FIRE/DECAY: MANAGING CODEPENDENT FOREST PROCESSES ACROSS THE LANDSCAPE

Alan E. Harvey, Russell T. Graham, Geral I. McDonald and Michael J. Larsen
USDA, Forest Service, Rocky Mountain Research Station
Forestry Sciences Laboratory, 1221 S. Main St., Moscow, Idaho, 83843
Phone: (208) 882-3557
E-mail: aharvey@forest.moscowfsl.wsu.edu; aharvey/rmrs_moscow@fs.fed.us

ABSTRACT

The balance of the two principal carbon-mediating processes (fire and biological decomposition) across forested landscapes requires differing approaches to managing fuel accumulation and dispersion. Relative dependency of harsh habitats (hot/cold/dry) on fire suggests management approaches will require at least some direct physical intervention via prescribed fire treatments, thinning and/or harvest removal. Conversely, moderate habitats (warm/moist), where biological decomposition plays a prominent role, provides opportunities for increasingly harnessing biological actions as a means of moderating fuel conditions. Management of forest structure to raise (or lower) temperatures and to improve ground-level moisture conditions, in combination with physically modifying fuel to enhance activities of endemic or introduced decomposers, holds considerable promise for reducing the long-term fuel accumulation problems in moderate forest environments.

Key words: Decomposition, fire effects, fuel treatment, partial cutting, soil microbes, thinning.

FIRE/DECAY CODEPENDENCIES

Perhaps the most notable characteristic of western interior forests is their tendency to rapidly accumulate carbon over time (Olsen 1981). The photosynthetic (carbon fixation) process is much less limited by this environment than is respiration-driven biological decomposition. Thus, fuel accumulates and eventually burns, or must be removed (Harvey et al. 1979).

Overview of Forest Condition:

Fire events in forests of the western U. S. vary from every few years to centuries. Weather patterns provide enough lightning to cause widespread ignitions, with or without the help of humans (Olsen 1981). In the absence of fire, succession advances, stand density increases, nutrients are sequestered in accumulating organic debris and turnover (carbon/other nutrients) slows. Specific benefits of charcoal (pH control, detoxification/adsorption of phenolic derivatives, enhanced microbial activity) in forest soils are likely reduced. Thus, ecosystem development without fire is eventually impaired (Zackrisson et al. 1996, Harvey 1994a,c, Harvey et al. 1976). Historical fire cycles processed fuel accumulations and maintained other critical processes. If accumulation persists over excessively long time periods, fire events can be extreme and potentially damage sites and nutrient cycling processes (Sampson and Clark 1995).

Success with fire control this century has placed most short-fire-cycle interior forests in the dense, high fuel accumulation category (Sampson and Clark 1995). These forests are generally successionally advanced with high mortality. Dry season wildfires can now put both soils and vegetation, including root systems, at inordinately high risk to mortality or outright loss (Harvey 1994a, Swezy and Agee 1991).

Succession and Structure:

Associated with the rapid change from open seral to dense climax dominated stands are significant alterations of both the above- and below-ground structure of trees and the stands and landscapes that support them. Perhaps the most striking, at least in dry forests, is the increased number of stems relative to historical forests (Covington et al. 1994, Gast et al. 1991, Baker 1988) and likely a corresponding change in root distribution. However, other changes are no less significant or important, if visually less striking. Some are even more widespread and are often typical of both dry and moist forests. For example, species composition, canopy height and shape, foliar dispersion, density (flammability) and nutrient content are all likely to be changed in both dry and moist ecosystems.

Western white pine (*Pinus monticola* Dougl. ex. D. Don) and western larch (*Larix occidentalis* Nutt.) tend to be tall and self prune well, even in moderately dense stands. They also carry large branches high in their crowns and have good foliar dispersion (Minore 1979).

Foliage and small branch wood from western white pine and western larch is of particularly low bulk density (and nutrient content) compared to most climax species (Minore 1979). Consequently, these stands carry their canopies well above surface fuels, tend not to have ladder fuels, do not carry crown fires well, and generally have low nutrient content. Thus, canopy nutrient stores are relatively well protected from fire.

In comparison, intermediate-age ponderosa pine (*Pinus ponderosa* Laws.), Douglas-fir (*Pseudotsuga menziesii* [Mirb.]Franco), grand fir (*Abies grandis* [Dougl. Ex. D. Don.]Lindl.), western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) and western red cedar (*Thuja plicata* Donn) are not tall, do not self prune well (especially when young), carry large branches low in their canopies (strong conical shape), do not have good foliar dispersion, and have relatively high bulk densities with resulting high nutrient concentrations in foliage and small branchwood (Minore 1979, Brown 1978, Van Wagner 1977). Therefore, stands dominated by these species often have ladder fuels, carry crown fires well and have a generally high nutrient content in tissues susceptible to loss from fire.

