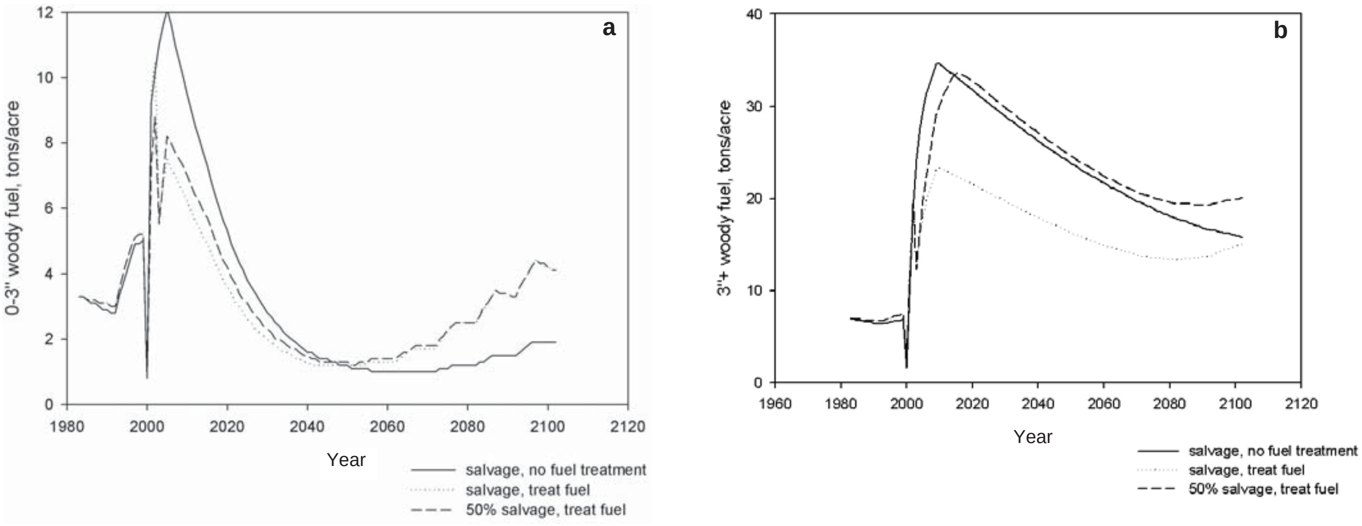

Figure 9—Simulated quantities of (a) small woody fuel and (b) coarse woody debris for vegetation response unit 3 for 100 percent salvage-no fuel treatment, 100 percent salvage-treat fuel and 50 percent salvage-treat fuel under high (100 percent tree mortality) fire severity conditions. The shaded band indicates desired ranges.

may only require 15 tons per acre from falldown of the trees directly killed by fire.

In VRU 2 where applying prescribed fire in the future might be necessary to maintain desired conditions, leaving excessive CWD, especially in the 3- to 6-inch diameter class, could hamper prescribed fire efforts. But also consider that prescribed fire will reduce the CWD loadings. On sites where most of the CWD loading comprises large pieces (greater than 12 inches), which would offer less of a hindrance to prescribed burning, consider retaining CWD loadings at the high end of the optimum range.

Conclusion

Management of CWD following fire requires consideration of its positive and negative values. The lower

