Overview of Agents and Patterns of Mortality and Resulting Coarse Woody Debris Recruitment in Western Forests[1]

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Abstract

We present an overview of many of the mortality agents in western coniferous forests of the United States that are responsible for coarse woody debris recruitment under natural conditions. Patterns and scale of occurrence of mortality agents for the six western USDA Forest Service Regions are examined at both historic and projected-risk time periods. The data indicates that bark beetles have been the most important source of mortality in the western U.S., and with the exception of the Northern Region, this trend is expected to continue. Defoliators, although important in growth loss, have not had as large a mortality impact. Recent-past and projected-risk data indicate that root disease may be an even more important factor in tree mortality and recruitment of coarse woody debris than indicated in recent literature. Although regional measures of actual mortality are not available, all western Regions show high impacts by dwarf mistletoe (*Arceuthobium* spp.) during the past 20 years. Fire affects relatively few hectares compared to insect and disease, but the effects on coarse woody debris (recruitment and conditioning) are important. Additional concerns for managers wishing to augment coarse woody debris are also presented.

Introduction

Coarse woody debris, both standing and fallen, is an important component in many physical, chemical, and biological processes of forested ecosystems (Graham and others 1994). Important functions include erosion control, nutrient cycling, and wildlife and microbial habitat (Harmon and others 1986, Li and Crawford 1994, Light and Burbridge 1985, Lofroth 1998, McGregor 1985b). The role of dead wood in these functions depends largely on such characteristics as size and form, orientation (standing or down), and resident flora and fauna. These characteristics, in turn, are formed by a number of environmental factors including habitat type, forest structure, site quality, climate, geography, disturbance agents, and decay organisms (Harmon and others 1986). Many of these environmental factors are integral to the ecosystem in which the dead wood is found. In other words, the forces that define what may be called a dead wood regime also comprise many of the processes that define ecosystems and communities (biologically delineated zones).

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Dead wood regimes are processes of intermediate time and spatial scales, and interrelated to disturbance and environmental processes, suggesting that analysis of dead wood in the western United States should be done by regions definable by such characteristics as forest type, geography, disturbance regimes, climate, and history; for time frames somewhere between seasonal and geologic; and by including aspects of the various processes in a dead wood regime, such as tree growth, method of death, decomposition and decay. If one process of a dead wood regime is to be used for analysis, disturbance or mortality agents are obvious choices.

The agent responsible for dead wood recruitment often acts on conditions of the live tree (Wargo 1995). These characteristics of the live tree, together with the unique attributes of the killing agent, determine much of the functional pathway followed by the wood in the ecosystem as it deteriorates (Bull and others 1997, Castello and others 1995, Geils and others 1995, Hadfield and Magelssen 1999). Impacts on characteristics of the living tree, either directly on the disturbance agent or on any part of the "death" processes, could change the disturbance process.

Changes in primary mortality agents over time or space could alter the character and distribution of dead wood in the system. Such changes could have important effects on many ecosystem processes (Graham and others 1994, Hagle and others 1995, Harmon and others 1986, Light and Burbridge 1985), and recognition of these changes would constitute valuable information for forest health management. For example, insect outbreaks, fire history, and rangeland condition in the Southwest can be directly related to changes in climate disturbances (Swetnam and Baisan 1994, Swetnam and Betancourt 1998, Swetnam and Lynch 1993).

Our analysis presents an overview of many of the mortality agents in western coniferous forests of the U.S. that are responsible for mortality and subsequent recruitment of coarse woody debris under natural conditions. Spatial and temporal differences in the importance of these agents are examined. Implications of these differences on the ecosystem, on management of coarse woody debris, and on forest health in general are discussed. Finally, risks associated with management activities designed to create coarse woody debris and their mitigation are summarized.

Material and Methods

Analysis Area

Data on the impact of mortality agents was gathered for western coniferous forests of the U.S. Most information was obtained from the USDA Forest Service, in particular, Forest Health Protection. Thus, discussion of patterns and scale of mortality agents will be presented by Forest Service Regions *(fig. 1)*. Because there is relatively little hardwood area in the West, data on forest health in western forests is largely data for coniferous species (USDA Forest Service 1958).

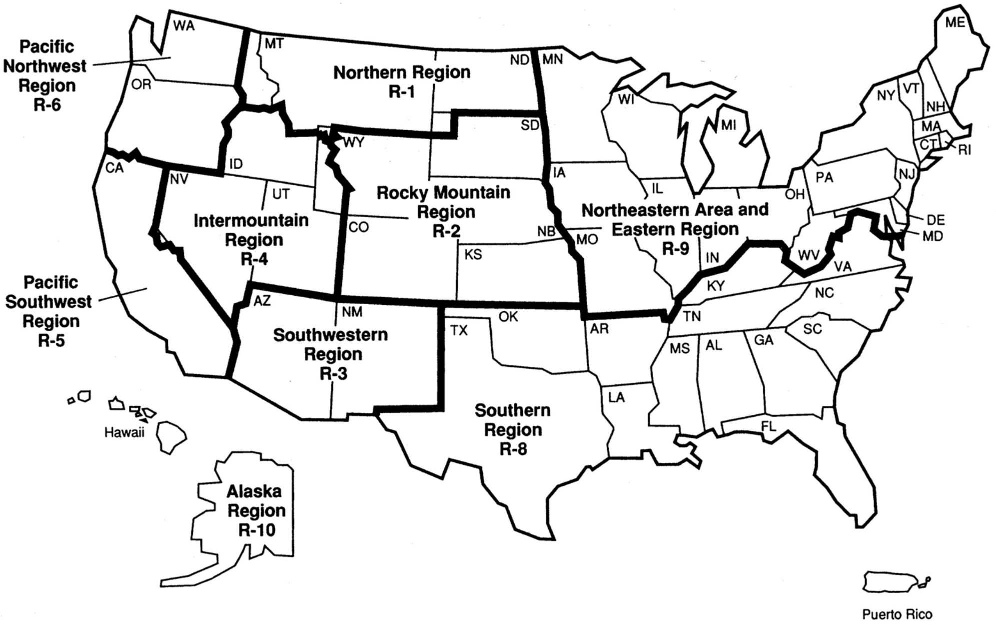

Figure 1—State boundaries and USDA Forest Service Regions.

Patterns and Scale of Occurrence of Mortality Agents

Studies in landscape ecology note that disturbance agents may operate at different spatial and temporal scales and are interrelated (Eng 1998, Harmon and others 1986, Holling 1992, Parminter 1998, Swetnam and Lynch 1993, White and others 1999). The most commonly recognized spatial scales include gap, stand, watershed, and landscape, while common temporal scales include seasonal, annual, and long term. These scales are intermediate in nature between the smallest, fastest, vegetation-directed scale and the largest, slowest, geologic, or evolutionary scale. Because activity at one level both influences the next higher level and contains all the levels found below it (Harmon and others 1986, Parminter 1998), our analysis of the effects of mortality agents on coarse woody debris could be done at many levels (Holling 1992). Ideally, the scale used to evaluate a process should be helpful in the explanation of observable patterns (Eng 1998). However, the availability and the scale (temporal and spatial) of that data may dictate at least the first steps in determining what sizes and time frames are considered.

In our analysis, we chose to review the entire western U.S. Thus, we were limited to a landscape spatial scale of Forest Service Regions and three long-term (approximately 15-20 years) temporal periods: up to and including 1952 (past), 1978-97 (recent past), and 2000-2015 (future based on projected risk). The availability of data for these temporal periods did differ, and in some cases the evaluation of the effects of some mortality agents was not possible. Also, the use of the geo-political Forest Service Region boundaries complicated analysis that ideally should have been related to biologically delineated boundaries.

Measurement of an agent's impact (severity and extent) also was limited. Total area affected was used as the measure for the recent-past and projected-risk data. However, volume measures were used in the 1952 data. The relationship of area affected to the volume of coarse woody debris or number of trees killed has not been determined, and no measure of dispersion (density and patchiness) is available. However, all three measures of impact (area affected, tree volume, stem number), as well as spatial and temporal scales and dispersion, are likely important in assessing the relative effects of any one agent on the ecosystem.