Soil:

Below ground there are similar changes. Pines and larch tend to be deep rooted while the true firs, hemlock and cedar all tend to be relatively shallow rooted with high levels of feeder root development (and mycorrhizae) in the high nutrient content, shallow soil organic layers (Gale and Grigal 1987, Harvey et al. 1976, Minore 1979). Douglas-fir also shows such trends when compared to ponderosa pine but less so than with other climax species (Minore 1979).

Thus, nutrients and nutrient turnover are likely to be dispersed vertically in soils dominated by seral species and concentrated in shallow soil horizons with climax species. Feeder roots of all plants tend to accumulate in the shallow, high resource organic horizons (Marschner and Marschner 1996, Robinson 1994). Therefore, soil surface nutrient stores and feeder roots in climax species dominated stands (or seral stands if surface organics accumulate from fire exclusion) can be more at risk to wildfire, or other disturbance, than those in pine and/or larch dominated stands. This risk can be magnified on infertile sites. In dense stands climax species may be much more demanding of resources (nutrients and water) than the historically open stands of seral species and, in some species combinations, they may also be less tolerant of short supply (Minore 1979).

Soils subjected to high intensity fires can lose not only surface reserves of organic matter and nutrients, but also those incorporated relatively deep within the soil profile: A problematic situation from the standpoint of practicing long-term sustainable forestry (Harvey et al. 1994c).

Genetics:

Even more subtle, but no less important, are differences in the overall genetic nature of these forests. Western white pine, ponderosa pine, western larch and western red cedar all tend to be broadly adapted to a wide range of sites and environments, while others tend to be more finely tuned within their respective ranges of sites and environments (Rehfeldt 1994).

Mortality Responses:

Tree stress based on site resource limitations, insect or pathogen activities, competition and short- or long-term environmental variation, is therefore much more likely in climax species stands (except for western red cedar) than with seral species stands. Similarly, tolerance to disturbances within the stand, or with climatic variations or trends that affect the stand externally, can be expected to cause rapid responses with climax and low or no responses in stands dominated by seral species.

LOCAL / GLOBAL REPERCUSSIONS

Fuel accumulations in western interior forests have made it increasingly difficult to suppress fires during the last decade. As a result, fires have become larger, more extreme and more environmentally damaging since the late 1980s. More lives, property, timber and soils have been at more risk than for the preceding century. The toll is adding up, and likely to continue doing so (Clark and Sampson 1995, Sampson and Clark 1995).

Rather than a natural and largely positive process in the development of ecosystems, fires now have high potential to become a significant threat to soils and biological systems (Harvey 1994a,c). Additionally, western interior forests this century have been a substantial and globally significant carbon sink prior to the early 1980s. However, wildfires have released more carbon than sequestered for most of the last decade (Auclair and Carter 1993). So, regional forest health and carbon cycling problems now have global as well as regional ramifications (Sampson and Clark 1995, Harvey 1994b).

WHERE TO FROM HERE?

Forested landscape patterns and processes result from a complex interaction of physical and biological processes acting over time spans of at least several hundred years, perhaps more. In the last hundred years the human dimension has significantly altered historical patterns. Current concerns by many biologists suggest a critical need to begin restoration of landscapes to more historically appropriate patterns of both disturbance and post-disturbance conditions in order to allow natural processes to function (U. S. Department of Agriculture, Forest Service 1996).

TRADITIONAL APPROACHES

Post-harvest Emphasis:

Traditional methodology for fuel treatment is largely limited to treating post-harvest or salvage situations where significant portions of the stand will or have been removed and portions of the funds generated offset the costs of treatment.

The unpopularity of harvest, prescribed fire and/or salvage operations introduces a significant political dimension, even in or around high value land developments where clear air and quality vistas are extremely valuable. Lack of opportunity has become a significant constraint!

Windows of Opportunity:

Regional climate may place severe limitations on the opportunities to create desirable burn characteristics, often delaying treatment several years and sometimes rendering successful treatment, especially with broadcast burning methodologies, essentially impossible.

Logistical and Cost Limitations:

Often the most appropriate burning method for environmentally friendly slash treatment, broadcast burning, has very narrow windows of opportunity, is risky, requires expensive logistical support and fire-control back-up capabilities. However, other options for effective treatment are limited and may also be costly.

Environmental Costs:

Although piling and/or windrowing and burning is much cheaper and easier from the standpoint of "upfront" costs and opportunities, the environmental costs in terms of compromising future forest development through increased compaction or decreased soil organic and nutrient reserves can eventually be very costly.

Economic Costs of Removal:

Unfortunately, the materials most often making the greatest contributions to undesirable fuel accumulations are also of least commercial value (small, stained, poor form, undesirable species, etc.) so there are limited opportunities for value of the material to subsidize site treatment, especially where the materials are distant from potential markets.

NEW POSSIBILITIES

Creating New Windows of Opportunity:

Current interest in and wide use of partial cutting methods potentially expands the windows of opportunity for treating slash progressively with several entries into forest stands.