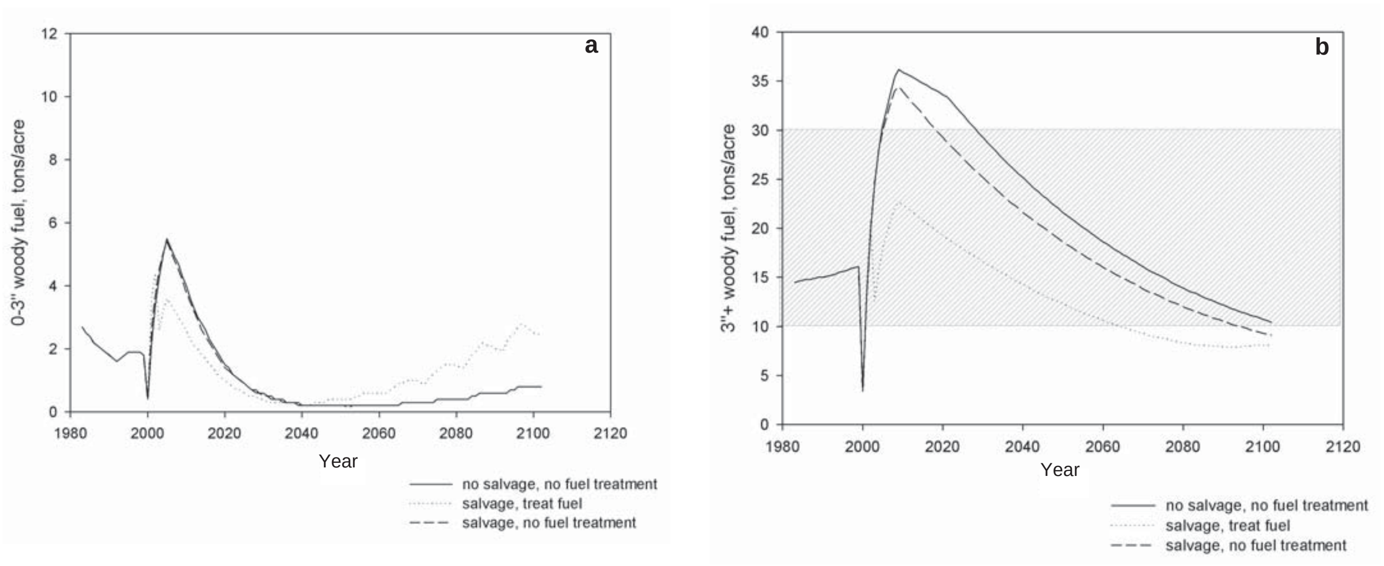

Figure 10—Simulated quantities of (a) small woody fuel and (b) coarse woody debris for vegetation response unit 4 for no salvage-no fuel treatment, 100 percent salvage-treat fuel and 100 percent salvage-no fuel treatment under high (100 percent tree mortality) fire severity conditions. The shaded band indicates desired ranges.

limit of the optimum range is determined by the ecological benefits of CWD, including wildlife habitat and site productivity, and the upper limit by excessive fire hazard. A wide range of CWD is acceptable depending on many individual site and landscape considerations including severity of burn, desired future stand conditions, restoration objectives, and desired structural diversity.

Because CWD amounts at a given site can be expected to change over time with or without management, simulation modeling can help with planning and designing treatments. Predicted quantities of CWD over time vary considerably with fire severity and postfire treatment, but they also depend on prefire stand structure. Site-specific analysis can strengthen decisionmaking by allowing managers to tailor postfire treatments to best achieve desired CWD quantities over time. Simulating snag recruitment, falldown, and subsequent decay allows decisions on fuel treatment (salvage harvest and/or surface fuel treatment) to be made in the context of expected future conditions as well as current conditions.

References

Albini, Frank A. 1976. Estimating wildfire behavior and effects. Gen. Tech. Rep. INT-30. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 92 p.

Andrews, Patricia L. 1986. BEHAVE: Fire behavior prediction and fuel modeling system—BURN Subsystem, Part I. Gen. Tech. Rep. INT-194. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 130 p.

Arno, Stephen F.; Scott, Joe H.; Hartwell, Michael G. 1995. Age-class structure of old growth ponderosa pine/Douglas-fir stands and its relationship to fire history. Res. Pap. INT-481. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 25 p.

Arno, Stephen F.; Smith, Helen Y.; Krebs, Michael A. 1997. Old growth ponderosa pine and western larch stand structures: influences of pre-1900 fires and fire exclusion. Res. Pap. INT-495. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 20 p.