Specific Mortality Agents: Patterns and Scale

Historical (Recent past)—Recent data was compiled for five specific mortality agents for the 20-year period of 1978 to 1997 (recent past). The mortality agents chosen, based on overall importance and data availability, included mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins), western spruce budworm (WSBW) (*Choristoneura occidentalis* Freeman), root disease (RD) (most likely *Armillaria* spp., *Phellinus weirri* Gilbertson, *Heterobasidion annosum* Bref., *Phaeolus schweinitzii* Pat., and *Ceratocystis* spp.), dwarf mistletoe (DM) (*Arceuthobium* spp.), and wildfire (FIRE). MPB was chosen as a principal bark beetle and WSBW as a principal defoliator.

Because of the nature of the mortality agent (slow or fast acting over a large or small area), the data available on the effects of these agents varied. For the insect pests and fire, data generally consisted of annual hectares affected, although the number of trees killed and volume killed were sometimes calculated. Information in national and many regional annual *Forest Insect and Disease Conditions Reports* (issued by the Forest Service's Forest Health Protection) was used to determine annual impacts (hectares) and calculate an annual average impact (total hectares/years) for the six Forest Service Regions and the West as a whole, and to evaluate discrepancies in reported numbers (Bridgwater 1985, DeNitto 1985, Johnson and Hawksworth 1985, McGregor 1985a). In the case of MPB, adequate data was not available for 1978 or 1984. For FIRE, national records were not available until 1984 (USDA Forest Service 1992, USDA Forest Service 1998), although longer fire histories have been reconstructed for areas such as the Southwestern Region by using tree ring data (Swetnam and Betancourt 1998)

Records of annual mortality for RD and DM are not readily available. Aerial detection of these diseases is more difficult and their impact is more gradual, creating problems in making annual mortality calculations. However, average annual impacts of these two agents were evaluated in the early 1980s by the Forest Service. Numbers from these studies and an updated summary of forest health conditions were used in our analysis (DeNitto 1985, Drummond 1982, Johnson and Hawksworth 1985, Smith 1984). RD mortality was estimated as the average annual volume killed (cubic meters) (Smith 1984). Estimates of effects of DM mortality were not available. Rather, volume loss (mortality plus growth loss) was given in both cubic meters and hectares of infestation (Drummond 1982).

In order to display RD mortality on a graph in terms of "number of hectares affected," a ratio was calculated using the available cubic meter measurement of RD from Smith (1984), and the cubic meter and hectare measurements of DM from Drummond (1982). Although these RD 'hectares' are not a true measure of the area of mortality, they do retain the relationship of the relative importance of RD to DM indicated in the volume measurements.

Projected Risk—Projections of future importance of principal mortality agents are found in the Forest Service's Forest Health Protection national risk assessment project. The risk assessment project delineates general areas that are expected to experience 25 percent or more tree mortality over the next 15 years based on the expert opinion of professional pest management specialists. Although this risk assessment process is both coarse as well as iterative (changing as better numbers become available), current predictions provide us an opportunity to evaluate possible future changes in mortality agent importance. Information on future trends may help managers prepare for possible changes in coarse woody debris recruitment. Because of regional differences in data availability and mortality agent activity, modeling of expected mortality was left to the discretion of the regional Forest Service Forest Health Protection specialists. Risk assessment methodologies are discussed by Lewis (2002).

We used preliminary risk data (hectares) to create graphics showing the relative importance of the same five mortality agents used in the evaluation of the recent-past data.[3] Fire data for the risk assessment project was not obtained, but the insect and disease agents were comparable. Actual hectares will not be presented here, but eminent modifications in the risk data are not expected to greatly alter the relative importance of the various agents. However, in the more distant future, introduction of exotic insects and diseases, or dramatic changes in forest type or climate could cause significant shifts in realized agent importance.

Mortality Agent Groups: Patterns and Scale

Projected Risk—The projected risk data contains a more complete list of mortality agents than the five specific agents we used. In order to evaluate the importance of bark beetles as a group (including MPB) as well as defoliators (including WSBW) and other insects and disease, the risk data was partitioned into the following six agent groups: bark beetles (BB), defoliators (DF), other insects (IO), root disease (RD), dwarf mistletoe (DM), and other pathogens (PO). Organisms within each group include: mountain pine beetle, Douglas-fir beetle (*Dendroctonus pseudotsuga* Hopkins), spruce beetle (*D. rufipennis* [Kirby]), western pine beetle (*D. brevicomis* LeConte), Jeffery pine beetle (*D. jeffreyi* Hopkins), round-headed pine beetle (*D. adjunctus* Blandford), southern pine beetle (*D. frontalis* Zimmerman), pine engraver (*Ips pini* Say), fir engraver (*Scolytus ventralis* LeConte), and western balsam bark beetle (*Dryocetes confusus* Swaine) for BB; western spruce budworm and Douglas-fir tussock moth (*Orgyia pseudotsugata* [McDunnough]) for DF; balsam woolly adelgid (*Adelges piceae* [Ratzeburg]) for IO; annosus root disease, subalpine fir decline, and other unnamed root diseases for RD; various dwarf mistletoes (*Arceuthobium* spp.) for DM; and comandra blister rust (*Cronartium comandrae* Peck) and white pine blister rust (*C. ribicola* Fisch) under PO. The relative importance of each of theses groups was calculated and presented graphically for comparison.

Historical (1952)—The best data on historical mortality trends for most of the same six agent groupings was collected in 1952 (USDA FS 1958). The more recent forest health data (recent past) contained too much missing data to calculate adequate

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[3] Unpublished date on file (12/24/99), USDA Forest Service, Forest Health Protection (Washington and Regional Offices).

numbers for the BB, DF, IO, and PO categories. Because of the differences in the 1952 data standards, two graphics were created. The first graphic uses information from the year 1952 for mortality groups similar to those delineated for the risk data: bark beetle (BB), defoliators (DF), other insects (IO), root disease (RD), heart rot, and stem disease (includes DM, heart rot, and blister rust) (HR/SD), and other pathogens (PO). The second graphic uses trend data as determined in 1952 for the broader groupings of insects, disease, fire, and other (USDA Forest Service 1958, specifically, Basic Statistical Tables 17, 66, and 76).

Mortality of sawtimber (board feet) was chosen to be most comparable to our other data. Thus, information on growth loss and on growing stock was not used. As with all data in this study, hardwoods are minimal and were not separated from conifers.

The 1952 information was not available for the Forest Service Regions *(fig. 1)*. Instead, data was either given by state or by different regional areas. For example, in place of the Northern, Rocky Mountain, Southwestern and Intermountain Regions, the 1952 study combines these four Regions into two larger Regions: the Northern Rocky Mountains and the Southern Rocky Mountains. The Northern Rocky Mountains contains all of the Northern as well as part of the Rocky Mountain and Intermountain Regions (Idaho, Montana, South Dakota and Wyoming). The Southern Rocky Mountain contains all of the Southwestern as well as the remainder of the Rocky Mountain and Intermountain Regions (Arizona, New Mexico, Colorado, Utah, Nevada). Differences in the measure of impact (volume, not area) and in regional delineations complicate comparisons, but relative importance of mortality agents is expected to remain indicative.

Results

Patterns and Scale of Occurrence of Mortality Agents

The terms "impact" and "area affected" used in the following results and discussion should be clearly understood to avoid confusion in interpretation of the data. As noted previously, impact of a mortality agent on a tree can be measured as volume, number of trees, or area killed. Available data, however, limited us to the measurement of "hectares affected." Thus, the word "impact" refers to this measurement of hectares only and should not be directly equated to "biological impact." The term "area affected" should also be clarified. Although we are principally interested in dead trees, mortality data was not always available. For agents whose principal consequence is growth loss and not death, the relationship between the number of hectares affected and hectares that experienced mortality are unclear. Thus, for agents such as WSBW and DM many of the hectares affected may not have experienced mortality.

Specific Mortality Agents: Patterns and Scale

Historical (Recent past)—Examples of the differences in the scales and temporal patterns of the five specific mortality agents from 1978 to 1997 are presented for the Forest Service's Northern Region *(fig. 2)* and the Southwestern Region *(fig. 3)*. As expected, area affected by insects (MPB and WSBW) and fire vary considerably from year to year, although long-term patterns often occur. MPB levels in the Northern Region show a clear example of an activity cycle spanning multiple years *(fig. 2).* RD and DM are more pervasive (more area affected) than insects and fire. The depiction of RD and DM effects using a straight-line average (annual values not available) does not display fluctuations known to occur in response to variations in environmental factors (e.g., drought stress). However, these yearly fluctuations are known to be less dramatic than those experienced by insects and fire (Dahms and Geils 1997, Drummond 1982, Smith 1984).