Restoring Vertical/horizontal Structure:

Complete treatment and restoration of appropriate (historical conditions - healthy forests) stand conditions with a single entry is at best difficult and potentially unreliable. However, again partial cutting with several entries provides the opportunity to restore density, species composition and fuel accumulations in stages where outcome trends can be adjusted over time. This approach is attractive because it is adjustable, but only if it can carried out in a timely enough fashion to be effective!

Use Slash for Soil/site Amelioration:

Appropriately managed slash accumulations can be pre-treated and arranged to protect soil resources at any stage of multiple entry scenarios. By so doing, use of prescribed fire, or unintended wildfires, will have much lower risk for generating soil damage.

Seral Species Retention:

Perhaps the most important fuel management problems we face are those tied to advancing forest succession. In dry forests density is a significant problem, along with conversion of ponderosa pine to Douglas-fir dominance. In wet forests density is probably not a significant problem. The loss of seral species (white pine, larch, ponderosa pine) as major stand components is! Thus, any entry in high resource, fire-dominated ecosystems should have the restoration of seral species as the primary objective. Reducing density, except as a side effect of adjusting species composition, should probably not be a primary objective.

Excessive reduction of density where resources are in good supply may be self defeating. Allowing natural selection processes to act in high resource forests may be extremely important, as long as these processes have the opportunity to function in a manner that at least resembles historical conditions (see McDonald et al. these proceedings).

Treating Materials Destined for Slash:

With more than one entry into a forest stand comes the opportunity to preselect materials destined to become slash at any point in stand development. Treating those materials, standing or down, for enhancing recycling processes can begin early enough that they do not become a fuel problem associated with later planned disturbances or wildfire. Thus, thinning from below may select for products or for materials that will become slash at later harvest, or remain as risky fuels during stand development. These materials can be treated in a manner consistent with initiation of rapid biological decomposition (see below).

Site and Landscape Opportunities:

Dispersion of slash can and should take advantage of the high moisture available in shaded areas and in drainage ways or other relief patterns. Availability of slash can also provide opportunities for protecting unstable soils, drainage ways, springs and/or small streams. As with any source of problems, there are usually opportunities within, if they can be seen that way.

Subsidizing "Friendly" Approaches:

All the above are likely to cost more than most traditional methods. However, when viewed as a contribution to future values, and as a savings in costs for continued fire management under the worst of conditions, significant investments in the form of subsidies appear more than warranted.

Enlisting the help of endemic biological agents for processing portions of excess accumulations of woody debris remains a far greater opportunity than is generally recognized. Improving the situation for biological decomposition can and should be a part of virtually all management operations and need not generally add greatly (perhaps not at all) to overall costs.

DECAY: AN ECOSYSTEM PROCESS

Biological decomposition is ongoing in both living and dead woody materials (Lowell et al. 1992, Wagener and Offord 1972, Buchanan 1940). A myriad of microorganisms including fungi, bacteria, protozoa and invertebrates, individually and/or collectively, contribute to the decomposition process. Climatic weathering and interactions of the substrates with existing flora and fauna also contribute significantly (Torgerson and Bull 1995, Moldenke and Lattin 1990, Edmonds and Eglitis 1989).

End Products of Decay:

There are two major types of decay in woody plants, white- and brown-rot. Typically, white-rot fungi break down carbohydrates and lignin at somewhat similar rates leaving a light-colored, stringy product. Brown-rot fungi break down carbohydrates and leave lignin essentially unchanged, producing a dark colored, crumbly product (Highly et al. 1979, Larsen et al. 1980). In the interior region of the western United States, the principal decay process for large dimensional, dead, coniferous woody materials is of the brown-rot type (Larsen et al. 1980) that is typical of conifer ecosystems (Gilbertson 1981).

The products from these two decay processes function quite differently in forest ecosystems. Brown-rot end products are rich in nutrients and water and in some situations can substitute for forest humus (Ponge et al. 1998, Larsen et al. 1980). They are also very persistent and form unique deposits in and on forest soils (or streams) that support a number of highly specific functions (Ponge et al. 1998, Harmon et al. 1986, Harvey 1994a, Larsen et al. 1980). In contrast, white-rot end products do not tend to be rich in resources, are rapidly incorporated into soil humus and function primarily as such (Boddy 1991, Hintikka 1970). See also Graham et al. (this proceedings).

HARNESSING DECAY

Moisture and Temperature Requirements:

Moisture and temperature regimes are the primary controlling factors for microbial actions driving wood decay processes (Edmonds 1990, Etheridge 1958). The effects of both are critical. Many decay fungi are unable to grow above 40^{o}C. They usually have temperature optima between 15-35^{o} C. Jensen (1967) indicated that minor temperature fluctuations stimulate growth. For many fungi, minimum temperatures for growth are below 0° C (Pechmann 1966). Many wood decay fungi can be expected to be active during the winter. Additionally, exposure to cold stimulates growth when temperatures do become optimal (Pechmann 1966).

