Moving towards a New Paradigm for Woody Detritus Management[1]

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Abstract

Woody detritus has become an important focus of many scientific and management questions in forests. Perspectives of the role of this part of the ecosystem have greatly changed over time. Today forest managers are moving away from a "blanket" removal of all the woody detritus possible to retaining and even enhancing the amounts in forests. To understand how much woody detritus is required to sustain ecosystem functions, we need to develop a dynamic and specific objective-oriented approach. This can be based on existing data on tree mortality and decomposition, but these will have to be coupled with process and species responses to coarse wood quantities as well as a landscape perspective.

Introduction

In the last decade, woody detritus, particularly the coarse fraction, has become an important focus of many scientific and management questions. Although the role of this material in providing habitat and carbon cycling is generally understood, perspectives on its role in nutrient cycling are still evolving. Based on what is known to date, forest managers are moving away from a complete removal of all the woody detritus to retaining and even enhancing the amounts in forests. This leaves open the question of how much woody detritus is required to sustain ecosystem functions. Initially, this has been solved by the application of static minimum standards based on a set of general objectives, but in the future a more dynamic and specific objective-oriented approach should be developed. The increasing number of studies on tree mortality and decomposition are giving a global view of how these processes vary with forest type and climate. These data also provide the basis for a dynamic rather than a static approach to the management of woody detritus. However, to be successful, this perspective must be coupled with a detailed understanding of how certain species and ecosystem processes vary with the amount of woody detritus.

Woody detritus is an important component of forest ecosystems, reducing erosion and affecting soil development; storing nutrients and water; providing a major source of energy and nutrients; serving as a seedbed for plants and as a major habitat for decomposers and heterotrophs (Ausmus 1977, Franklin and others 1987, Harmon and others 1986, Kirby and Drake 1993, McCombe and Lindenmayer 1999, McMinn and Crossley 1996, Samuelsson and others 1994). As knowledge of these important roles in forest ecosystems has increased, the need to manage this material

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to maintain these functions has also increased. Although we are moving away from a period when woody detritus was given only economic, engineering, or safety considerations, we have not fully replaced this paradigm with a new one. In this paper, I outline what this new paradigm might be and point out the types of scientific knowledge that will be required to make it a reality.

Historical Perspective on Management: The U.S. Pacific Northwest Case

The old adage, "Those who ignore the past are doomed to repeat it," is sound advice. Thus, before describing what the future of woody detritus management might look like, it might be best to describe what has happened in the past. As forest resources have been harvested throughout the world, the attitudes toward that harvest and the value of those resources have changed with time. Although each region of the globe has had a unique development, there are certain trends they share. These general patterns can be illustrated by the historical trends in the U.S. Pacific Northwest, a major region of timber resource development, and one of the regions where woody detritus management has been rapidly changing.

The Unlimited Resource

The timber resources of the Pacific Northwest were initially regarded as limitless. Moreover, the timber resource was often viewed as a roadblock to "progress." This attitude had two consequences: low utilization standards with the highest quality wood harvested and the rest left to decompose, and a removal of forests by harvest or other means such as fire. Early this century some stumps were up to 6 m tall (Gibbons 1918), and stumps 3-4 m tall were not unusual (Conway 1982). Trees were cut this way to avoid butt rots and flair at the base of the trees. Reports at this time indicate > 10 percent of the stand volume was left in stumps (Gibbons 1918) with considerably more in the form of unharvested "undersized" trees. Between 1920 and 1930, stump height was reduced to 1-1.75 m, amounting to 6-7 percent of the total bole volume. In the 1910s the average diameter of logs left after harvest was 43 cm (Hanzlik and others 1917). During the 1920s it was common to leave logs < 35-56 cm diameter depending upon the length (Hodgson 1930). In 1910, the typical harvest of an old-growth stand would have retained 65 percent of the live woody organic matter aboveground as slash. This is close to the amount that would be retained on site after a catastrophic fire or windthrow with no subsequent timber salvage (Agee and Huff 1987, Spies and others 1988). Although woody detritus in forest ecosystems was not deliberately managed at this stage, it was certainly changing. In upland forest the amount of wood detritus increased at this time because the catastrophic disturbance rate was increasing as timber harvest increased (i.e., the mean fire return interval was 200 years, whereas timber was harvested at a rate in which the mean return interval was > 100 years). This change increased the input of woody detritus and therefore increased the average landscape level of woody detritus above those of the historical average *(fig. 1).* In contrast to the upland system, in the riverine system woody detritus was being removed and burned to improve safety and transportation, effectively increasing the decomposition rate-constant. This lead to a decrease in woody detritus stores in riverine systems at the time that upland stores were increasing.

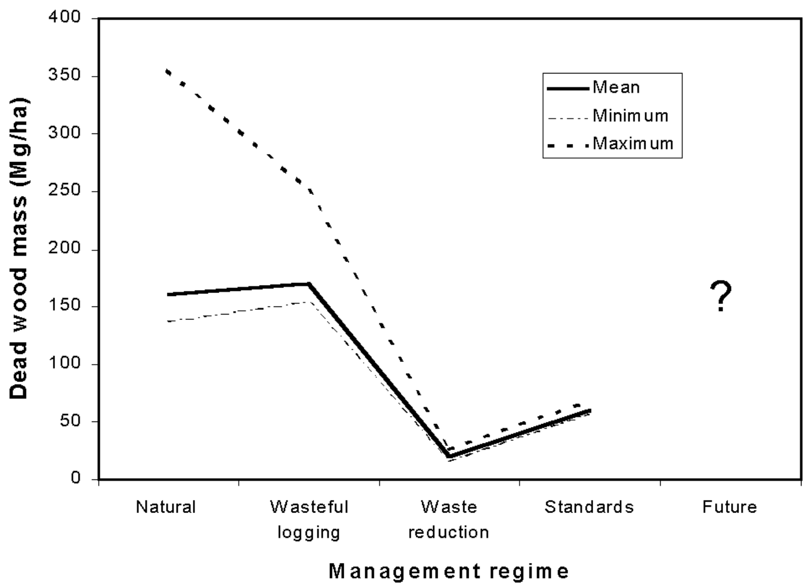

Figure 1—Hypothetical amounts of woody detritus found in upland landscapes during various stages in development, using the Pacific Northwest as an example. The values were derived using a simulation model (similar to the one described in *fig. 2*) and parameterizing it by using data from Harmon and others 1996. The heavy line represents the mean, whereas the light lines indicate the range over succession.

