I. Effects of Riparian Thinning on Wood Recruitment: A Scientific Synthesis

Science Review Team Wood Recruitment Subgroup

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Executive Summary

For forests in northwest Oregon, we were asked to provide a scientific perspective on "…*the anticipated contributions of large woody debris from young (up to 120 years) unthinned (and generally even-aged) riparian forests, in the short term and long term, and describe how that recruitment changes under various riparian thinning regimes. Describe how the outcomes are affected by the tree species composition. Include information regarding large woody debris for aquatic and terrestrial systems"*

Approach

We used published empirical and theoretical studies, simulation modeling (done especially for this project) and professional opinion to synthesize the science. In general, there is very little published science about the effects of thinning on dead wood recruitment and virtually none on thinning effects on wood recruitment in riparian zones. We conducted some limited simulation modeling to illustrate some of the relationships between thinning and dead wood recruitment. The simulations (and comparison of models) were not comprehensive or a rigorous analysis of thinning effects and should be viewed as preliminary. Below we provide 15 key points from our efforts:

Key Points

1. Thinning is most beneficial in dense young stands. Existing literature and stand development theory suggest that the greatest potential ecological benefits of thinning to accelerate the development of older forest structure (e.g. large trees, large dead trees, spatial structural and compositional heterogeneity, etc.) comes in dense uniform plantations less than 80 years and especially less than 50 years old. The benefits of thinning for older forest ecological objectives are less clear in stands over 80 years of age. Hence, our report focused primarily on plantations less than 50 years of age.

2. Results may not be applicable to all stand conditions. For this synthesis, many of our conclusions were based on modeling the effects of thinning 30 to 40 year old Douglas-fir plantation stands that range

in density from 200 to 270 trees per acre (tpa). We consider such stands moderately dense, as young plantation stand densities range from less than 100 to greater than 450 tpa. In terms of dead wood production, higher density stands are likely to see more benefits from thinning, and lower density stands less benefits.

3. Accurate assessments of thinning effects requires site-specific information. The effects of thinning regimes on dead wood creation and recruitment (relative to no-thinning) will depend on many factors including initial stand conditions, particularly stand density, and thinning prescription—it is difficult to generalize about the effects of thinning on dead wood without specifying the particulars of the management regime and stand conditions.

4. Conventional thinning generally produces fewer large dead trees. Thinning with removal of trees (conventional thinning) will generally produce fewer large dead trees across a range of sizes over the several decades following thinning and the life-time of the stand relative to equivalent stands that are not thinned. Generally, recruitment of dead wood to streams would likewise be reduced in conventionally thinned stands relative to unthinned stands.

5. Conventional thinning can accelerate the development of very large diameter trees. In stands that are conventionally thinned, the appearance of very large diameter dead trees (greater than 40") may be *accelerated* by 1 to 20 years relative to unthinned plantations, depending on thinning intensity and initial stand conditions. Trees of such sizes typically begin to appear 5 to 10 decades after thinning 30 to 40 year old stands.

6. Nonconventional thinning can substantially accelerate dead wood production. Stands thinned with prescriptions that leave some or all of the dead wood may more rapidly produce both large diameter dead trees in the short-term and very large diameter dead trees (especially greater than 40") in the long-term, relative to unthinned stands. Instream wood placement gets wood into streams much sooner than by natural recruitment, and can offset negative effects of thinning on dead wood production.

7. Assessments of thinning effects may vary depending on the forest growth model. The previous statements are supported by three stand simulation models (FVS, ORGANON, and ZELIG). However, the magnitude and timing of effects of thinning on dead wood recruitment and stand growth varied among models.

8. Dead wood in streams comes from multiple sources. Dead wood in streams is primarily recruited through near-stream inputs (e.g. tree mortality and bank erosion) and landslides and debris flows. All types of recruitment are important and the relative importance varies with site and stream characteristics.

9. 95% of near-stream wood inputs come from within 82 to 148 feet of a stream. The distance of near-stream inputs to streams varies with forest conditions and geomorphology. Empirical studies indicate that 95% of total instream wood (from near-stream sources) comes from distances of 82 to 148 feet. Shorter distances occur in young, shorter stands and longer distances occur in older and taller stands.

10. Thinning can increase the amount of pool-forming wood under certain conditions. Thinning can increase the amount of pool-forming wood only when the thinned trees are smaller in diameter than the average diameter of pool-forming wood (which varies with stream size).

11. The function of instream wood varies with size and location. Large instream wood can serve as stable "key" pieces that create instream obstructions and form wood jams by racking up numerous

smaller pieces of wood that are mobile during high flows. Such wood jams typically consist of a wide range of piece sizes and provide multiple ecological functions that vary with stream size and gradient.