Temperature extremes and moisture deficits have been reported as decay limiting by Kimmey (1955), Childs and Clark (1953), Buchanan (1940) and Hubert (1920), among others.

Moisture extremes also limit the rates of wood decay (Yoneda 1980). Pechmann et al. (1967), reported that substrates with moisture contents below 30 or above 120 percent were not colonized readily by decay fungi. White rot fungi are generally more prevalent in high moisture substrates, brown-rot fungi mor so in low moisture substrates (Zabel and Morrell 1992).

Wood in close proximity to or in contact with soil readily absorbs moisture and nutrients from it. Substrates in such a location generally decay much faster than variously suspended material (Edmonds et al. 1986, Levy 1979, Aho 1974).

Chemical Treatment of Slash:

Lack of nitrogen is one of the primary factors governing rates of invasion and decomposition of woody materials (Cowling and Merril 1966, Bollen and Glennie 1961). Infusing stem sections with nitrogen can greatly enhance decomposition rates under laboratory conditions (Merril and Cowling 1965). It follows then that applying nutrients (fertilizers, sludge, fire retardants, etc. [Bollen 1974]) to woody litter might bring about more rapid decomposition in the forest. However, historic attempts to apply nutrients, with or without added fungal inoculum, have not been greatly encouraging, with either chips or intact woody litter (Bollen and Glennie 1961, Lohman 1959). Sufficient penetration into the substrates is a problem with either chips or slash (Bollen 1974).

Direct applications of several nutrients to the forest floor can induce fruiting of some fungi in soil litter and humus (Sagara and Hamada 1965). However, it is not clear whether such treatments can effectively enhance decay rates.

Converting Slash to Chips:

There has been considerable interest in the use of chips, including sawdust, as a means of dealing with excess or non-merchantable woody residue (fuel), or as a site amelioration treatment (Bensen 1982, Allison 1965, Bollen and Glennie 1961). However, leaving slash on site in the form of chips or sawdust to accelerate biological disposal has not yet proven effective. The persistence of sawdust piles at old mill sites serve as graphic examples. If chips or sawdust are incorporated into the soil, there is an immediate tie up of all available nitrogen to support the resulting microbial decomposition of the chips. This practice is good for wood decomposition but bad for growth of vegetation (Allison 1965, Bollen and Glennie 1961).

Rapid decomposition of chips on or in soil is short-lived, they soon absorb an excess of moisture and decomposition is slowed. Decomposition becomes primarily a bacterial-driven soft rot! When placed uniformly on the soil surface as a shallow layer, chips act as an insulator insuring cool temperatures, along with limited oxygen. On high elevation sites, near Dubois, Wyoming (3,000m), where a uniform layer of chips (ca. 15-20 cm deep) was returned to the site, soils were still frozen under the chips in early August ("Styrofoam effect")! Further, moisture collecting in low spots had visible brown discoloration from wood leachates ("extractive effect") even five years after the treatment. After bleaching in the sun these chips provided a highly efficient reflective surface.

Lodgepole pine seedlings planted in this treatment could not produce root systems in the cold soils, were killed directly by water soluble phenolic toxins or suffered extensive cambium damage from reflected sunlight. On the other hand, non-symbiotic nitrogen fixation rates in the chips, particularly in piles, were some of the highest ever measured (Jurgensen et al. 1979).

Experiments on inoculations of chip piles in the inland northwest with both pure and mixed cultures of fungal decomposers, and various bacteria and yeasts have been encouraging. These studies show substantial increases in early chip pile decay rates (up to 40% wt. loss compared to less than 1% for controls), especially with mixed culture inoculations (Blanchette and Shaw 1978a,b).

Similar efforts by the authors and others in the California Sierras, adjacent to the University of California's Blodgett Experimental Forest, used small, elongated chip piles to avoid the "Styrofoam" effect and to minimize problems with "extractives"). Some were inoculated with pure cultures of several aggressive decomposers, including *Postia placenta* (Fr.) M. Lars. et Lomb., a brown rotter shown to be an aggressive wood colonizer (Blanchette and Shaw 1978a). Early (first two years) accumulation of excess moisture appeared to be a problem in even these small piles. However, after five years the interiors are decomposing nicely with little residual signs of anaerobic conditions. There is excellent fungal development and clear evidence of both white and brown rot fungal activity in the centers of the piles. Some softening of the pile centers is also evident. Inoculations do not yet appear to have been effective for hastening decomposition.

Redefining Chips:

Our current approach is to redefine "chips" to include much larger material than would be traditional. These chips would look more like "chunks" and include material more the size of golf balls, baseballs or even basketballs, rather than coins. Such material should provide more "natural" environments for both white- and brown-rot fungi.