Woody Detritus as Waste

The next stage of development was largely a response to the previous one. As the timber resource was removed deliberately or by accident, it became scarcer and therefore more valuable. What was originally an unlimited resource was then seen as a limited resource that required more efficient management. Forests were therefore seen to be in the need of protection from natural (wind, fire, insects, fungal) and man-caused disturbances (fire, agricultural clearing). Moreover, utilization standards that removed only the "best" volume became viewed as wasteful. Improvements in utilization standards by the 1940s lead to a five- to tenfold drop in stumps height to 0.6 m (Poole 1950). More significantly a trend of removing smaller diameter trees and tops started with a minimum of 30 cm in the 1930s and steadily decreased to 13-15 cm today. The forestry literature at that time in the Pacific Northwest was full of examples of economic waste. For example, Hodgson (1930) calculated that the mass of sound wood retained after harvest in western Oregon and Washington forests during the 1920s exceeded the entire amount cut for pulp over the entire U.S.! As another example, re-logging of former harvest units was economically viable for several decades (Hodgson 1930).

Although changing to a more efficient form of harvest made economic sense as resources became scare, it also had some very important consequences that did not make ecological sense. The earlier harvest practices were viewed as wasteful, and therefore woody detritus became the symbol of that waste regardless of its origin. Forest utilization standards were not only improved to reduce this wastefulness but also the symbol of that waste had to be removed. It was the latter step that led to potential ecological problems, but these were not anticipated. Rather, many justifications concerning sanitation, productivity, fire protection, and logger safety that went far beyond changing wasteful practices were developed. These justifications took on a life of their own even though they often had no basis in fact. For example, pathogens were thought to spread from dead trees, but with very rare exceptions this was not true as the pathogens lived primarily on living trees (Cramer 1974). Fire-killed trees and windthrows had to be removed because pathogens and insects would threaten the surrounding living trees. Bark beetles became a general rationale for dead tree removal, despite that many species of trees (e.g., *Tsuga heterophylla* and *Thuja plicata*) are generally not attacked by these pest insects. Even those trees that do support these insects *(Pseudotsuga menziesii)* often do not form good habitat for beetles that cause extensive and long-term infestations (Powers and others 1999). Snag felling was extensively practiced to promote safety, and yet many of the areas in which this practice was carried out had vanishingly low probabilities of snags damaging buildings, vehicles, or humans (at least there was no detectable increase in incidents when the practice was stopped). Logs were removed to ease tree planting, although the major problem in slowing planting was small and not large slash material.

The ultimate expression of this phase of development occurred when not only the wasteful practices were stopped and recently killed trees that could be economically utilized were removed, but when woody detritus that could not be utilized for anything except firewood was removed and eliminated by burning. This era of piling unmerchantable material (PUM) and yarding unmerchantable material (YUM) represented a phase in which the existence of woody detritus was not to be tolerated even if it cost a great deal of money to remove it. As such it represented waste removal carried to its illogical extreme. It also led to a landscape in which woody detritus was far below any historical level *(fig. 1).*

Ecological Functions

Not only did PUM and YUM practices have an economic downside associated with the cost of yarding and burning, they started to have impacts on the ecological system. Research started in response to these practices that revealed many of the functions we take for granted today (Harmon and others 1986, Maser and Trappe 1984). The search also began for a more balanced way to deliberately manage woody detritus in the ecosystem. The first idea was to develop minimum standards for the amount of woody detritus to be retained in harvested units. Minimum standards were set a number of ways, but most frequently in the Pacific Northwest they were based on the minimum numbers of pieces or volume found in old-growth forests (Spies and Franklin 1991). To serve certain functions it was also recognized that minimum diameters and lengths needed to be provided. While the emphasis on upland systems was on the time of harvest, a point when woody detritus could either be enhanced or retained, the focus on riparian systems was on restoration with wood actually either being added artificially from outside the system or produced naturally in designated riparian buffer zones.

Although minimum standards are an improvement in terms of retaining ecological functions, they also have certain problems as currently practiced. First, while they have the potential to increase woody detritus above the level of the previous era, they also have the effect of homogenizing the amount of woody detritus over space and time. As woody detritus in a natural system is highly variable it is not clear what this homogenization implies for many ecosystem functions. Minimum standards are easy to set and enforce but often are difficult to apply—how should stages of succession or forest types be managed in which the amount of woody detritus is naturally lower than the minimum? Should wood be added to make it comply with the standards? These questions often confront the manager trying to apply one-size-fits-all standards. Second, the minimum standard approach is mute on how the minimum should be determined. Ideally, this should be determined by the tradeoff between ecological and economic gains and desired outcomes (Wilström and Ericksson 2000). However, in practice this has been settled by balancing the amount of woody detritus against the economic cost. This system inevitably leads to the factor that can be quantified (i.e., economics) becoming more important than the qualitative factor (i.e., we need some more woody detritus). Third, because the management intervention for the upland system occurs during harvest, minimum standards lead to static management of a dynamic entity. Thus, once the minimum standard has been met, the tendency is to assume that ecosystem functions will be provided despite that the system is very likely to change over the decades between harvests.