12. Effects of thinning on instream wood needs to be placed in a watershed context. Assessing the relative effect of riparian thinning on instream wood loads at a site and over the long term requires an estimation of the likely wood recruitment that will occur from the opposite bank, from upstream transport, and the rate of decay and downstream transport of wood from the site.

13. The ecological effects of thinning needs to be placed in a watershed context. Watershed-scale perspectives are needed to restore streams and riparian vegetation. The ecological effects of thinning on instream habitat will vary depending upon location in the stream network. Riparian management practices can be varied to match the ecological functions of streams.

14. Variation in thinning is essential (i.e. don't do the same thing everywhere). Variation in thinning prescriptions will produce more variable forest and wood recruitment conditions, which may more closely mimic natural forest conditions. Using a variety of treatments is also consistent with the tenets of adaptive management in situations where the outcomes of treatments are uncertain.

15. Healthy, diverse forests contain many dead trees. Numerous terrestrial forest species require large dead or dying trees as essential habitat. Some directly, others indirectly; to support the food web within which they exist. Abundant large snags and large down wood on the forest floor are common features of natural forests and essential for the maintenance of biological diversity.

Contents

Charge To SRT From Interagency Coordinating Subgroup:

Characterize the anticipated contributions of large woody debris from young (up to 120 years) unthinned (and generally even-aged) riparian forests, in the short term and long term, and describe how that recruitment changes under various riparian thinning regimes.

- *Describe how the outcomes are affected by the tree species composition.*
- *Include information regarding large woody debris for aquatic and terrestrial systems.*

Introduction

The future abundance of dead wood in aquatic and terrestrial systems is difficult to accurately predict because the natural processes that produce dead wood in ecosystems are highly variable. In stream networks, dead wood abundance and structure is a function of four major processes: stand mortality, bank erosion that recruits trees from streamside areas, debris flows and landslides that recruit trees and/or redistribute wood across stream networks, and wood depletion (loss) in streams. General predictions about the long-term effect of thinning on dead wood production are also difficult to make because of variation in thinning prescriptions and stand conditions, as well as, the absence of empirical long-term scientific studies and the limited number of modeling studies. Consequently, to answer the charge, we relied on a combination of theory, relevant scientific literature, unpublished simulation models, and professional opinion. We were not asked to develop management guidelines for thinning in riparian areas nor did we comment on the adequacy of current or alternative management practices to meet management goals.

We primarily used English units of measure, because that is what most foresters use, even though scientific journals generally use metric (SI) units. However, we occasionally provide metric conversions in places throughout the document. For those wanting to convert to metric, helpful conversions for this document are: 100 cm = 40”, 50 cm = 20”, 30 cm = 12”, 1 hectare = 2.5 acres.

Stand Age And Thinning Effects

In northwest Oregon (Coast Range and western Cascades), the greatest opportunity to influence old forest tree and stand development through thinning appears to be in young uniform stands (roughly less than 80 years), when stem growth and crown expansion rates are highest (McArdle et al. 1930) and have a strong influence on the diameters of future old trees (100 to 300 years old) (Tappeiner et al. 1997, Poage and Tappeiner 2002). Individual Douglas-fir trees can respond to changes in density (Gray et al. in press) in older stands (greater than 80 years) but by this age, if not sooner, most of these stands will be near the end of self-thinning period, when most density dependent mortality already occurred (Franklin et al. 2002). Consequently, the potential to accelerate the development of late-successional forest structure by silvicultural thinning is limited. For example, in many stands over 80 years on productive sites the majority of the trees will already be relatively large (greater than 20” dbh), so thinning these stands could remove ecologically valuable large diameter trees and growth enhancement from density reduction would be less than in denser, smaller diameter stands. Based on these considerations the largest potential benefits of thinning on ecological structures and functions related to old forests will likely occur in dense young stands that are less than 80 years old, and in many cases less than 50 years old (Poage and Tappeiner 2002). The following discussion of thinning effects focuses on young, moderately dense plantations and naturally regenerated stands about 30 to 50 years of age, and may not necessarily be applicable to older or younger stands, or stands with higher or lower tree densities.

Evaluating Thinning Effects On Dead Wood Production With Stand Development Models