Beukema, S. J.; Reinhardt, E. D.; Kurz, W. A.; Crookston, N. L. 2000. An overview of the Fire and Fuels Extension to the Forest Vegetation Simulator. In: Neuenschwander, L. F.; Ryan, K. C., tech. eds. Proceedings, the joint fire science conference and workshop—cossing the millennium: integrating spatial technologies and ecological principles for a new age in fire management. Volume II; 1999 June 15–17; Boise, ID. University of Idaho and the International Association of Wildland Fire: 80–85.

Bitterroot National Forest. 2000. Bitterroot fires 2000: an assessment of post-fire conditions with recovery recommendations. Hamilton, MT: U.S. Department of Agriculture, Forest Service, Bitterroot National Forest. 108 p.

Brown, James K. 1985. The “unnatural fuel buildup” issue. In: Lotan, James E.; Kilgore, Bruce M.; Fischer, William C.; Mutch, Robert W. , tech. coords. Proceedings—symposium and workshop on wilderness fire; 1983 November 15–18; Missoula, MT. Gen. Tech. Rep. INT-182. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station: 127–128.

Brown, James K. 2000. Chapter 9: Ecological principles, shifting fire regimes and management considerations. In: Brown, James K.; Smith, Jane Kapler, eds. Wildland fire in ecosystems: effects of fire on flora. Gen. Tech. Rep. RMRS-GTR-42-vol. 2. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 185–203

Brown, James K.; Johnston, Cameron M. 1976. Debris prediction system. Office report on file at: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, Missoula, MT. 27 p.

Brown, James K.; Reinhardt, Elizabeth D.; Fischer, William C. 1991. Predicting duff and woody fuel consumption in northern Idaho prescribed fires. Forest Science. 37(6): 1550–1566.

Brown, James K.; See, Thomas E. 1981. Downed woody fuel and biomass in the Northern Rocky Mountains. Gen. Tech. Rep. INT-117. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 48 p.

Brown, James K.; Snell, J. A. Kendall; Bunnell, David L. 1977. Handbook for predicting slash weight of western conifers. Gen. Tech. Rep. INT-37. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 35 p.

Bull, Evelyn L. 1994. Conserving wildlife habitat. In: Everett, Richard L. , comp. Restoration of stressed sites and processes. Gen. Tech. Rep. PNW-GTR-330. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 37–38.

Bull, Evelyn L.; Holthausen, Richard S. 1993. Habitat use and management of pileated woodpeckers in northeastern Oregon. Journal of Wildlife Management. 57(2): 335–345.

Bull, Evelyn L.; Parks, Catherine G.; Torgersen, Torolf R. 1997. Trees and logs important to wildlife in the Interior Columbia River Basin. Gen. Tech. Rep. PNW-GTR-391. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 55 p.

Carey, A. B.; Johnson, M. L. 1995. Small mammals in managed naturally young and old growth forests. Ecological Applications. 5: 336–352.

Chandler, Craig; Cheney, Phillip; Thomas, Philip; Trabaund, Louis; Williams, Dave. 1983. Fire in forestry. Vol. I. Forest fire behavior and effects. New York: John Wiley and Sons. 450 p.

DeBano, Leonard F.; Neary, Daniel G.; Ffolliott, Peter F. 1998. Fire’s effects on ecosystems. New York: John Wiley and Sons. 333 p.

Everest, Fred H.; Harr, Dennis R. 1982. Influence of forest and rangeland management on anadromous fish habitat in western North America silvicultural treatments. Gen. Tech. Rep. PNW-134. Portland, OR: Pacific Northwest Forest and Range Experiment Station. 19 p.

Faurot, James L. 1977. Estimating merchantable volume and stem residue in four timber species: ponderosa pine, lodgepole pine, western larch, Douglas-fir. Res. Pap. INT-196. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 55 p.

Finney, Mark A. 1998. FARSITE: Fire Area Simulator—model development and evaluation. Res. Pap. RMRS-RP-4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 47 p.

Fischer, William C. 1981. Photo guide for appraising downed woody fuels in Montana forests. Gen. Tech. Rep. INT-96. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 53 p.

Fischer, William C.; McClelland, Riley. 1983. A cavity nesting bird bibliography—including related titles on forest snags, fire, insects, disease, and decay. Gen. Tech. Rep. INT-140. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 79 p.