"Morticulture" and the Elements of a New Management System

Clearly a paradigm that moves beyond minimum standards needs to be developed. But how will it be developed and what will it look like? We might start with the name of this new system and see where that leads us. Suppose in the future there will be a "morticulture" as well as a silviculture. Although I often offer this name in jest, it does have some serious points in its favor. It emphasizes the culturing of something, in this case woody detritus. As with silviculture it would meet future needs, but instead of the type of logs to be harvested, it would deal with the methods to produce woody detritus structures for ecosystem function. It would have a similar attitude about manipulating stand structure and, as in modern silviculture, acknowledge the dynamic nature of the system being managed. And morticultural practices would not be implemented unless the ecosystem response was exactly understood (just as in silviculture, methods should not be applied without trying to reach some goal in terms of species mixtures, forest product markets, etc.). In addition to these obvious parallels, morticulture should take advantage of past silvicultural experience. In fact its implementation should be considered in close conjunction with silviculture and not in isolation. The next section outlines in more detail some of the features of this new system.

Linking Live and Dead Trees

Although developing a viable morticulture will require new knowledge, in many cases it will require that we apply what we already know. For example, we already know that live trees eventually form dead trees, but it is amazing that this dynamic is often missing from current forest management thinking. Thus, the current tendency is to use wood produced from the old-growth stand at the time of forest conversion and harvest to meet the future needs of the system. Unfortunately, the new plantation forest system does not have the capacity to maintain this amount of woody detritus unless it is modified considerably in terms of rotation length and fraction of live trees retained (Franklin and others 1997, Spies and others 1988).

A similar disjunction occurs between standing dead trees (i.e., snags) and downed dead trees (i.e., logs). Clearly snags eventually fall to the ground to become logs, although some live trees fall to become logs without first becoming snags. An examination of management plans, inventories, and even the scientific literature indicates that there is both a significant failure to link snags and logs and to link live and dead trees. Yet, they are clearly all part of the same overall system. One way to functionally link these forms of wood is to use a common currency to examine their state and dynamics. The actual units used may differ depending on the objectives, but the current tendency to compare, for example, volume of logs to numbers of snags is unnecessarily reinforcing their separation.

The Dynamic Wood Pool

Managers of woody detritus currently tend to think about woody detritus management in static terms. Rather than ask at which rate woody detritus is created or lost, they tend to think about the amount that should be there. This is another case where we already know the processes that control woody detritus dynamics, but we are not applying this knowledge. Clearly, we need to learn more about the processes of mortality, disturbance, decomposition, fire consumption, and movement, but I maintain the most significant problem is switching from a static to a dynamic perspective.

Mortality is the process that creates woody detritus. It can occur by natural causes or by human-related causes. It can occur as single parts (e.g., branch pruning), as single individuals, or as entire stands (i.e., as landscape units). Forest management in the past century has focused on how to lower mortality rates via thinning, fire protection, etc. Ironically, the next century of forest management may be occupied with how to increase mortality when and where we want it. Despite the foresters preoccupation with reducing mortality, it is surprising how little is known about the actual rates of mortality in forests (Franklin and others 1987). This lack of knowledge may have been caused by the fact one needs to observe a population over time to determine rates and causes, although some stand reconstruction methods can give rough approximations of long-term rates (McCune and others 1988). Mortality rates are commonly thought to be highest in older forests (shades of our old friend waste reduction?), but they actually tend to be highest during the self-thinning stage of succession. For the forests that have been studied, old-growth rates appear to be one-third to half those of the self-thinning stage (Franklin and others 1987). There is also a tendency to only consider self-thinning in models of mortality, but this too is a mistake. Trees are often killed by causes unrelated to density such as wind, ice damage, insects, pathogens, and sometimes accidents (e.g., the second highest cause of death in Pacific Northwest forests is crushing by another tree or snag [Franklin and others 1987]). At the continental scale the tendency is for mortality to increase with productivity, although the cause of this relationship is not clear. Tropical forests have the highest mortality rates (0.0167 yr^{-1}) followed by deciduous (0.012 yr^{-1}) and then evergreen forests (0.01 yr^{-1}) (Harmon and others 2001).

Although disturbances such as fire and timber harvest obviously cause mortality directly, they also increase the chances that the surviving trees will die (Franklin and others 1997) because survivors are exposed to increased insect attack and/or to wind damage. While often viewed as a waste, this might also be an opportunity if increasing woody detritus is the management objective.

Decomposition is the fundamental process that regulates the loss of woody detritus. Although many insect species are associated with this process, basidiomycete fungi are probably the most important wood decomposers. Many factors control the rate of wood decomposition, ranging from the chemical and physical nature of the wood, to decomposers involved, to the environment at the micro- and macro-levels. This leads to a very complicated pattern of decomposition that is variable over the scale of meters. In northwestern Russia, for example, one can find logs under moss mats that are waterlogged, next to stumps that have optimum moisture, next to snags that are too dry to decompose except in their lowest meter of height (Krankina and Harmon 1995). There have been some attempts to measure the rate of the decomposition process over time (Harmon and others 1999, 2000), but these are relatively rare today. The majority of studies of woody detritus decomposition use a chronosequence approach that substitutes space for time. There is a great deal of data on decomposition rates of wood relative to mortality. On the macro-scale decomposition rates decrease from tropical (0.176 yr^{-1}) to deciduous (0.080 yr^{-1}) to evergreen forests (0.032 yr^{-1}) (Harmon and others 2001). Deciduous shrublands of the tropical zone appears to have the highest decomposition rate-constant, possibly due to the presence of termites. Although tropical forests have the highest decomposition rate-constants of any major biome, the distribution of values appears bimodal with a peak at $< 0.04\ yr^{-1}$ and another at $> 0.12\ yr^{-1}$ (Harmon and others 2001). This may be a reflection of two groups of species: one containing compounds toxic to fungi and insects in their heartwood and a second group that has little decay-resistance. In contrast, evergreen and deciduous ecosystems appear to have unimodal distributions of decomposition rates.