The average annual area affected (thousands of hectares/year) by MPB, WSBW, RD, DM, and for each of the six Forest Service Regions of the West was determined using regional data from 1978 through 1997 *(fig. 4).* Although numbers used for RD are not actually the 'area affected,' they do maintain the relationship between DM- and RD-affected volume. Interestingly, in the Northern, Rocky Mountain, and Southwestern Regions these calculations of RD hectares resemble the 'area of management concern' for RD presented in the 1985 forest health summary (DeNitto 1985). Also, comparison with other data for the Pacific Southwest shows that our relative area for RD preserves relationships among agents in terms of overall impact (USDA Forest Service 1979). The difficulty in interpreting these hectare totals lies in the disproportional area within each Region.

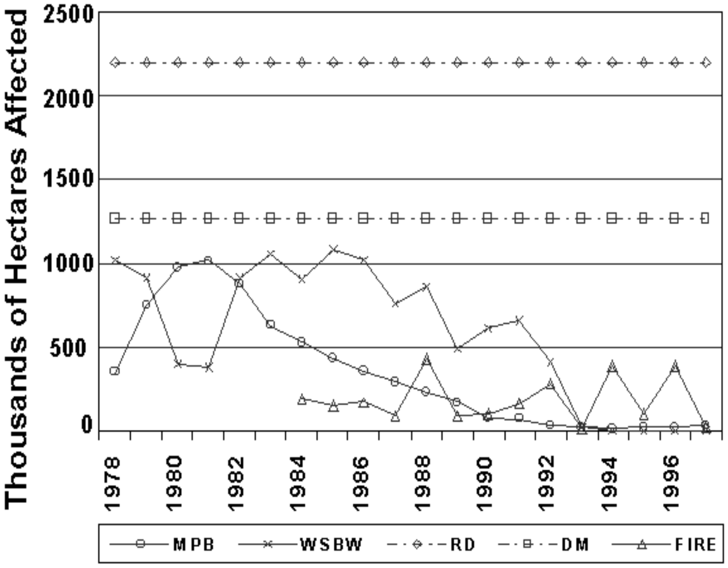


Figure 2—Fluctuation patterns of hectares affected by five specific mortality agents in the Forest Service's Northern Region, 1978-1997. Agents included mountain pine beetle (MPB) *(Dendroctonus poderosae),* western spruce budworm (WSBW) *(Choristoneura occidentalis),* root disease (RD) (most likely *Armillaria* spp., *Phellinus weirri*, *Heterobasidion annosum*, *Phaeolus schweinitzii*, and *Ceratocystis* spp.), dwarf mistletoe (DM) (*Arceuthobium* spp.), and wildfire (FIRE). Areas of WSBW and DM are affected hectares rather than hectares of mortality. In order to graphically display RD in terms of "number of hectares affected," a ratio was calculated using the available cubic meter measurement of RD mortality (Smith 1984) and the cubic meter and hectare measurements of DM volume loss (Drummond 1982). Although the RD "hectares" are not a true measure of area, they do retain the relationship of the relative importance of RD volumes to DM volumes. RD and DM are known to fluctuate somewhat, but these patterns have not been followed closely. FIRE numbers for the Northern Region are actually for Idaho and Montana rather than the Forest Service regional area.

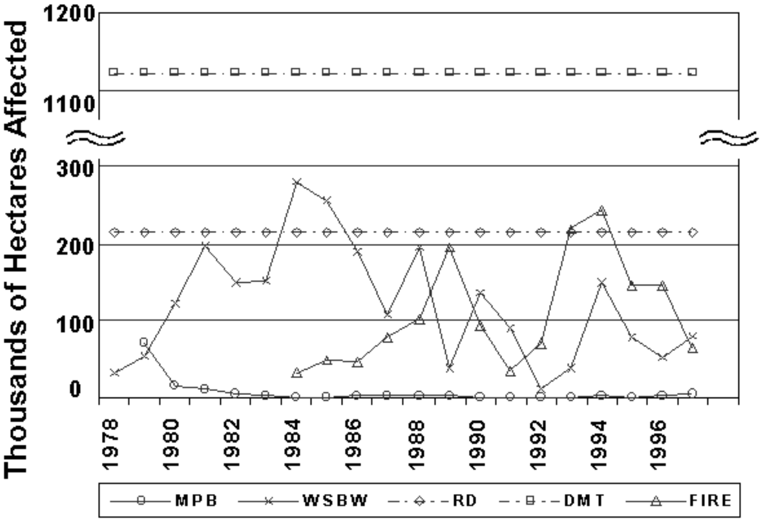


Figure 3—Fluctuation patterns of hectares affected by five specific mortality agents in the Forest Service's Southwestern Region, 1978-1997. Agents included mountain pine beetle (MPB) *(Dendroctonus ponderosae),* western spruce budworm (WSBW) *(Choristoneura occidentalis),* root disease (RD) (most likely *Armillaria* spp., *Phellinus weirri*, *Heterobasidion annosum, Phaeolus schweinitzii*, and *Ceratocystis* spp.), dwarf mistletoe (DM) (*Arceuthobium* spp.), and wildfire (FIRE). Areas of WSBW and DM are affected hectares rather than hectares of mortality. In order to graphically display RD in terms of "number of hectares affected," a ratio was calculated using the available cubic meter measurement of RD mortality (Smith 1984), and the cubic meter and hectare measurements of DM volume loss (Drummond 1982). Although the RD "hectares" are not a true measure of area, they do retain the relationship of the relative importance of RD volumes to DM volumes. RD and DM are known to fluctuate somewhat, but these patterns have not been followed closely.

All hectares affected by the five specific agents were combined, and the relative importance (as a percent of the total affected area) was determined for each Region *(fig. 5)*. This interpretation lacks the ability to show quantitative levels of agent impact (e.g., hectares/Region or hectares affected/hectares available). However, it does provide a basis for the evaluation of which agents may be principal in creation of coarse woody debris within a Region.

As expected, MPB is relatively important in the Northern, Rocky Mountain, Intermountain, and Pacific Northwest Regions where it attacks mostly lodgepole pine (*Pinus contorta* Dougl. ex. Loud.) and some ponderosa pine (*P. ponderosae* Dougl. ex. Laws.) *(fig. 5)*. However, MPB is relatively less important in the Southwestern and Pacific Southwest Regions. WSBW incidence is widespread but is relatively more important in the Rocky Mountain Region. RD has been active in the Northern, Pacific Northwest, and Pacific Southwest Regions with some impact noted in the Southwestern and very little noted in the Rocky Mountain and Intermountain Regions. DM is the most active agent over the entire West and is particularly important in the Southwestern, Intermountain, and Pacific Southwest Regions. The limited number of hectares affected by other agents in these Regions would explain why DM shows higher importance in the southern Regions. Fire affects few hectares on average but is active in all Regions. Over the entire West, diseases affect a greater area than do insects and fire combined.