This substrate size and character will permit rapid penetration of microbes through end cut or crushed conductive tissues. It should remain moist and relatively intact, even if the site burns. It should also provide for gradual export of extractives to the soil and not be as quick to accumulate excess moisture as would small materials. Several studies of such material are currently being installed.

MANAGING THE ORGANISMS

The use of wood inhabiting fungi (or arthropods) to ameliorate accumulations of residues, whether in whole-log form, as chips or as "fines," is a process that has seen relatively little work and modest success.

Small Fuels:

With small logging slash, primarily in the form of foliage and fine branches, Larsen et al. (1981) concluded that fresh material lost much of it's biomass and substantial portions of bound nutrients after even a single winter. This suggests rapid downward movement of nutrients into the soil, along with the accompanying reduction in "flash" fuels. It also indicates such fuels will be dispersed rapidly where snow is an effective force for compressing it onto or in the proximity of the soil.

Self pruned branch materials are frequently up to 40% decayed, even before they arrive on the ground (Boddy 1991). For the most part, branches and twigs are completely decomposed, primarily by white rot fungi, in most forest ecosystems in less than 20 years, often within the first 4 or 5 years (Rayner and Boddy 1988). Fine fuels, although temporarily dangerous as a source of ignition, are a short-term problem.

Large Fuels:

Large branches and logs, in contrast, can remain a fuel problem for perhaps a century or more, especially on sites where decomposition is severely limited (cold, dry). Brown-rot fungi are usually the predominant decomposers of large residues in conifer ecosystems, especially those with developed heartwood (Boddy 1991, Gilbertson 1981, Larsen et al. 1980, Levy 1979). This, despite the fact that brown-rot fungi are very much in the minority, when compared to white-rots, at least in terms of numbers of species in the system (Boddy 1991, Gilbertson 1981).

Discussions with regard to fungi or other organisms targeted as potentially useful for direct inoculation of slash, or for manipulating micro environments to encourage activities of specific natural populations, must be generalized and speculative. But, there is enough information on the ecology of several organisms, including both white- and brown-rot fungi, to indicate there are fertile areas for investigation of specific organisms and environments that could lead to significant progress in accelerating biological decomposition of slash. Early capture of substrates will be critical for introduced white rotters to establish themselves, especially in large materials (Rayner and Boddy 1988, Rayner and Todd 1979). However, brown-rot fungi will likely overwhelm white-rot fungi in large materials of interior ecosystems (Harvey et al. 1998).

UPSIDES AND DOWNSIDES

Significantly increasing the participation of biological decomposition in delaying or treating excessive fuel accumulations should improve opportunities for variations of partial cutting to create more historically appropriate conditions, especially with regard to density and species composition. Similarly, reducing fuels without the high risk to soil resources associated with fire could be a significant advantage. Particularly helpful where fuel accumulations are especially large, where site resources are in short supply or where high property values render fire treatments especially risky.

On the other hand, completely eliminating fire, or other major disturbance, from forested landscapes for protracted periods can create problems. For example, reducing the ability of soils to buffer acidification processes, to detoxify many chemicals (natural or other) or to support charcoal and high pH-dependent microbial communities (Zackrisson et al. 1996, Harvey et al. 1976). Lack of significant disturbance in moist forests may result in immobilization of nutrients and increasing moisture retention (Bormann et al. 1995).

The latter can initiate loss of tree cover and possibly formation of bog, muskeg or treed shrub-heath vegetation types, rather than closed forest (Kimmens 1994). Thus, long-term absence (200-400 yrs.) of significant soil disturbance can result in substantially degraded site conditions, potentially rendering them no longer able to support healthy forest cover (Bormann et al. 1995).

Additionally, leaving inappropriate types of slash on forested sites has the potential to be a significant attractant to and substrate for increasing potentially harmful insect activities (Fellin 1980). The nature of these "downsides" have not been fully explored in interior forests but early trials should be mindful of potential problems.

In any case, adding improved biological dimensions to current approaches for fuel treatment should provide a wider range of potential methodologies and contributions for restoring problematical forested landscapes to conditions more in tune with their biological history! Such approaches should be particularly effective on productive sites (relatively warm/moist) where physical modifications have high potential to improve moisture/temperature conditions for decay of fuel accumulations.

CONCLUSIONS

Human settlement-driven reductions in fire frequency have seriously altered accumulations of all types of fuel, including woody debris, in most north temperate forest ecosystems, especially in the interior west. Many are now sufficiently laden with fuel that fires, either wild or prescribed, can cause excessive soil damage. Many of the most problematical situations are located in, or proximal to, valuable properties and people where smoke or harvest removals are generally frowned upon and application of planned burning is expensive, risky and likely to be unpopular. Public, private and corporate forest operations are faced with circumstances where available methodologies to manage fuels are often not practicable or acceptable and fuels will continue to accumulate until the inevitable worst-case fire events occur.