Gorte, Ross W. 1996. Salvage timber sales and forest health. Report for Congress. 4 p. Available from: Committee for the National Institute for the Environment, 1725 K Street, NW, Suite 212, Washington, DC 20006; 95-364 ENR.

Graham, Russell T.; Harvey, Alan E.; Jurgensen, Martin F.; Jain, Theresa B.; Tonn, Jonalea R.; Paige-Dumroese, Deborah S. 1994. Managing coarse woody debris in forests of the Rocky Mountains. Res. Pap. INT-RP-477. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 12 p.

Gresswell, Robert E. 1999. Fire and aquatic ecosystems in forested biomes of North America. Transactions of the American Fisheries Society. 128: 193–221.

Habeck, James R. 1976. Forests, fuels, and fire in the Selway-Bitterroot Wilderness, Idaho. In: Tall Timbers fire ecology conference proceedings 14; Fire and land management symposium; 1974 October 8–10; Missoula, MT. Tallahassee, FL: Tall Timber Research Station: 559–572.

Harmon, M. E.; Franklin, J. F.; Swanson, F. J.; Sollins, P.; Gregory, S. V.; Lattin, J. D.; Anderson, N. H.; Cline, S. P.; Aumen, N. G.; Sedell, J. R.; Lienkaemper, G. W.; Cromack, K. , Jr.; Cummins, K. W. 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research. 15: 133–302.

Harris, Richard B. 1999. Abundance and characteristics of snags in western Montana forests. Gen. Tech. Rep. RMRS-GTR-31. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 19 p.

Harrod, Richy J.; Gaines, William L.; Hartl, William E.; Camp, Ann. 1998. Estimating historical snag density in dry forests east of the Cascades Range. Gen. Tech. Pep. PNW-GTR-428. Portland OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 16 p.

Harvey, A. E. 1994. Integrated roles for insects, diseases and decomposers in fire dominated forests of the Inland Western United States: past, present and future forest health. Journal of Sustainable Forestry. 2: 211–220.

Harvey, Alan E.; Jurgensen, Martin F.; Graham, Russell T. 1989. Fire-soil interactions governing site productivity in the Inland Northwest. In: Baumgartner, David M.; Breuer, David W.; Zamora, Benhamin A.; [and others], comps. Prescribed fire in the Intermountain Region: forest site preparation and range improvement; symposium proceedings; 1986 March 3–5; Spokane, WA. Pullman, WA: Washington State University, Conferences and Institutes: 9–18.

Hungerford, Roger D.; Harrington, Michael G.; Frandsen, William H.; Ryan, Kevin C.; Niehoff, Gerald J. 1991. In: Proceedings—management and productivity of western montane soils. Gen. Tech. Rep. INT-280. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station: 32–50.

Hutto, Richard L. 1995. Composition of bird communities following stand-replacement fires in Northern Rocky Mountain conifer forests. Conservation Biology. 9(5): 1041–1058.

Lyon, L. Jack; Huff, Mark H.; Smith, Jane Kapler. 2000. Chapter 6: Fire effects on fauna at landscape scales. In: Smith, Jane Kapler, ed. Wildland fire in ecosystems: effects of fire on fauna. Gen. Tech. Rep. RMRS-GTR-42-vol. 1. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 43–49.

Lyon, L. Jack; Stickney, Peter, F. 1976. Early vegetal succession following large Northern Rocky Mountain wildfires. In: Tall Timbers fire ecology conference proceedings 14; Fire and land management symposium; 1974 October 8–10; Missoula, MT. Tallahassee, FL: Tall Timber Research Station: 355–375.

McDade, M. H.; Swanson, F. S.; McKee, W. A.; Franklin, J. F.; Van Sickle, J. 1990. Sources distances for coarse woody debris entering small streams in western Oregon and Washington. Canadian Journal of Forest Research. 20: 326–330.

McIver, James D.; Starr, Lynn. 2001. A literature review on the environmental effects of postfire logging. Western Journal of Applied Forestry. 16(4): 159–168.