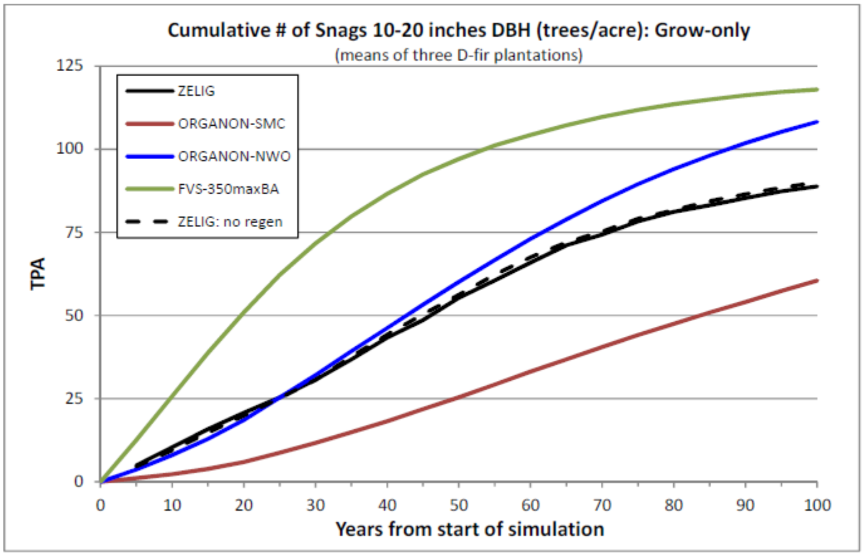
The (Limited) Scientific Literature On Thinning And Dead Wood Production

No empirical studies have documented the effects of thinning on dead wood production in Pacific Northwest forests over the lifetime of a natural or planted stand. However, one experimental study (Dodson et al. 2012) found that 11 years after thinning young conifer stands, the stands produced fewer dead trees than in the unthinned control and most residual live trees grew faster than in the control. We are aware of only one published study that modeled future trajectories of dead wood from thinning over many decades (Garman et al. 2003). That study found that dead wood production in thinned stands was less than in unthinned stands, and that dead trees had to be artificially created to accelerate the development of snags to meet old-growth forest structure objectives.

Given the lack of empirical and modeling studies of the effects of thinning on dead wood recruitment we conducted our own simulation experiments. *These simulations are preliminary and should not be viewed as a robust analysis of the subject*. However, we believe the findings are useful for the purposes of illustrating the general effects of thinning on dead wood production.

Comparison Of 3 Different Forest Growth Models Used To Evaluate Thinning Effects

For one of our analyses we compared the results of three forest growth and/or succession models used to evaluate thinning effects: FVS, ORGANON and ZELIG. Results (see below) of all three models show that conventional thinning (i.e. removal of all or most of the dead wood from the site) can greatly reduce the total number of the future dead trees that would be produced in a young Douglas-fir stand. Some of the simulations also showed that thinning can accelerate the appearance of very large (greater than 40”) dead trees. However, models differ in trajectories of dead wood production and rates at which some size classes of dead trees develop (Figures 1-3). For example, FVS tended to grow big trees faster than the other models and produce larger numbers of large dead trees over most of the simulations we examined. FVS also tended to show a greater difference in dead wood production between unthinned and thinned prescriptions. ORGANON (both variants but especially the SMC variant) on the other hand, appears to have lower growth rates and very low competition mortality rates compared to the other models for the scenarios examined. ZELIG is a gap succession model (Garman et al. 2003) that is fundamentally different from FVS and ORGANON, which are based on statistical relationships for use in growth and yield prediction. ZELIG simulates succession using ecological relationships (processes) related to growth, competition, mortality, light, and belowground resources. It is designed to simulate succession over long time frames and across a range of forests types without the need for empirical data sets on forest growth. For these runs, ZELIG included non-density-dependent mortality (e.g. disease, windthrow) but did not include successional changes from regeneration of shade tolerant trees. Differences between models can be attributed in part to how growth and mortality rates are parameterized. For example, parameters in the FVS model can be adjusted to better match the growth and mortality of a particular set of stands and ZELIG, although is it an ecological process model, can be calibrated against empirical data to improve its predictions power (Pabst et al. 2008). It appears that options for adjusting growth and mortality rates in ORGANON may be more limited.



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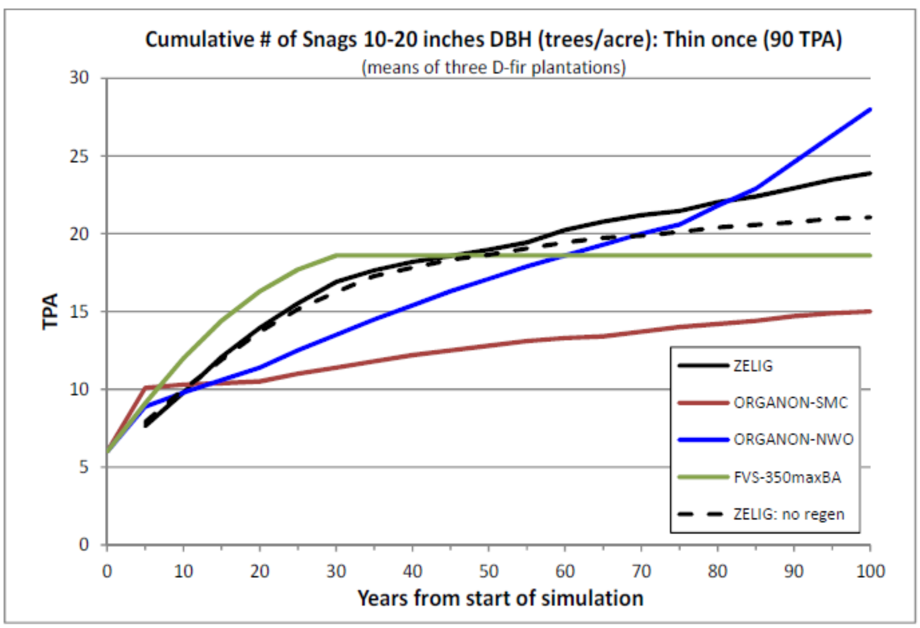