Accelerating biological decomposition in ecosystems where the process is normally both temperature and moisture limited is not a trivial problem. However, changing forest structures to raise (or lower) temperatures and/or to improve available moisture, in combination with modifying the physical structure and arrangements of resulting slash to enhance activities of native decomposers holds promise as an approach for reducing fuel and flammability of high fuel forests. It also seems probable that harnessing specific organisms (perhaps different ones [or mixes] with different environments and substrates) has potential to add to this process.

On balance, incorporating more active contributions from biological processors to both traditional and non-traditional methodologies for managing fuel has great potential to contribute significantly to solutions for managing west-wide fuel accumulations, species composition changes and related forest health and sustainability problems.

LITERATURE CITED

Aho, P. E. 1974. Decay. pp Q1-Q17, In: Cramer, O. P. (Tech. ed.), Gen. Tech. Rep. PAW-24, Environmental effects of forest residues management in the Pacific Northwest. USDA, Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland: OR.

Allison, F. E. 1965. Decomposition of wood and bark sawdusts in soil, nitrogen requirements, and effects on plants. Tech. Bull. 1332, USDA, Agricultural Research Service, Washington, D.C., 58pp.

Auclair, A. N. D. and T. B. Carter. 1993. Forest wildfires as a recent source of CO_2 at northern latitudes. *Can. J. For. Res.* 23:1528-1536.

Baker, W. L. 1988. Effects of settlement and fire suppression on landscape structure. *Ecology* 73:1879-1887.

Benson, R. E. 1982. Management consequences of alternative harvesting and residue treatment practices-lodgepole pine. GTR-INT-132, USDA, Forest Service, Intermountain Forest and Range Experiment Station, Ogden:UT, 58pp.

Blanchette, R. A. and C. G. Shaw. 1978a. Associations among bacteria, yeasts, and basidiomycetes during wood decay. *Phytopathology* 68:631-637.

Blanchette, R. A. and C. G. Shaw. 1978b. Management of forest residues for rapid decay. *Can. J. Bot.* 56:2904-2909.

Boddy, L. 1991. Importance of wood decay fungi in forest ecosystems. pp. 507-540. In: Arora, D. K., et al. (eds.), Handbook of Applied Mycology, Vol. I: Soil and Plants, Marcel Dekker, Inc., New York, NY. 720pp.

Bollen, W. B. 1974. Soil microbes. pp. B1-B41, In: Cramer, O. P. (Tech. ed.), Gen. Tech. Rep. PAW-24, Environmental effects of forest residues management in the Pacific Northwest. USDA, Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland: OR.

Bollen, W. B. and D. W. Glennie. 1961. Sawdust, bark and other wood wastes for soil conditioning and mulching. *Forest Prod. J.*, Jan., pp. 38-46.

Bormann, B. T., H. Spaltenstein, M. H. McClellan, et al. 1995. Rapid soil development after windthrow disturbance in pristine forests. *J. Ecol*. 83:747-757.

Brown, J. K. 1978. Weight and density of crowns of Rocky Mountain conifers. Res. Pap. INT-197, USDA, Forest Service, Intermountain Forest and Range Experiment Station: Ogden, UT: 5p.

Buchanan, T. S. 1940. Fungi in wind-thrown northwest conifers. *J. of Forest*. 38:276-281.

Childs, T. W., and J. W. Clark. 1953. Decay of windthrown timber in western Washington and northwestern Oregon. USDA, Forest Service, Forest Path. Spec. Release 40, Washington, D.C., 20pp.

Clark, L. R. and R. N. Sampson. 1995. Forest ecosystem health in the Inland West: a science and policy reader. American Forests, Forest Policy Center, Washington, D. C., 37pp.

Covington, W. W., et al. 1994. Historical and anticipated changes in forest ecosystems of the inland west of the United States. *J. Sustain. For.* 2:13-64.

Cowling, E. B. and W. Merril. 1966. Nitrogen in wood and its role in wood deterioration. *Can. J. Bot.* 44:1539-1554.

Edmonds, R. L. 1990. Organic matter decomposition in western United States forests. pp. 118-128, In: Proceedings-Management and productivity of western-montane forest soils. Harvey, A. E. and Neuenschwander, L. F. (compilrs.), GTR-INT-280, USDA, Forest Service, Intermountain Research Station, Ogden:UT, 254pp.

Edmonds, R. L. and A. Eglitis. 1989. The role of the Douglas-fir beetle and wood borers in the decomposition of and nutrient release from Douglas-fir logs. *Can. J. Forest. Res.* 19:853-859.

Edmonds, R. L., D. J. Vogt, D. H. Sandberg and C. H. Driver. 1986. Decomposition of Douglas-fir and red alder wood in clear-cuttings. *Can. J. For. Res.* 16:822-831.

Etheridge, D. E. 1958. The effects of variation in decay of moisture content and rate of growth in subalpine spruce. *Can. J. Bot.* 36:187-206.