Fire consumption is another process that removes woody detritus. This process is highly variable and likely to change from ecosystem to ecosystem and even from fire to fire. Past research indicates consumption of woody detritus increases as moisture and piece diameter decrease, and as the degree of decay increases (Brown and others 1985, Rienhardt and others 1991). It is also clear that in most situations the consumption of large woody detritus is linked to consumption of the forest floor. The reason appears to be related to the extremely loose packing of woody detritus. To burn there must be a positive feedback of energy between pieces; and given the distance between large pieces of wood, this feedback is very low. Therefore, for coarse wood this positive feedback is with the underlying forest. This is important because it means that without deep forest floor layers, large pieces of woody detritus will not be completely consumed even when the moisture content is extremely low (similar to attempting to burn a single dry log in a fire place without another log or finer fuels).

The nature of the fire can also determine future decomposition rates. The classic idea is that charring slows decomposition, but this is probably only true for wood that is in the intermediate stages of decomposition. Fire charred trees are typically quite attractive to decomposers such as insects, many of which specialize on this form of mortality. Wood that has been fully colonized by decomposers is also likely to be little affected by charring, although increasing light absorbance is likely to heat the wood and lead to faster biological activity. Charring seems to only slow decomposition in logs that have the decayed portions fully removed, thus eliminating the normal sequence of colonization. Finally, it is often stated that fires removed much of the woody detritus prior to fire protection efforts; therefore, after decades of fire suppression current levels of woody detritus are artificially high. Perhaps, but these same fires would have killed trees that replaced the dead ones they consumed.

Given the ratio of dead to live trees observed in most forests (0.05 to 0.30 on a mass basis), very little mortality would be required to offset these losses (Harmon 1992). This may be the reason why two fire regimes in Oregon that differed fourfold in the frequency of fires had very similar amounts of woody detritus (Wright 1998). Those differences that did exist were more likely caused by environmental differences that lead to an increased rate of decomposition in the more frequent fire regime.

All these process rates vary with time, a dynamic that causes woody detritus to undergo changes over succession. Although there are undoubtedly many patterns of change after a disturbance, a few common patterns can be created by varying: the interval between disturbances, the amount of wood removed by the disturbance, the mortality rate, and the decomposition rate. The simplest case is for old-field succession where both live and dead mass start at 0 *(fig. 2).* In this case live and dead mass accumulation parallel each other. A more complicated situation occurs after a catastrophic natural disturbance. Assuming the disturbance removes a minimum of wood (e.g., wind throw), woody detritus at the time of disturbance is equal to former live biomass and the dead wood mass just before the disturbance. This peak is followed by a monotonic decline to a steady-state mass that is determined by the mortality and decomposition rates. When the disturbance removes a fraction of the woody mass (e.g., timber harvest) the quantity right after the disturbance can range anywhere between zero to that found after windthrow. In the example given in *figure 2,* the woody detritus mass declines below the steady-state value and then increases to this level. This is because the replacement of woody detritus lags behind decomposition in the middle stages of succession (Harmon and others 1986, Spies and others 1988). Perhaps the most complicated case is when forests are converted to intensive, short-rotation forestry. Here the live mass does not recover to the steady-state level and a large fraction of the mortality is removed as intermediate timber harvest in thinning and salvage. This leads to a decrease in the store of woody detritus to a value much lower than the steady-state value.

Response Functions

Knowing the dynamics of the woody detritus is not sufficient for deciding how much woody detritus is adequate. This requires knowledge of how various organisms or ecosystem functions vary with the amount and arrangement of this material. Unfortunately, this is probably the weakest portion of the science behind morticulture (and the hardest type of question to answer). The first problem is that we have tended to examine ecosystem and habitat functions either with or without woody detritus. But what we really need at this stage is a continuous response. Although there are few examples of continuous response functions, some do exist. Butts and McCombe (2000) examined the response of salamanders in western Oregon to the presence of woody detritus *(fig. 3).* They found that the abundance of some genera (*Aneides* and *Ensatina*) was highly correlated to the volume of woody detritus present, while others were completely indifferent *(Taricha).*