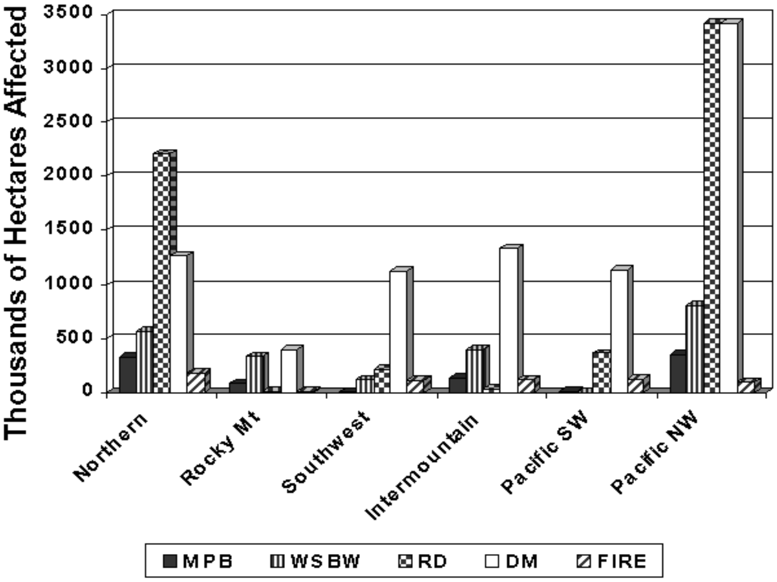


Figure 4—Average annual area (in thousands of hectares) affected by five specific mortality agents in each of six of the Forest Service's western Regions: recent past (1978-1997). Agents included mountain pine beetle (MPB) *(Dendroctonus ponderosae),* western spruce budworm (WSBW) *(Choristoneura occidentalis),* root disease (RD) (most likely *Armillaria* spp., *Phellinus weirri, Heterobasidion annosum*, *Phaeolus schweinitzii*, and *Ceratocystis* spp.), dwarf mistletoe (DM) (*Arceuthobium* spp.), and wildfire (FIRE). Areas of WSBW and DM are affected hectares rather than hectares of mortality. In order to graphically display RD in terms of "number of hectares affected," a ratio was calculated using the available cubic meter measurement of RD mortality (Smith 1984) and the cubic meter and hectare measurements of DM volume loss (Drummond 1982). Although the RD 'hectares' are not a true measure of area, they do retain the relationship of the relative importance of RD volumes to DM volumes. RD and DM are known to fluctuate somewhat, but these patterns have not been followed closely. FIRE numbers for the Regions are actually by state boundaries resulting in slightly different areas for the Northern, Rocky Mountain, and Intermountain Regions.

Projected Risk—The expected importance of the four insect and disease agents (fire excluded) over the next 15 years is based on predicted mortality (not growth loss) *(fig. 6),* which may explain the principal changes in importance between predicted and past agent importance. In the recent-past data MPB was not the principal active agent in any Region. However, when predicted mortality is considered, MPB is expected to be the principal mortality agent in half of the Regions (Rocky Mountain, Intermountain, and Pacific Northwest). RD was and is predicted to be the principal active agent in the Northern Region and is predicted to be the principal agent in the Pacific Southwest. In the Southwestern Region, DM is predicted to be the most important mortality agent, with considerable activity in the Pacific Southwest. Despite their large area of influence in all Regions during the past 20 years (recent past), predicted importance of WSBW and DM is much lower due to the minimal associated mortality.

Differences in agent past and predicted importance *(figs. 5, 6)* may be indicative of changes in host availability, advances in detection of agents, increased recognition of agent roles, differences between area affected (recent past) and area of mortality (projected risk), or differences in methodologies used to determine affected area. Small changes are also expected due to the exclusion of fire from the projected mortality data. We should note that relative importance of an agent over the entire western U.S. differs depending on whether relative importance (by hectares) or average percent importance (sum of percentages divided by six Regions) is used. These differences between relative importance values are due to the very high number of hectares of RD mortality predicted by the Northern Region.

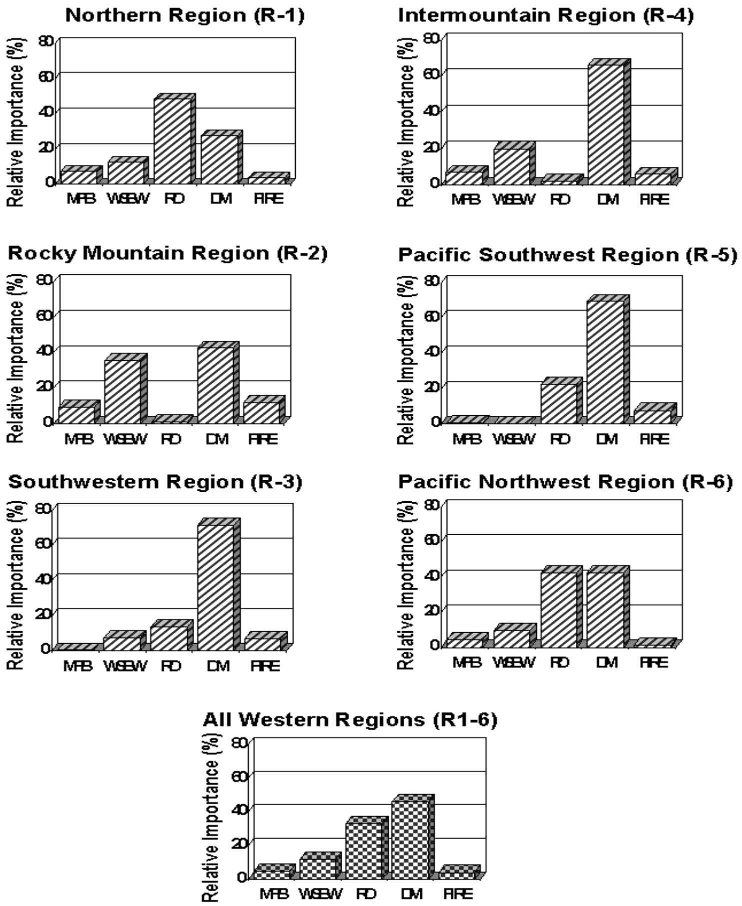


Figure 5—The historical relative importance of five specific mortality agents in the western U.S.: recent past (1978-1997). Agents included mountain pine beetle (MPB) *(Dendroctonus ponderosae),* western spruce budworm (WSBW) *(Choristoneura occidentalis),* root disease (RD) (most likely *Armillaria* spp., *Phellinus weirri*, *Heterobasidion annosum*, *Phaeolus schweinitzii*, and *Ceratocystis* spp.), dwarf mistletoe (DM) (*Arceuthobium* spp.), and wildfire (FIRE). Data from 1978 to 1997 were used to calculated annual averages. In some cases data was missing. MPB data was complete for 18 of the 20 years. FIRE data was available from 1984 to 1997 for a total of 14 years. Data for RD and DM were from the early 1980s. Importance of WSBW and DM are based on affected hectares rather than hectares of mortality. RD importance was calculated based on a ratio of the volume impacts of RD to DM. FIRE numbers for the Regions are actually by state boundaries resulting in slightly different areas for the Northern, Rocky Mountain, and Intermountain Regions.