Fellin, D. G. 1980. A review of some interactions between harvesting, residue management, fire and forest insects and diseases. pp. 335-414, In: Environmental consequences of timber harvesting in Rocky Mountain coniferous forests. GTR-INT-90, USDA, Forest Service, Intermountain Forest and Range Experiment Station, Ogden:UT, 526pp.

Gale, M. R. and Grigal, D. F. 1987. Vertical root distribution of northern tree species in relation to successional status. *Can. J. For. Res.* 17:829-834.

Gast, W. R.; Scott, D. W.; Schmitt, C. et al. 1991. Blue Mountains forest health report-new perspectives in forest health. Special Report. U.S.D.A., Forest Service, Pacific Northwest Region: Portland, OR.

Gilbertson, R. L. 1981. North American wood-rotting fungi that cause brown rots. *Mycotaxon* 12:372-416.

Harmon, M. E. et al. 1986. Ecology of coarse woody debris in temperate ecosystems. *Adv. Ecol. Res.* 15:133-302.

Harvey, A. E., M. J. Larsen and R. T. Graham. 1998. Can we harness biological decomposition to offset the effects of fire as a primary carbon cycling agent? pp. 108-118, Proceedings, 46th Annual Western International Forest Disease Work Conference, Sept. 28 - Oct. 2, 1998, Reno, NV., 189pp.

Harvey, A. E. 1994a. Integrated roles for insects, diseases and decomposers in fire dominated forests of the Inland Western United States: Past present and future forest health. *J. Sustain. For.* 2:211-220.

Harvey, A. E. 1994b. Interactions between forest health and the carbon cycle: inland northwestern American and global issues. pp. 86-91, In: Proceedings, Ann. Conv. Society of American Foresters and the Canadian Institute of Forestry, Anchorage, AK., SAF-95-02, Society of American Foresters, Bethesda, MD: 543pp.

Harvey, A. E., et al. 1994c. Biotic and abiotic processes in eastside ecosystems: the effects of management on soil properties, processes, and productivity. Gen. Tech. Rep. PNW-GTR-323, USDA, Forest Service, Pacific Northwest Research Station, Portland, OR. 71pp.

Harvey, A. E., M. J. Larsen and M. F. Jurgensen. 1979. Fire-decay: Interactive roles regulating wood accumulation and soil development in the Northern Rocky Mountains. Res. Note INT-263, USDA, Forest Service, Intermountain Forest and Range Experiment Station, Ogden:UT, 4pp.

Harvey, A. E., M. J. Larsen and M. F. Jurgensen. 1976. Distribution of ectomycorrhizae in a mature Douglas-fir/larch forest soil in western Montana. *For. Sci*. 25:350-358.

Highley, T. L., S. S. Bar-Lev, T. K. Kirk and M. J. Larsen. 1979. Influence of O_2 and CO_2 on wood decay fungi in sapwood and heartwood by four heart-rot fungi. *Phytopathology* 69:1151-1157.

Hintikka, V. 1970. Studies on white-rot humus formed by higher fungi in forest soils. *Comm. Inst. For. Fenn.* 69:1-68.

Hubert, E. E. 1920. The disposal of infected slash on timber sale areas in the northwest. *J. Forest.* 18:34-56.

Jensen, K. F. 1967. Oxygen and carbon dioxide affect the growth of wood decaying fungi. *Forest Sci.* 13:344-389.

Jurgensen, M. F., S. F. Arno, A. E. Harvey, M. J. Larsen and R. D. Pfister. 1979. Symbiotic and nonsymbiotic nitrogen fixation in Northern Rocky Mountain forest ecosystems. pp. 294-308, In: Symbiotic nitrogen fixation in the management of temperate forests. Gordon, J. C., et al. (eds.), Oregon State University, Corvallis: OR, 501pp.

Kimmens, J. P. 1994. The health and integrity of forest ecosystems: are they threatened by forestry. pp. 22-40, In: SAF-95-02. Managing forests to meet peoples needs, Proceedings 1994 Society of American Foresters/Canadian Institute of Forestry Convention, Sept. 18-22, 1994, Anchorage, AK.

Kimmey, J. W. 1955. Rate of deterioration of fire-killed timber in California. Circular 962, Washington, D. C.: U. S. Department of Agriculture. 22p.

Larsen, M. J., A. E. Harvey and M. F. Jurgensen. 1980. Residue decay processes and associated environmental functions in Northern Rocky Mountain forests. pp. 157-194, In: Environmental consequences of timber harvesting in Rocky Mountain coniferous forests. GTR-INT-90, USDA, Forest Service, Ogden: UT, 526pp.

Larsen, M. J., M. F. Jurgensen, and A. E. Harvey. l98l. Athelia epiphyla associated with colonization of subalpine fir foliage under psychrophilic conditions. *Mycologia* 73:ll95-l202.

Levy, J. P. 1979. The place of basidiomycetes in the decay of wood in contact with the ground. pp. 161-178, In: Frankland, J. C. and J. N. Hedger (eds.), Decomposer basidiomycetes: their biology and ecology. Symposium of the British Mycological Society, London: UK, Cambridge University Press, Cambridge, UK, 355pp.