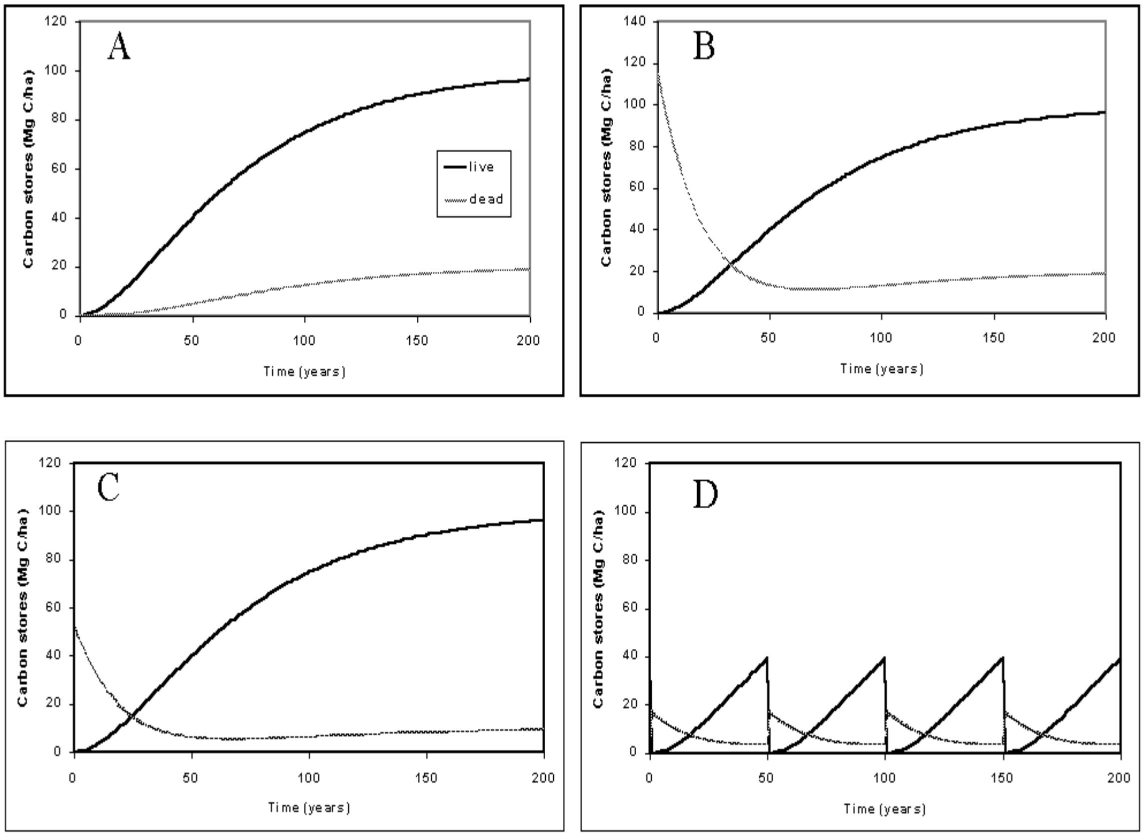

Figure 2—Hypothetical woody detritus stores relative to live woody stores for various management regimes. Stores are from a simple simulation model that uses a Chapman-Richards function to simulate live biomass and determines woody detritus mass from mortality from disturbances and regular death from competition, etc. as well as losses from fire and decomposition (Harmon and others 2001). For comparative purposes, woody detritus stores have been set relative to live woody stores and the maximum live woody stores were set to 1. A) old-field succession with no woody detritus at the start, B) succession after a natural disturbance that leaves all the woody detritus, C) a single clear-cut without subsequent harvest, and D) multiple harvests every 50 years with salvage of half the mortality.

From a theoretical standpoint, the expectation is that different ecosystem and habitat functions would have different responses to the amount of woody detritus *(fig. 4)*. A relatively small volume of wood might fulfill some functions, such as insect habitat, as long as the right species, size, and decay stage are provided. One might expect this type of response from any species with a small size, high reproductive rate, and high vagility. Vertebrates on the other hand might require larger volumes of woody detritus, in part because of their larger individual size, but also because they may require more connectivity of the wood itself to serve the function required (e.g., travel corridors). Some response functions might increase to a saturation point, whereas others might reach an optimum above which the function decreases. A possible example of the latter might be the response of fish to increases in woody detritus abundance. At first habitat quality might be increased; however, with too much woody detritus in the stream movements, food production and other factors might become limiting. The same might be true for nutrient cycling. Adding wood initially might increase the addition of nitrogen via asymbiotic fixation and might provide habitat for some mycorrhizae. But at some point woody detritus would tie up too many nutrients and cover too much of the forest floor so that plants might have limited places to establish. Although all of these are theoretical responses, they indicate range of types one is likely to see in nature.

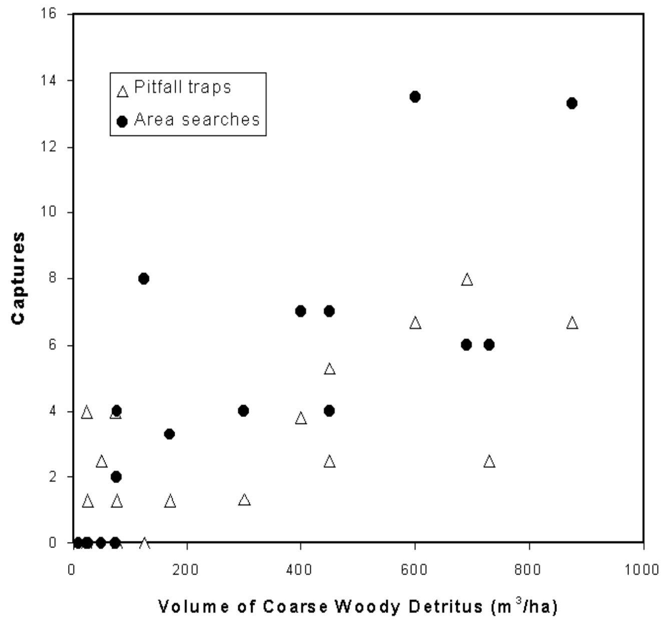

Figure 3—The response of ensatina salamander (*Ensatina eschscholtzi)* abundance to coarse woody debris volume (Butts and McCombe 2000).

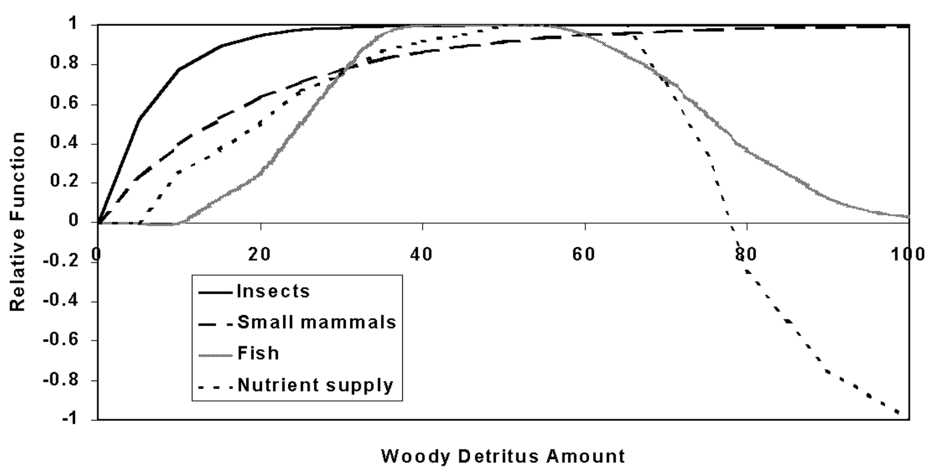

Figure 4—Hypothetical examples of species and ecosystem response functions to changes in the abundance of woody detritus. Note that both scales are relative, with the response function having a maximum of 1.0 and a minimum of –1, and the woody detritus scale ranging from 0 (no woody detritus) to 100 units of mass or volume.