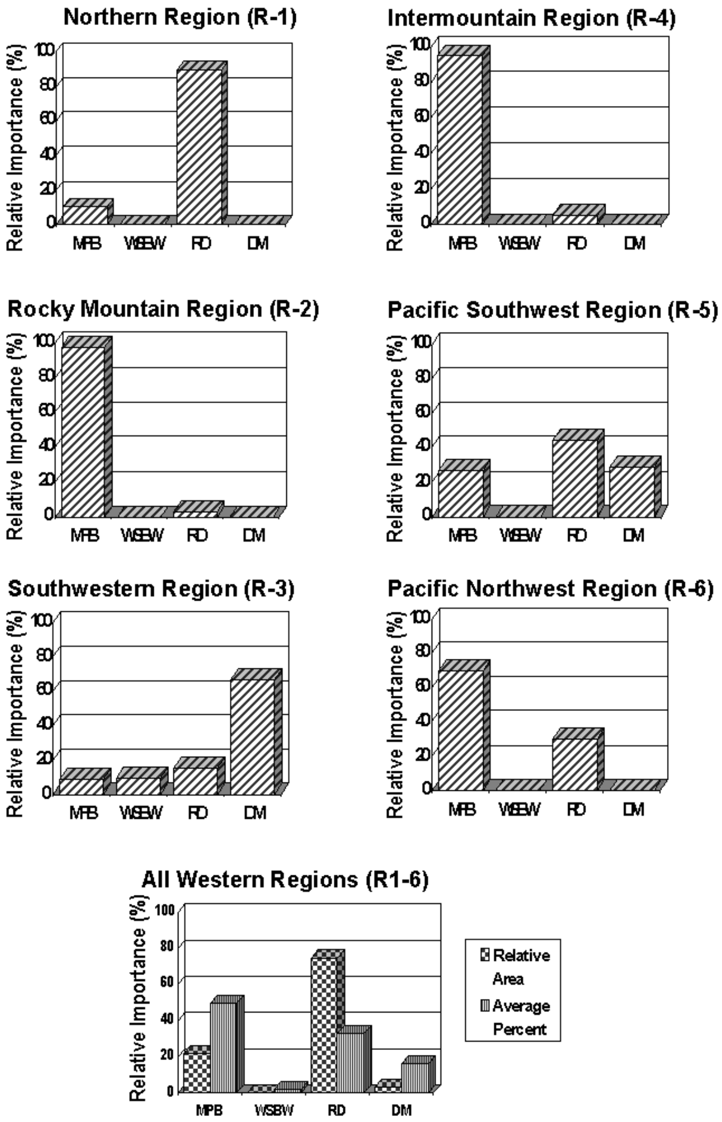


Figure 6—The predicted relative importance of four specific insect and disease mortality agents in the western U.S.: projected risk (2000-2015). Agents include mountain pine beetle (MPB) *(Dendroctonus ponderosae),* western spruce budworm (WSBW) *(Choristoneura occidentalis),* root disease (RD) (most likely *Armillaria* spp., *Phellinus weirri*, *Heterobasidion annosum*, *Phaeolus schweinitzii*, and *Ceratocystis* spp.), and dwarf mistletoe (DM) (*Arceuthobium* spp.). Data are from a Forest Service risk assessment project being conducted by the Washington, D.C. office and is preliminary only. Revisions are being completed by the Forest Service. However, relative importance relationships are expected to remain similar. Because FIRE is not graphed, the importance of each agent is not directly comparable to *figure 5.*

Mortality Agent Groups: Patterns and Scale

Projected Risk—Because of the inclusion of many other bark beetles species and of white pine blister rust (under other pathogens [PO]) *(fig. 7),* the expected relative importance of the "agent groups" differs somewhat from the "specific agents" *(figs. 5, 6).* MPB used in *figures 5-6* is only one of many important bark beetles of the western U.S. Risk data predicts MPB will contribute approximately half of the bark beetle mortality over the next 15 years in the Northern, Rocky Mountain, and Pacific Northwest Regions. In the Southwestern Region, MPB constitutes only about 7.5 percent of the predicted BB mortality, while in the Intermountain and Pacific Southwest, MPB constitutes only 13 and 22 percent, respectively. Additional mortality in the West is expected from Douglas-fir beetle, western pine beetle, round-headed pine beetle, Jeffery pine beetle, spruce beetle, fir engraver, western balsam bark beetle, and ips (*Ips* spp.).[3] Most Regions maintain similar importance profiles whether "specific agents" or "agent groups" are used. Only in the Southwestern and the Pacific Southwest Regions did MPB impact fail to represent BB impact. WSBW successfully represented DF in all of the Regions except Intermountain, where Douglas-fir tussock moth (*Orgyia pseudotsugata* McDunnough) is expected to cause considerable defoliation impact. Information indicates that insects other than BB and DF are not expected to contribute significant additional mortality to western conifers. However, recent and future exotic insect introductions could have considerable unpredicted impacts.

The "specific agents" and "agent groups" *(figs. 6, 7)* used the same hectare numbers for RD and DM quantities. Thus, changes in relative importance are due to changes in hectare values of the other agent groups. Notably, the inclusion of other pathogens (PO) was important in representing both historic and predicted impact of disease in the western U.S. In all Regions except the Pacific Southwest, the exotic white pine blister rust (included in PO) is predicted to cause significant areas of mortality.[3] In the Rocky Mountain Region, comandra blister rust is also expected to be important.[3] The relatively high RD impact is still evident in the Northern Region and influences the overall importance value of RD in the West when total hectares at risk are considered.

Historical (1952)—Data from 1952, using similar mortality agent groupings for slightly different regional delineations, shows a number of variations between historical and predicted importance values. In 1952 bark beetles were the primary source of mortality (by tree volume) over all Regions *(fig. 8).* Future predictions indicate the continued relative importance of bark beetles, except in the Northern Region where the dramatic increase in RD importance overshadows effects of all other agents. Both historical data and future predictions indicate limited DF mortality across the West with highest impact in the Southern Rocky Mountains. It is unclear which insect was responsible for the significant "other insect" mortality in California in 1952 *(fig. 8).* However, over the West, other insects (IO) besides bark beetles and defoliators have not had a large effect.

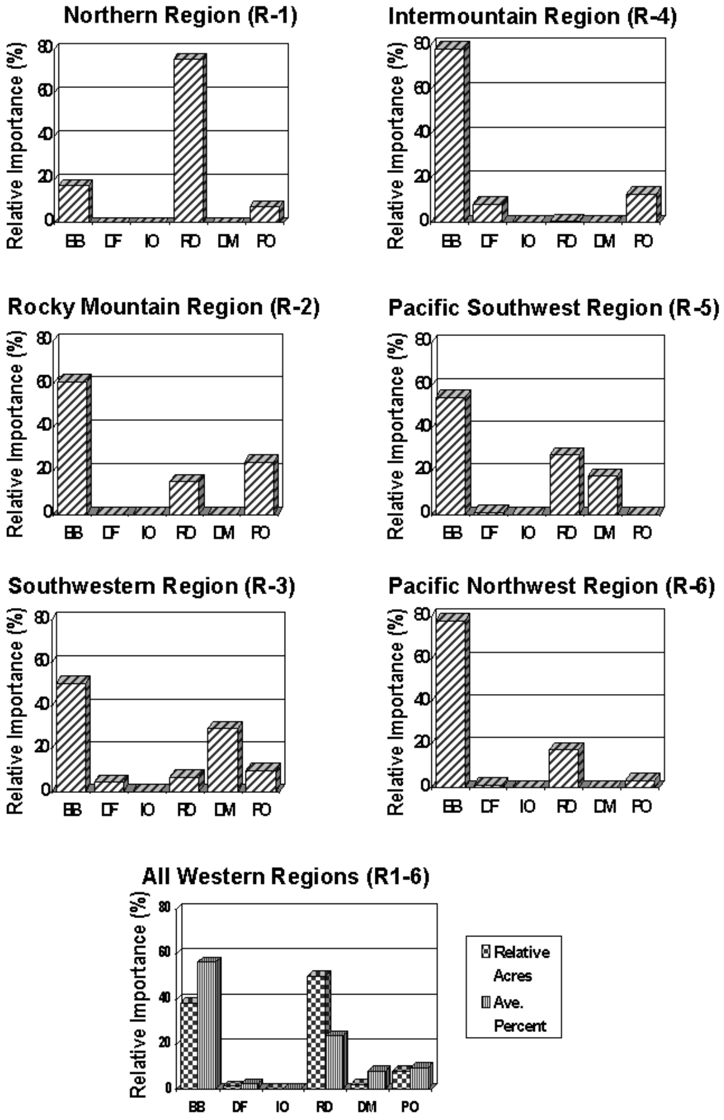
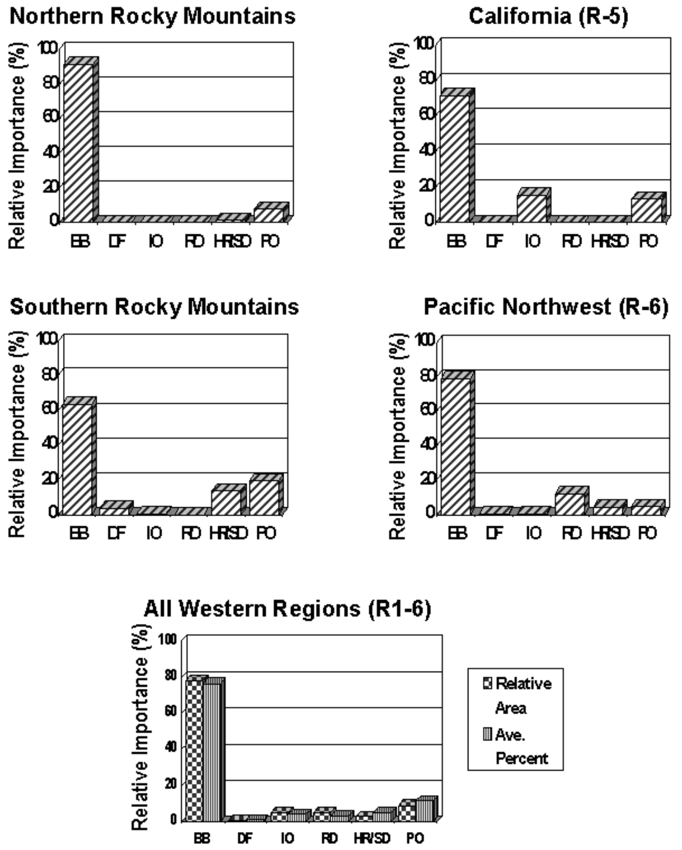