Lohman, A. A. 1959. Deterioration by decay of lodgepole pine logging slash near Strochan, Alberta. Interim Rep. Canada Agricultural Research Branch, Forest Biology Lab, Calgary, ALB., Canada.

Lowell, E. C., S. A. Willits and R. L. Krahmer. 1992. Deterioration of fire-killed and fire-damaged timber in the western United States. PNW-GTR-292, USDA, Forest Service, Pacific Northwest Research Station, Portland: OR, 27pp.

Marschner, G. E., and Marschner, H. 1996. Nutrient and water uptake by roots of forest trees. *Z. Pflanzen. Bodenk*. 159:11-21.

Merril, W. and E. B. Cowling. 1965. Effect of variation in nitrogen content of wood on rate of decay. *Phytopathology* 55:1067-1068.

Minore, D. 1979. Comparative autecological characteristics of northwestern tree species—a literature review. Gen. Tech. Rep. PNW-87, U. S. Department of.Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station: Portland, OR: 72pp.

Moldenke, A. R. and J. D. Lattin. 1990. Dispersal characteristics of old-growth soil arthropods: the potential for loss of diversity and biological function. *Northw. Environ. J.* 6:408-409.

Olsen, J. S. 1981. Carbon balance in relation to fire regimes. pp. 377-378, In: Mooney, H. A., et al. (coords.), Fire regimes and ecosystem properties. GTR-WO-26, USDA, Forest Service, Washington, D. C.

Pechmann, H. Von. 1966. Der einfluss der Temparatur auf das Wachstum van Blavepilzen. *Mat. Org.* 1:237-250.

Pechmann, H. Von., A. Foess, H. Von. Liese and V. Amer. 1967. Untersuchungen uber die Rotstreifigkeit des fichtenholzes. *Forstwissench. Forsch.* 27:1-12.

Ponge, J. F., et al. 1998. The forest regeneration puzzle: Biological mechanisms in the humus layer and forest vegetation dynamics. *Bioscience* 48:523-530.

Rayner, A. D. M. and L. Boddy. 1988. Fungal communities in the decay of wood. *Adv. Microb. Ecol.* 10:115-166.

Rayner, A. D. M. and N. K. Todd. 1979. Population and community structure and dynamics of fungi in wood. *Adv. Bot. Res.* 7:333-420.

Rehfeldt, G. E. 1994. Evolutionary genetics, the biological species, and ecology of the interior cedar-hemlock forests. pp. 91-100, In: Baumgartner, D. M.; Lotan, J. E; Tonn, J. R. comp., Interior cedar-hemlock-white pine forests: ecology and management. Washington State University, Cooperative Extension: Pullman, WA: 365pp.

Robinson, D. 1994. The responses of plants to non-uniform supplies of nutrients. *New Phytol*. 127:635-674.

Sagara, N. and M. Hamada. 1965. Responses of higher fungi to some chemical treatments of forest ground. *Trans. Mycol. Soc. Japan* 6:72-74.

Sampson, N. R. and L. R. Clark. 1995. Wildfire and carbon emissions: a policy modeling approach. American Forests, Forest Policy Center, Washington D.C., 23pp.

Swezy, D. M. and J. K. Agee. 1991. Prescribed-fire effects on fine-root and tree mortality in old-growth ponderosa pine. *Can. J. For. Res.* 21:626-634.

Torgerson, T. and E. Bull. 1995. Down logs as habitat for forest-dwelling ants—the primary prey of pileated woodpeckers in northeastern Oregon. *Northw. Sci.* 69:294-303.

United States Department of Agriculture, Forest Service. 1996. Status of the interior Columbia basin: summary of scientific findings. Gen. Tech. Rep. PNW-GTR-385. Portland, OR: U. S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; U. S. Department of Agriculture, Bureau of Land Management. 144p.

Van Wagner, R. C. 1977. Conditions for the start and spread of crown fire. *Can. J. Bot*. 7:23-24.

Wagener, W. W. and H. R. Offord. 1972. Logging slash: it?s breakdown and decay at two forests in northern California. Res. Pap. PSW-83, USDA, Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkely: CA. 11pp.

Yoneda, T. 1980. Studies on the rate of decay of wood litter on the forest floor. III. Effect of moisture content on CO_2 evolution from decaying wood. *Jap. J. Ecol.* 30:55-62.

Zackrisson, O., M. C. Nilsson and D. A. Wardle. 1996. Key ecological function of charcoal from wildfire in the Boreal forest. *Oikos* 77:10-19.

Zabel, R. A. and J. J. Morrell. 1992. Factors affecting the growth and survival of fungi in wood (fungal ecology). pp. 90-115, In: Wood microbiology - Decay and its prevention. Academic Press, San Diego, CA. 476pp.