Compensatory Factors

It would be a simple world indeed if we could treat responses to woody detritus in isolation. In reality the woody detritus resource interacts with others to determine the overall function of the ecosystem. To some degree these interactions might compensate for a decrease in woody detritus. For example, bacteria in woody detritus undoubtedly fix nitrogen that eventually becomes available to plants. It stands to reason that removal of this woody detritus would therefore decrease nitrogen inputs, but this might be compensated for by symbiotic nitrogen fixation in plants or lichens. Unfortunately, the same zealous attention to decreasing waste and increasing productivity of merchantable volume that has lead to the removal of woody detritus has also lead to the removal of both these symbiotic forms of nitrogen inputs.

Perhaps the more complicated question to answer is why other types of structures may or may not compensate for woody detritus. For some organisms, such as insects and fungi, this compensation is easily determined given that they often require woody detritus to fulfill certain life stages (Jonsell and others 1998, Renvall 1995, Rydin and others 1997). For others such as small mammals there may not be such a clear obligate relationship. If woody detritus serves as cover for small mammals, then another form of cover might be able to compensate for a lack of woody detritus. This suggests that in addition to developing response curves, we must understand what exactly the woody detritus is providing the organism or ecosystem. If there are no other ways to provide this function, then the amount of woody detritus is crucial. If on the other hand other structures or processes can provide them, then we may be more flexible in the amount of material retained.

Spatial Considerations

The final element to forming a new management paradigm for woody detritus management involves spatial arrangement. This can be at the level of pieces, stands, and landscapes. At the landscape level the first consideration might be whether the process or habitat provided by woody detritus is ubiquitous or restricted to certain locations. If it is ubiquitous then keeping a minimum level throughout the landscape may be adequate. An example of a ubiquitous process might be nutrient cycling, as it is continual regardless of the amount of woody detritus. If the habitat is restricted, the connectivity to other similar habitats or locations must be considered. If the species using woody detritus habitats have a high reproductive capacity and are vagile, spatial distribution may be of minor concern as long as the habitat appears somewhere each year (Jonsell and Norlander 1995, Jonsell and others 1999). On the other hand, for species with low reproductive capacity and restricted movements, one may need to carefully design where and when the woody detritus habitat occurs in the landscape. In addition, metapopulation dynamics may need to be considered (Hanski 1991). This problem might be addressed by providing stable areas in which populations dependent on woody detritus are kept high and can serve as sources to the surrounding, lower quality, and shifting habitats that are population sinks. While the latter are temporary, they would function to keep the overall abundance of the organism high at the landscape level. Metapopulation structure considerations may be influenced by the direction from which the landscape is being developed. In regions that have a great amount of high quality habitat, one might be able to design a self-sufficient landscape of source and sink populations. This will not be the case if restoring woody detritus functions to a “degraded” landscape is the goal. In this case, one might have to locate source populations outside the landscape of interest or create the woody detritus habitat and then wait for the chance dispersal of the desired organisms.

Although the bulk of recent ecological thinking about the spatial dimension has been on the landscape level, spatial considerations may also influence the function of woody detritus at finer levels of spatial resolution. If the primary function of downed woody detritus for small mammals is as protective cover from predators, the connectivity of individual logs might be important. One would hypothesize that the greater the connectivity of pieces, the lower the exposure to predation. Unfortunately, there are no studies that I know of that have looked at this problem from a theoretical or empirical perspective. Another question involving the spatial distribution of logs involves the effect of logs on soil forming processes. Tinker and Knight (2001) asked how long it takes logs to influence the entire soil surface. In lodgepole pine forests they found that it depends on the woody detritus management regime, with natural disturbances having a much shorter "log-rotation" time than current intensive forest practices. Interestingly, they found that minor modifications of current practices would shorten the log-rotation time to that observed for natural disturbances. Further work along these lines might add a great deal of insight into the long-term function of woody detritus in ecosystems.

Integration

Given these elements, how might this new paradigm of morticulture work? It would probably start by answering the question of which species or processes are to be maintained, restored, or otherwise managed *(fig. 5)*. Then the target levels for these functions should be determined. Before assessing the amount of woody detritus to be maintained or added to meet this functional target, the landscape context for the management action should be assessed. Are there limitations of populations or processes that would limit the desired response? If not, a plan to add wood would be designed to maintain the desired level. But if there are landscape limitations, then these should be addressed before planning at the stand-level proceeds. The ability to circumvent these limitations will probably be highly dependent on the given landscape; in some cases the particular patch treated might be part of an overall plan to reduce these landscape-level limitations. The plan to produce a given amount of woody detritus would have to be dynamic, linking the live trees and the different forms of dead trees so that there is compensation for losses caused by decomposition and fire. The plan would then be implemented and might consist of several interventions. Finally, the results of the action should be monitored for effectiveness (not just implementation), and a true adaptive management system should be put in place. The latter system will have real costs in money, time, and training, but will be necessary to really assess if things are working as anticipated.

This paradigm is admittedly a "fine filter" approach that emphasizes small scale processes and patterns. There is no reason, however, why it could not be coupled with a "coarser filter" landscape level view of the system. In fact the assessment of the landscape context would probably be the most logical point to reconcile these two perspectives.