Figure 7—The predicted relative importance of six insect and disease agent groups in the western U.S.: projected risk (2000-2015). Agent groups are bark beetles (BB), defoliators (DF), other insects (IO), root disease (RD), dwarf mistletoe (DM), and other pathogens (PO). Organisms within each group include: Douglas-fir beetle *(Dendroctonus pseudotsuga),* fir engraver *(Scolytus ventralis),* pine engraver *(Ips pini),* Jeffery pine beetle *(D. jeffreyi),* MPB, roundheaded pine beetle *(D. adjunctus),* spruce beetle *(D. rufipennis),* southern pine beetle [in Arizona] *(D. frontalis),* western pine beetle *(D. brevicomis),* and western balsam bark beetle *(Dryocetes confusus)* for bark beetles; Douglas-fir tussock moth *(Orgyia pseudotsugata),* and western spruce budworm *(Choristoneura occidentalis)* for defoliators; balsam woolly adelgid *(Adelges piceae)* for other insects; annosus root disease *(Heterobasidion annosum),* subalpine fir decline, and other unnamed root diseases under root disease; various dwarf mistletoes (*Arceuthobium* spp.); comandra blister rust *(Cronartium comandrae)* and white pine blister rust *(C. ribicola)* for other diseases. Data are from a Forest Service risk assessment project being conducted by the Washington, D.C. office and is preliminary, only. Revisions are being completed by the Forest Service. However, relative importance relationships are expected to remain similar.



Northern Rocky Mountains

California (R-5)

Southern Rocky Mountains

Pacific Northwest (R-6)

All Western Regions (R1-6)

Figure 8—The historical relative importance of six insect and disease agent groups in the western U.S.: historical (1952). Regions in the 1952 data are different from the Forest Service Regions. In place of the Northern, Rocky Mountain, Southwestern and Intermountain Regions, the 1950s study combines these four Regions into two Regions; the Northern Rocky Mountains and the Southern Rocky Mountains. The Northern Rocky Mountains contains all of the Northern as well as part of the Rocky Mountain and Intermountain Regions (Idaho, Montana, South Dakota, and Wyoming). The Southern Rocky Mountain contains all of the Southwestern, as well as the remainder of the Rocky Mountain and Intermountain Regions (Arizona, New Mexico, Colorado, Utah, and Nevada). The six insect and disease agent groups include bark beetles (BB), defoliators (DF), other insects (IO), root disease (RD), heart rot and stem disease (HR/SD) and other pathogens (PO). Organisms within each group are not defined. However, IO includes borers, tipmoths, turpentine beetles, and balsam wooly aphid. RD is primarily Douglas-fir root rot (possibly *Phellinus weirii* = *Inonotus sulphurascens*). HR/SD is heart rot, blister rusts (*Cronartium* spp.) and dwarf mistletoe (*Arceuthobium* spp.). OP includes foliage and systemic diseases (*Elytroderma deformans* and pole blight). Differences in the measure of impact (volume not hectares) and in regional delineations complicate comparisons, but relative importance of mortality agents is expected to remain indicative. Data are from the year 1952 and are similar to trend data, except in the Northern Rocky Mountains where insect mortality was higher and disease mortality was lower than trends had indicated (USDA Forest Service 1958).

Historically, only the Pacific Northwest was noted for important RD mortality, while future expectations are of significant mortality in all Regions except the Intermountain (part of both the historic Southern Rocky Mountain and Northern Rocky Mountain Regions). In the 1952 data DM is grouped with heart rots and other stem diseases (HR/SD). This inclusion of other agents could explain why the historic Pacific Northwest HR/SD value *(fig. 8)* is higher than predicted DM values *(fig. 7)*. In the Pacific Southwest, however, the only explanation for the predicted increase in the DM value over the historic HR/SD is an actual increase in DM in the Region. Other pathogens have also changed. In 1952 elytroderma (*Elytroderma deformans* Darker) and pole blight were the principal "others," while future predictions denote white pine blister rust and comandra blister rust as important "other" pathogens. Primary causes for these differences likely include the use of volume impact (1952 data) in place of area, progress in understanding and detection of agents, differences in assigning causal agent in areas where many agents are active, and actual changes in forest susceptibility due to exotic pests, fire exclusion, and silvicultural practices (USDA Forest Service 1988).

Our analysis focused principally on insect and disease mortality agents, and on fire where data was available. It is important to remember, however, that there are other agents that can be locally very important in the recruitment of coarse woody debris. Mortality due to wind is very important in some regions, as are snow and ice, floods, drought, lightning, avalanches, animals, and suppression by other trees (USDA FS 1958, Harmon and others 1986, Parminter 1998). In the Rocky Mountain and Southwestern Regions, "other" agents may actually have caused greater mortality of sawtimber than insects, diseases, or fire (USDA FS 1958) *(fig. 9)*. In all Regions except the Pacific Southwest, "other" mortality was caused by weather with some animal damage. In the Pacific Southwest mortality was due to suppression by other trees. More recent regional information on mortality due to weather is patchy but indicates its continued importance (Harmon and others 1986). Also locally important may be the effects of pollution (e.g., air, water, or ground) (Carlson and Dewey 1971).

Discussion

Temporal and Spatial Scales of Coarse Woody Debris Recruitment

Recent mortality data (1978-1997) presented here show some of the differences in the spatial and temporal patterns of the various mortality agents *(figs. 2, 3)*. Such differences in disturbance regimes have been previously noted (Geils and others 1995, Parminter 1998) but not often quantified (see Swetnam and Betancourt [1998] for a quantitative example.) It is these differences in mortality patterns, as well as the character of the mortality agent, that affects the scales (spatial and temporal) of the coarse woody debris recruitment (Clark and others 1998, Li and Crawford 1994, Lundquist and others 1998).

This paper presents spatial scale only in terms of the number of hectares affected within a geo-political landscape unit (Regions) and does not give information on the distribution or extent of mortality incidences within the Region. For example, it is possible for an agent to create many small patches of mortality across the landscape, or to disturb a large contiguous area and yield similar values of hectares affected. However, literature on past effects of various disturbance agents does provide qualitative understanding of the possible differences in the spatial distribution of created dead wood. For example, epidemic MPB in monotypic stands of lodgepole pine are likely to create a larger, more continuous area of mortality than will Douglas-fir beetle in mixed forest type under endemic conditions.

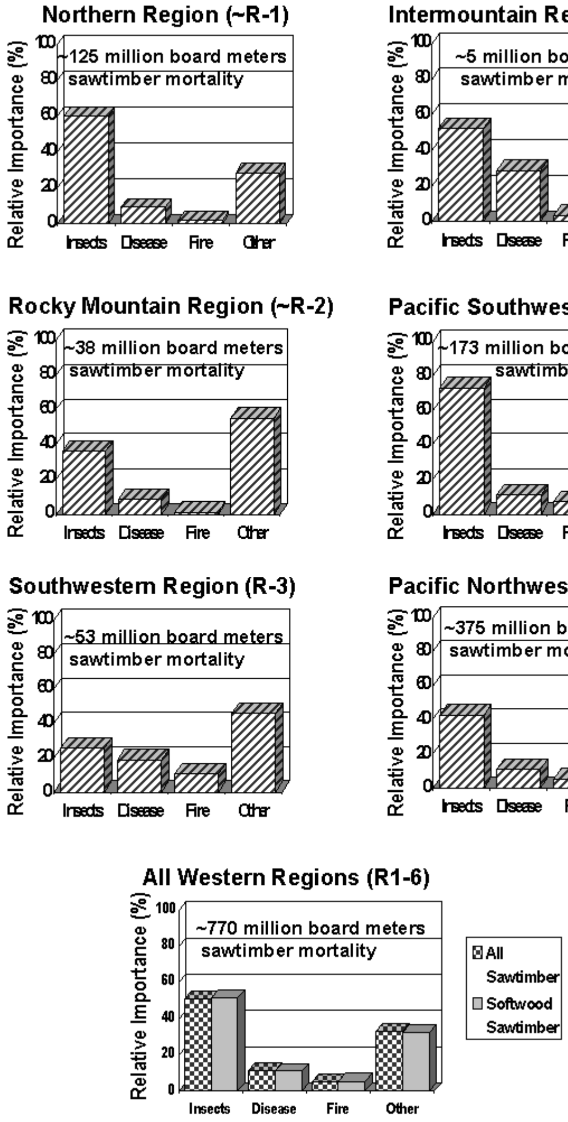


Figure 9—Relative importance of four mortality agent groups in the western U.S.: historical (pre-1952 trend). Region delineations differ from the Forest Service Regions. Because data were given by state, the Northern, Rocky Mountain, and Intermountain Regions had to be approximated using state boundaries (e.g., Northern Region as Montana and Idaho; Rocky Mountain as Wyoming, Colorado, and South Dakota; Intermountain as Nevada and Utah). The “other” category is principally suppression by other trees, timber harvest damage, weather, and animals. West and U.S. graphs show values for all sawtimber and softwood sawtimber on commercial lands (USDA Forest Service 1958).