Miller, Melanie. 2000. Chapter 2: Fire autecology. In: Brown, James K.; Smith, Jane Kapler, eds. Wildland fire in ecosystems: effects of fire on flora. Gen. Tech. Rep. RMRS-GTR-42-vol. 2. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 9–34.

Morgan, Penelope; Neuenschwander, Leon F. 1988. Shrub response to high and low severity burns following clearcutting in northern Idaho. Western Journal of Applied Forestry. 3(1): 5–9.

Murphy, Micheal L.; Koski, K. V. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. North American Journal of Fish Management. 9: 427–436.

Olson, J. S. 1963. Energy storage and balance of producers and decomposers in ecological systems. Ecology. 44: 322–331.

Pfister, R. D.; Kovalchik, B. L.; Arno, S. F.; Presby, R. C. 1977. Forest habitat types of Montana. Gen. Tech. Rep. INT-34. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 174 p.

Pyne, Stephen J. 1982. Fire in America: a cultural history of wildland and rural fire. Princeton, NJ: Princeton University Press. 654 p.

Reinhardt, Elizabeth D.; Keane, Robert E.; Brown, James K. 1997. First Order Fire Effects Model: FOFEM 4. 0, user's guide. Gen. Tech. Rep. INT-GTR-344. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 65 p.

Rothermel, Richard C. 1983. How to predict the spread and intensity of forest and range fires. Gen. Tech. Rep. INT-143. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 161 p.

Rothermel, Richard C. 1991. Predicting behavior and size of crown fires in the Northern Rocky Mountains. Res. Pap. INT-438. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 46 p.

Ryan, Kevin C. 2000. Chapter 8: Global change and wildland fire. In: Brown, James K.; Smith, Jane Kapler, eds. Wildland fire in ecosystems: effects of fire on flora. Gen. Tech. Rep. RMRS-GTR-42-vol. 2. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 175–184.

Ryan, Kevin C.; Noste, Nonan V. 1985. Evaluating prescribed fires. In: Lotan, James E.; Kilgore, Bruce M.; Fischer, William C.; Mutch, Robert W. , tech. coords. Proceedings—the symposium and workshop on wilderness fire; 1983 November 15–18; Missoula, MT. Gen. Tech. Rep. INT-182. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station: 230–238.

Saab, Victoria A.; Dudley, Jonathan G. 1998. Responses of cavity-nesting birds to stand-replacement fire and salvage logging in ponderosa pine/Douglas-fir forests of southwestern Idaho. Res. Pap. RMRS-11. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 17 p.

Scott, Joe H.; Reinhardt, Elizabeth D. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. Res. Pap. RMRS-RP-29. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 59 p.

Smock, Lenard A.; Metzler, Glenn M.; Gladden, James E. 1989. Role of debris dams in the structure and functioning of low-gradient headwater streams. Ecology. 70(3): 764–775.

Society of American Foresters. 1995. Below cost timber sales on the National Forests: the role of salvage and sanitation harvesting in the restoration and maintenance of healthy forests [position statement]. Bethesda, MD: Society of American Foresters. 3 p.

Stage, Albert R. 1973. Prognosis model for stand development. Res. Pap. INT-137. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 32 p.

Stickney, Peter F. 1990. Early development of vegetation following holocaustic fire in Northern Rocky Mountain forests. Northwest Science. 64(5): 243–246.

Stoszek, K. J. 1988. Forests under stress and insect outbreaks. Northwest Environmental Journal. 4: 247–261.

Tobalske, Bret W.; Shearer, Raymond C.; Hutto, Richard L. 1991. Bird populations in logged and unlogged western larch/Douglas-fir forest in northwestern Montana. Res. Pap. INT-442. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 12 p.

Ucitel, Dalit. 1999. Vole use of coarse woody debris and its implications for habitat and fuel management. Missoula, MT: University of Montana. Thesis.

U.S. Department of Agriculture, Forest Service, Region Five. 1976. Resistance to control calculation matrix. USDA Forest Service Manual, Region Five Supplement 5151. 14-2.

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