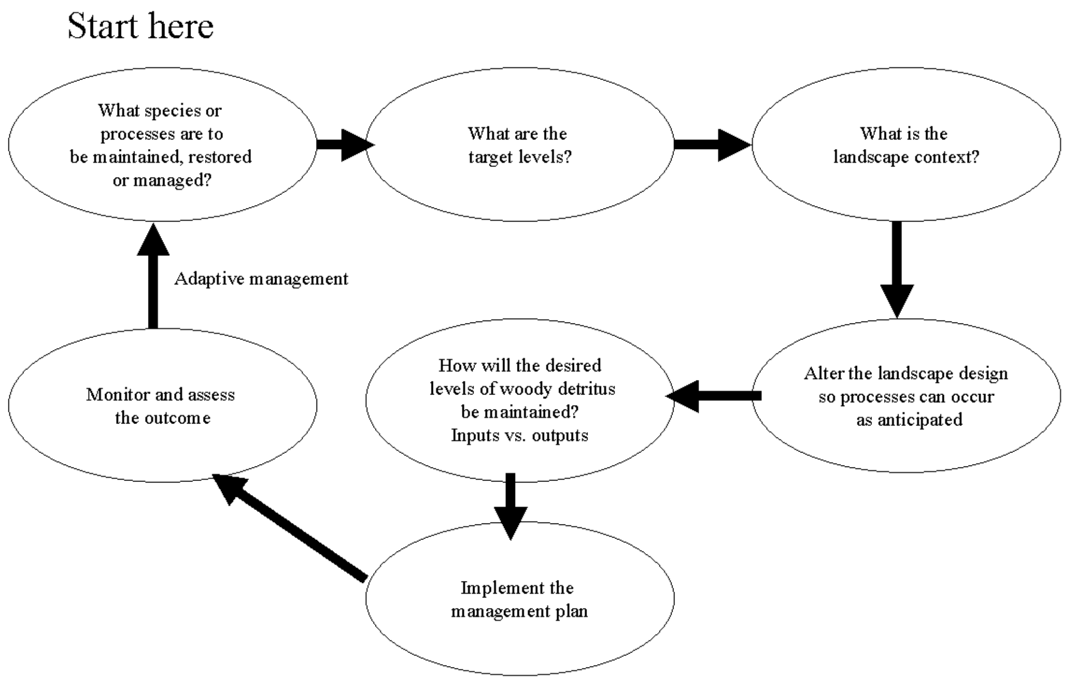

Figure 5—Integrating the elements of a new paradigm for woody detritus management.

Science Needs

Despite the need to improve our understanding of woody detritus dynamics in terms of mortality, decomposition, and consumption by fires, we already have enough knowledge of these processes to make reasonable projections of temporal dynamics at the level of stands. The same cannot be said about the response functions that are required to match the amount of woody detritus to the expected level of functionality at the ecosystem or landscape level. Clearly science needs to make major progress in this arena within the next decade if we are to see a new management paradigm take root in the near future.

Unfortunately, this is difficult research. In some cases it will be long term. For example, we have made many assumptions about the irrelevance (and relevance) of woody detritus in the nutrient cycles of forests. But very few of these assumptions have actually been tested. Perhaps it is time they are tested. Equally problematical, but perhaps easier to solve in the short term, is the specific link between woody detritus and specific organisms (e.g., is it a nesting site, transport corridor, food source, etc.?). We need to be able to establish these relationships if we are to have any faith in the response functions that are generated. The design of experiments that actually test the response of various organisms to the abundance of woody detritus will be harder but by no means impossible. This might be conducted using existing gradients in wood amounts, or it could be done in manipulative experiments where wood is either added or removed. One complicating factor is the ability of organisms to disperse between these treatments. Adding woody detritus to systems that are depleted might not result in a response if the organisms cannot find or disperse to these locations. Conversely, removing woody detritus in a landscape with an abundance of this material might not result in a decline if the treatment area is too small. Finally, we need to understand the historic and present dynamics of woody detritus at the landscape scale. We are beginning to understand these dynamics at the level of forest stands and other landscape elements such as streams. We must build up this understanding to the landscape level so that we can predict how managed landscapes differ from historical ones.

Conclusions

We have made progress in the last several decades in the management and understanding of woody detritus. Although the creation of minimum standards has been a useful first step in acknowledging the ecological function of woody detritus, it is not the ultimate solution to the problem. Rather, we need to develop a long-term, broad-scale view that is dynamic and that includes everything from proto-dead trees (live trees) to snags to logs to highly decomposed material that functions as soil organic matter. We also need to move away from arbitrarily setting amounts to a system based on the response of specific ecosystem function and species. This will be challenging to scientists and managers alike, but will be necessary if we intend to preserve, conserve, and restore the role of woody detritus in our forested landscapes.

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References

Agee, J. K.; Huff, M. H. 1987. **Fuel succession in a western hemlock/Douglas-fir forest**. Canadian Journal of Forest Research 17: 697-704.

Ausmus, B. S. 1977. **Regulation of wood decomposition rates by arthropod and annelid populations.** Ecological Bulletin (Stockholm) 25: 180-192.

Brown, J. K. 1985. **Predicting duff and woody fuel consumed by prescribed fire on the northern Rocky Mountains**. Res. Paper INT-337. Ogden UT: USDA Forest Service.

Butts, S. R.; McCombe, W. C. 2000. **Associations of forest floor vertebrates with coarse woody debris in managed forests of western Oregon**. Journal of Wildlife Management 64: 95-104.

Conway, S. 1982. **Logging practices.** Revised edition. Miller Freeman.

Corn, P. S.; Bury, R. B. 1991. **Terrestrial amphibian communities in the Oregon Coast Range.** Gen. Tech. Rep. PNW-GTR-285. USDA Forest Service; 533 p.

Cramer, O. P., ed. 1974. **Environmental effects on forest residues management in the Pacific Northwest.** Gen. Tech. Rep. PNW-24. USDA Forest Service; 416 p.

Franklin, J. F. 1997. **Alternative silvicultural approaches to timber harvesting: Variable retention harvest systems.** In: Kohm, K. A.; Franklin, J. F., eds. Creating a forestry for the 21st century. Washington DC: Island Press; 111- 139.

Franklin, J .F.; Shugart, H. H.; Harmon, M. E. 1987. **Tree death as an ecological process.** Bioscience 37: 550-556.

Gibbons, W. H. 1918. **Logging in the Douglas-fir region.** United States Department of Agriculture Forest Service Contribution Bulletin 711.