Parminter (1998) makes two important points for understanding the differential spatial effects of agents. First, small-scale disturbances are the primary source of heterogeneity in forest structure and composition, including the dead wood component. Regular patches created by BB tree- or patch-attacks, RD pockets, or some windthrow events operate at the tree or stand level but cause landscape patterns and landscape consequences. Second, large-scale disturbances such as wildfire, blowdown, floods, and other often weather-related events act on all tree species, sizes, and ages, resulting in significant or complete mortality over a large area. Often the result is a shift in successional stage and sharp increases or pulses of coarse woody debris input. Additional discussion on the role of disturbance scale on the resulting ecosystem structure can be found in Holling (1992).

Data on the effects of agents over the past 20 years (1978-1997) *(figs. 2, 3)* exhibit annual differences, as well as possible long-term temporal patterns of mortality agents. For example, MPB activity shows a long-term cycle, while fire hectares appear to fluctuate greatly on a yearly basis. Likely, this is due to the population dynamics of the beetles and continuity of stand structure from year to year, as compared to the high variability of precipitation, temperature, wind, and humidity that greatly affect fire. Longer-term patterns in fire activity are not evident *(figs. 2, 3),* but have been found in long-term data sets (e.g., Swetnam and Betancourt [1998]). Seasonal variations, also, are not visible, but literature indicates that seasonal coarse woody debris recruitment often occurs in relation to seasonal weather patterns (e.g., heavy rains, wind, fire, floods, etc.). We should also note that, although hectares affected do not directly translate into mortality or amount of coarse woody debris created, *figures 2-3* do illustrate the dynamic variability inherent in the agents.

Differences in agent activity between Regions, such as the Northern and Southwestern, are indicative of the principal regional ecosystem processes at work *(figs. 2, 3).* For example, RD is much more active in the Northern than in the Southwestern Region while the opposite is true of DM. These differences are directly related to precipitation and principal forest types of the two areas. However, because these two Regions are not comprised of equal acreages, it would be incorrect to assume that DM has a nearly equal impact over the Northern as the Southwestern Region.

The Pacific Northwest has both the most forested hectares and the most commercial forest hectares of the six Regions (USDA FS 1958). Because of this larger area, agent impacts (as total hectares) are likely to appear greater in the Pacific Northwest than in smaller Regions *(fig. 4).* Data on the total number of hectares surveyed is not readily available, although reports indicate that more than just the commercial forested lands are surveyed. If hectares affected were related to average yearly hectares surveyed, some additional regional trends might be visible.

Although an agent may act principally at one spatial or temporal scale, it is important to recognize its effects at all scales (Parminter 1998). The determined importance of an agent on the ecosystem depends on which of these levels is being evaluated. For example, outbreaks of bark beetles such as Douglas-fir beetle can kill many trees at the patch or stand scale within 3 or 4 years. Yet, over the landscape, these clustered or widely dispersed groups of dead trees can create greater landscape heterogeneity over many decades (Parminter 1998). At the patch level the beetle may be described as a negative influence, killing trees. Yet, at the landscape level the positive effects of heterogeneity might be noted.

Differential Activity of Mortality Agents

In addition to differences in spatial and temporal scales of coarse woody debris recruitment, mortality agents produce types of dead wood that serve varying roles in the ecosystem (Bull and others 1997, Harmon and others 1986). A basic understanding of the differences in agent groups will augment further interpretation of the significance of the regional variations presented.

Bark beetles tend to be tree species- and size-specific, generally affecting trees already weakened, diseased, or otherwise stressed (Amman and McGregor 1985, Barbosa and Wagner 1989, Dahms and Geils 1997). The area affected may fluctuate annually with weather and stand conditions, but when considerable amounts of favorable host become suitable habitat, outbreaks can occur, killing trees over entire watersheds (Amman and others 1989). Defoliator populations are more influenced by favorable synchrony between host phenology and defoliator life cycles, and are often influenced by environmental factors, such as weather, stand and site conditions, and enemy populations (Barbosa and Wagner 1989, USDA Forest Service and others 1999, Wulf and Cates 1985). Although defoliators don't generally kill trees, they can have significant impacts with repeated and complete defoliation (Barbosa and Wagner 1989, Swetnam and Lynch 1989, 1993). The dead wood that remains after insect attacks is often in the form of snags (Harmon and others 1986). Longevity of these snags, rate of bark slough, amount of stem breakage, and other traits depends on factors such as the tree species, tree size, other biotic agents (e.g., heart rot, staining fungi, arthropods, other animals) and abiotic forces (e.g., soil type, wind, rain, fire, temperature) (Brown and others 1998, Dahm 1949, Harrington 1996, Lowell and others 1992, Morrison and Raphael 1993, Schmid and others 1985).

Diseases are numerous and their effects so variable that a generalization of effects is difficult. Disease species may act principally on one host species (e.g., DM) or have effects on several host species in an area (e.g., RD) (USDA Forest Service and others 1999). Regional variation in effects may be due to disease virulence, tree or species resistance, climate, and other site conditions (Hawksworth and Wiens 1996, USDA Forest Service and others 1999). In many ecosystems disease contributes little coarse woody debris directly but predisposes large areas to other killing agents such as bark beetles (Otrosina and Ferrell 1995). In other ecosystems, disease, especially RD, may directly contribute considerable amounts of coarse woody debris (Byler 1978). The types and sizes of debris created by disease are also variable (Lundquist and others 1998). RD may kill several tree species of various sizes, and often causes trees to fall, creating mostly downed material of many sizes. DM may cause only top-kill or dropping of infected branches (Hawksworth and Wiens 1996), while, in large western white pine (*Pinus monticola* Dougl. ex. D. Don), white pine blister rust can create large snags (Monnig and Byler 1992).

All fire size classes and sources of ignition were included in the fire data, yet these can be biologically very different. Actual effects of fire depend largely on the type of fire (e.g., ground, surface, or crown) and its intensity, as well as the tree species and stand structure. Low intensity fire (surface or ground) acts more like DF or DM in that it does not cause large-scale mortality. Such fire generally consumes the downed debris. Mortality that does occur is selective for less fire tolerant tree species and smaller individuals. High intensity crown fire, however, is different from most insects and disease in that it can kill all trees of all species, sizes, and ages over a large area. Mortality in high intensity fires is condensed in time and space, providing considerable dead wood in relation to the area affected. It is calculated that a single intense fire could create between 105 and 575 years' worth of "normal" coarse woody debris input (Harmon and others 1986).

The dead wood created by other, often weather related agents (wind, snow and ice, avalanches, and flood) will likely include many tree species and sizes as described for high-intensity fire. However, because the tree is killed "by force," the coarse woody debris is usually downed material with broken snags. Other forces such as lightning, animals, and suppression by other trees may be more tree-selective or act on smaller patches, resulting in more specific species or size class mortality visible as standing snags.

Wind has been noted as being a particularly important mortality agent in some regions. For example, hurricanes and typhoons have damaged large areas of coastal North America, Europe, and Asia (Harmon and others 1986). Smaller patches of wind damage are also possible and occurrence can range from chronic seasonal damage to sporadic high recruitment spikes. Damage may differ by forest type as well as by soil type, topographic position, and edaphic conditions (Harmon and others 1986). Wind can leave broken snags, but the majority of the coarse woody debris is downed material.