Gore, J. A.; William, A. P. 1986. **Mass of downed wood in north hardwood forests in New Hampshire: potential effects in forest management**. Canadian Journal of Forest Research 16: 335-339.

Hanski, I. 1991. **Single species metapopulation dynamics: concepts, models and observations**. Biol. J. Linn. Soc. 42: 17-38.

Hanzlik, E. J.; Fuller, F. S.; Erickson, C. 1917. **A study of breakage, defect, and waste in Douglas-fir.** Forest Club Annual, University of Washington; V: 32-39.

Harmon, M. E. 1992. **Fire influences on coarse woody debris.** In: Kauffman, J. B. Fire in Pacific Northwest Ecosystems: exploring emerging issues. 1992 January 21-23. Portland OR: Oregon State University; 13-14.

Harmon, M. E.; Krankina, O. N.; Yatskov, M.; Matthews, E. 2001. **Predicting broad-scale carbon stores of woody detritus from plot-level data.** In: Lai, R.; Kimble, J.; Stewart, B. A. Assessment methods for soil carbon. New York: CRC Press; 533-552.

Harmon, M. E.; Krankina, O. N.; Sexton, J. 2000. **Decomposition vectors: A new approach to estimating woody detritus decomposition dynamics.** Canadian Journal of Forest Research. 30: 74-84.

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

Harmon, M. E.; Garman, S. L.; Ferrell, W. K. 1996. **Modeling historical patterns of tree utilization in the Pacific Northwest: carbon sequestration implications.** Ecological Applications 6: 641-652.

Harmon, M. E.; Nadelhoffer, K. J.; Blair, J. M. 1999. **Measuring decomposition, nutrient turnover, and stores in plant litter.** In: Robertson, G. P.; Bledsoe, C. S.; Coleman, D. C.; Sollins, P., editors, Standard soil methods for long term ecological research. New York: Oxford University Press; 202-240.

Hodgeson, A. H. 1930. **Logging waste in the Douglas-fir region.** West Coast Lumberman 56: 6-13.

Jonsell, M.; Nordlander, G.; Jonsson, M. 1999**. Colonization patterns of insects breeding in wood-decaying fungi.** Journal of Insect Conservation 3: 145-161.

Jonsell, M.; Nordlander, G. 1995. **Field attraction of Coleoptera to odours of the wood-decaying polypores *Fomitopsis pinicola* and *Fomes fomentarius***. Annl. Zool. Fennici 32: 391-402.

Jonsell, M.; Weslien, J.; Ehnström, B. 1998**. Substrate requirements of red-listed saproxylic invertebrates in Sweden.** Biodiversity and Conservation 7: 749-764.

Kirby, K. J.; Drake, C. M. 1993. **Dead wood matter: the ecology and conservation of saproxylic invertebrates in Britain.** English Nature Science No. 7. Peterbourough, UK.

Krankina, O. N.; Harmon, M. E. 1995. **Dynamics of the dead wood carbon pool in northwestern Russian boreal forests.** Water, Air and Soil Pollution 82: 227-238.

Maser, C.; Trappe, J. M. 1984. **The seen and unseen world of the fallen tree.** Gen. Tech. Rep. PNW-164. Portland, OR: Pacific Northwest Research Station: USDA Forest Service.

McCombe, W.; Lindenmayer, D. 1999. **Dead, dying, and down trees.** In: Hunter, M. L., ed. Maintaining biodiversity in forest ecosystems. Cambridge University Press; 335-372.

McCune, B.; Cloonan, C. L.; Armentano, T. V. 1988. **Tree mortality and vegetation dynamics in Hemmer Woods, Indiana.** American Midland Naturalist 120: 416-431.

McMinn, J. W.; Crossley, D. A. 1996**. Biodiversity and coarse woody debris in southern forests.** Gen. Tech. Rep. SE-94. Southeastern Research Station, USDA Forest Service.

Pool, C. G. 1950. **An analysis of falling and bucking.** Timberman 51(7): 78-82.

Powers, J. S.; Sollins, P.; Harmon, M. E.; Jones, J. A. 1999. **Plant-pest interactions in time and space: a Douglas-fir bark beetle outbreak as a case study.** Landscape Ecology 14: 105-120.

Renvall, P. 1995. **Community structure and dynamics of wood-rotting Basidiomycetes on decomposing conifer trunks in northern Finland.** Karstenia 35: 1-51.

Rienhardt, E. D. 1991. **Woody fuel and duff consumption by prescribed fire in northern Idaho mixed conifer logging slash.** Res. Paper INT-43. Intermountain Research Station, USDA Forest Service.

Rydin, H.; Diekmann, M.; Hallingbäck, T. 1997. **Biological characteristics, habitat associations, and distribution of macrofungi in Sweden.** Conservation Biology 11: 628-640.

Samuelsson, J.; Gustafsson, L.; Ingelög, T. 1994**. Dying and dead trees: A review of their importance for biodiversity.** Swedish Environmental Protection Agency Report 4306. Uppsala; 109 p.

Spies, T. A.; Franklin, J. F. 1991. **The structure of natural young, mature, and old-growth forests in Washington and Oregon.** Gen. Tech. Rep. PNW-GTR-285. Portland, OR: Pacific Northwest Research Station, USDA Forest Service.

Spies, T. A.; Franklin, J. F.; Thomas, T. B. 1988**. Coarse woody debris in Douglas-fir forests of western Oregon and Washington.** Ecology 69: 1689-1702.

Tinker, D.; Knight, D. 2001. **Temporal and spatial dynamics of coarse woody debris in harvested and unharvested lodgepole pine forests.** Ecological Modeling 141: 125-149.

Wikström, P.; Eriksson, L. O. 2000**. Solving the stand management problem under biodiversity-related considerations.** Forest Ecology and Management 126: 361-376.

Wright. P. 1998. **Coarse woody debris in two fire regimes of the central Oregon Cascades.** Corvallis, OR: Oregon State University; M.S. thesis.