Implications of Findings for Ecosystem Managers

Kile and others (1991) noted that until the 1970s, the overall impact of RDs such as *Armillaria* had not been appreciated. Smith (1984) calculated that 18 percent of the tree mortality in the western U.S. was due to RD. Recent past and projected-risk data presented here indicate that RD may be an even more important factor in tree mortality and recruitment of coarse woody debris than recent literature has indicated. Areas where RD is a principal agent of mortality include the Northern and Pacific Northwest Regions *(fig. 5)*. Projections also indicate that in the Pacific Southwest, RD is expected to be of increasing importance *(fig. 6)*. A greater proportion of susceptible tree species (Douglas-fir [*Pseudotsuga menziesii* Franco] and true firs [*Abies* spp.]) in these areas could account for the greater impact compared to areas dominated by more resistant pines. Overall, it is expected that harvest practices (especially selective logging), fire exclusion, and mortality caused by white pine blister rust have resulted and will continue to result in less tolerant forests and increased incidence of RD (Castello and others 1995, Smith 1984).

All Regions throughout the West show high hectare impacts by DM during the past 20 years—the Southwestern, Intermountain, and Pacific Southwest Regions in particular *(figs. 4, 5)*. The principal effect of DM is growth loss. However, increased DM would result in weakened trees that may succumb to secondary agents (e.g., BB) or environmental stress (e.g., drought) (Byler 1978, Wood 1983). Unfortunately, pulses of mortality due to these additional stressors have not been well documented but should be expected. The Southwestern and the Pacific Southwest Regions are predicted to experience DM as an important mortality agent in the years to come *(figs. 6, 7)*.

Pathogens other than RD and DM have caused mortality in the past (pre-1952) and are projected to continue doing so in the future. Historically, pathogens of importance included elytroderma and pole blight. In the future, pathogens of importance in the Northern, Rocky Mountain, Southwestern, and Intermountain Regions are predicted to be white pine blister rust (exotic) and comandra blister rust.

The introduction of additional exotic pathogens could also cause significant future tree mortality.

BB have historically been the most important source of tree mortality in the western U.S. and, in 1952, made up 60 to 90 percent of insect- and disease-caused mortality *(fig. 8)*. With the exception of the Northern Region, mortality risk projections predict that 50 to 80 percent of insect- and disease-caused mortality in the next 15 years also will be due to bark beetles *(fig. 7)*. Except in the Southwestern and Pacific Southwest Regions, MPB is expected to be the principal BB. Differences in the resulting snags will depend on site conditions, tree species and pre- and post-mortality agents.

The principal DF in the West is WSBW, but Douglas-fir tussock moth is also noted (USDA Forest Service 1988). Although these insects can affect large areas, defoliation rarely results in death unless nearly complete defoliation occurs over 3 or more years, or secondary agents take advantage of the tree's stressed condition (van Sickle 1985). The only area that shows relatively high defoliation in the recent past is the Rocky Mountain Region *(fig. 5)*. High WSBW incidence is closely related to available host forests (Douglas-fir, true fir and spruce forest types), a history of fire exclusion and selective logging, and conducive climate patterns (Fellin 1985). Projected defoliation-related mortality (although limited) is expected in the Southwest (by WSBW) as well as the Intermountain, Pacific Southwest, and Pacific Northwest Regions (by Douglas-fir tussock moth) *(fig. 7)*.

Also of importance to dead wood recruitment is the build-up of dead wood during the period of fire exclusion, and the resulting increased incidence of catastrophic (high intensity) fire (Carlson and others 1995, Johnson 1995). In areas like the Southwestern Region where fire (low intensity) is the primary force cycling nutrients (Carlson and others 1995, Harvey 1994), the actual pathway through which the dead wood passes is altered by changes in fire regimes. Moreover, this history of fire exclusion has helped alter forest types across the West towards dense, multi-story stands of shade-tolerant, fire-intolerant tree species (Schmidt 1985). These new stands, in turn, have different insect, disease, and fire susceptibilities, and produce different types of coarse woody debris. Unique regional and forest-type fire regimes are well described in other literature (DeBano and others 1998, Mooney and others 1981, Swetnam and Betancourt 1990).

In general, management of insects and disease is management of the forest and use of proper silvicultural practices (Barbosa and Wagner 1989, USDA Forest Service 1988, USDA Forest Service and others 1999). For example, outbreaks of most bark beetles require a large amount of susceptible host of suitable size, age, and stem density (Amman and others 1977). Decreasing stem densities, removing the preferred hosts, and allowing controlled burning are all considered important strategies in control of most bark beetles (USDA Forest Service and others 1999). In many cases, these same practices may also be used to control other insects and diseases (Miller 1979). The idea is that insect and disease problems can be mitigated by increasing the vigor of the tree and decreasing the amount of susceptible host (Kegley and others 1997).

Implications for Ecosystem Processes

Changes in the regimes of deadwood recruitment can have effects on various ecosystem processes, including soil retention (physical), nutrient cycling (chemical), and wildlife habitat (biological) (Harmon and others 1986). For example, because orientation and size of coarse woody debris effects soil retention on slopes and in streams (Harmon and others 1986), large quantities of small 'jack straw' stems broken from an ice storm might not have the same soil stabilizing effect that large, ground-contacting root diseased trunks would have. Since logs from older trees decay faster than young trees (Harmon and others 1986), debris from MPB activity might exhibit faster nutrient cycling than that from a windstorm (due to beetles selecting the larger, older trees) (Amman and others 1977, Amman and McGregor 1985, Cole and Amman 1980). And in terms of wildlife habitat, a large tree with heart rot that succumbs to bark beetles differs from a small tree that falls from RD (Bull and others 1997) or a RD-created brush field (Monnig and Byler 1992).

Available information about changes in regional disturbance regimes may help determine regional changes in the coarse woody debris recruitment. For example, we would expect that historic low intensity, high frequency fires of the Southwestern Region would have created different coarse woody debris properties than the more recent high intensity, low frequency fires (Harvey 1994, DeBano and others 1998, Touchan and others 1994). And in the Pacific Northwest, the effects of white pine blister rust, selective logging, and fire suppression in changing forest type from pine to Douglas-fir and true firs have already begun to produce a higher incidence of RD (Kile and others 1991, Monnig and Byler 1992). In both examples, the resulting dead wood will influence insect communities, fire patterns, and numerous other biological processes.

Management of Coarse Woody Debris

Management of coarse woody debris must consider not only active mortality agents and needs for specific types of debris but also the interaction of the coarse woody debris within the ecosystem. The agents we have mentioned not only create woody debris but also may take advantage of dead wood created by other agents including humans. For example, bark beetles may build to epidemic proportions in blowdown or logging slash, and RD can proliferate via freshly dead root systems (stumps, snags, etc.; USDA Forest Service and others 1999). An understanding of the management of human created coarse woody debris and its interactions with insects and disease is important for forest managers. The influence of coarse woody debris on BB populations is just one of many considerations.

A good example of the importance of coarse woody debris management is the case of the pine engraver (*Ips pini* Say) in the Southwestern Region. Slash left from thinning or logging operations is often suitable habitat that allows for a dramatic population increase leading to pine engraver outbreaks. However, we know that proper treatment of the slash can prevent these population buildups. Preventative treatments emphasize cutting and disposing of trees in such a way as to dry out the slash, rendering it less suitable for beetle reproduction (Kegley and others 1997, Massey and Parker 1981, Wilkinson and Foltz 1982). In addition to outbreak prevention techniques, there are suppression techniques that can kill beetle larva, adult beetles, or disrupt future mating (Kegley and others 1997, Massey and Parker 1981, Shea 1994, Wilkinson and Foltz 1982).

If managers are interested in creating coarse woody debris for the ecological services it provides, it may be beneficial to look at both past and projected agent activity. Although we have presented mortality agents as isolated forces, interaction between agents is the rule not the exception (Rogers 1996). Geils and others (1995) note that most managers work at the gap or stand level. However, our analysis is at a much larger scale. A finer scale evaluation of the mortality agents and the forest types in the stands of interest will result in better management decisions.

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