Figure 1. *Comparison of cumulative snag production for 10 to 20" dbh trees under a no-thin and thin once prescription for three different forest growth/succession models and their variants. ZELIG no- regeneration simulations do not include ingrowth but do include mortality from non-density dependent sources. Stands were Douglas-fir dominated and 31 to 35 years old with an average density of 293 trees per acre (range 267 to 308 tpa). The thinning prescription was thin from below to 90 tpa and create 6 snags/ac in year one of the simulation. Simulations courtesy of Stu Johnston, Siuslaw N.F. and Rob Pabst, Oregon State University.*

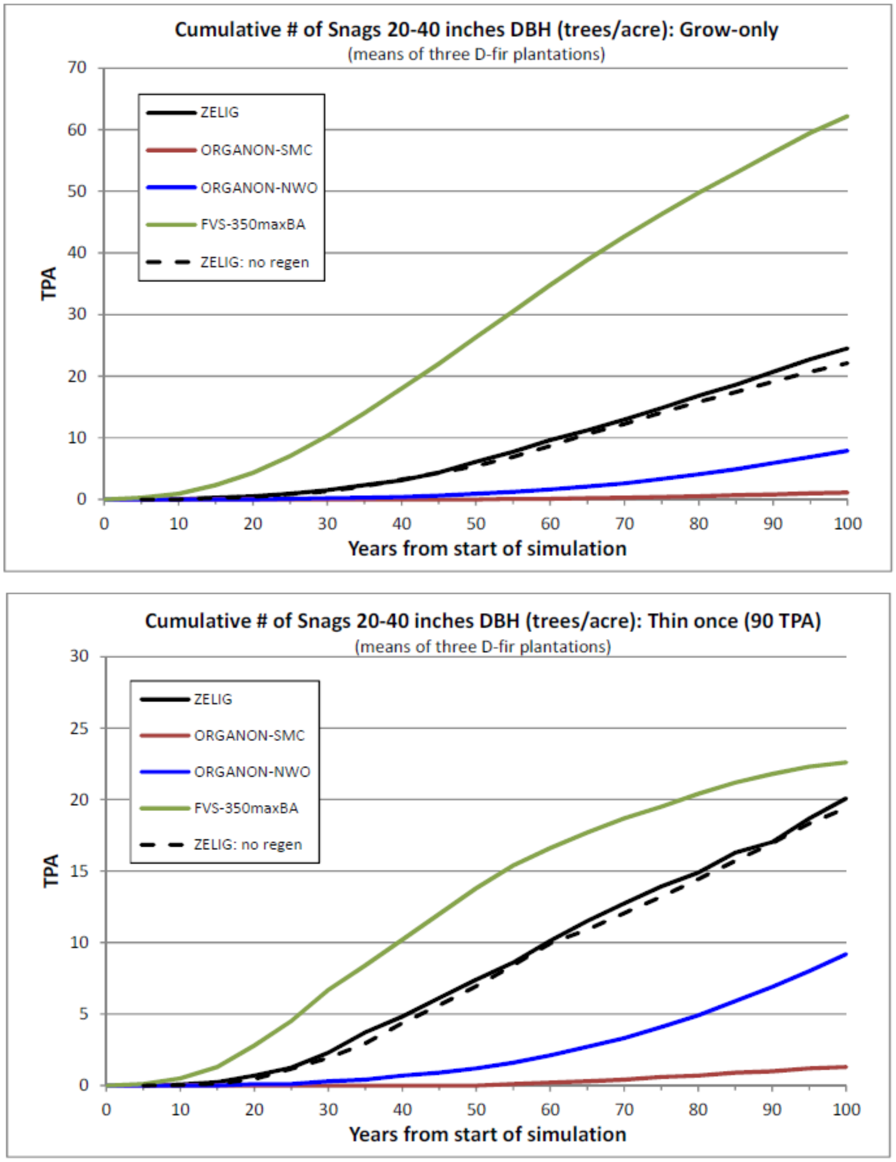

Figure 2. *Comparison of cumulative snag production for 20 to 40" diameter at breast height (dbh) trees under a no-thin and thin once prescription for three different forest growth/succession models and their variants. See Figure 1 caption for details.*

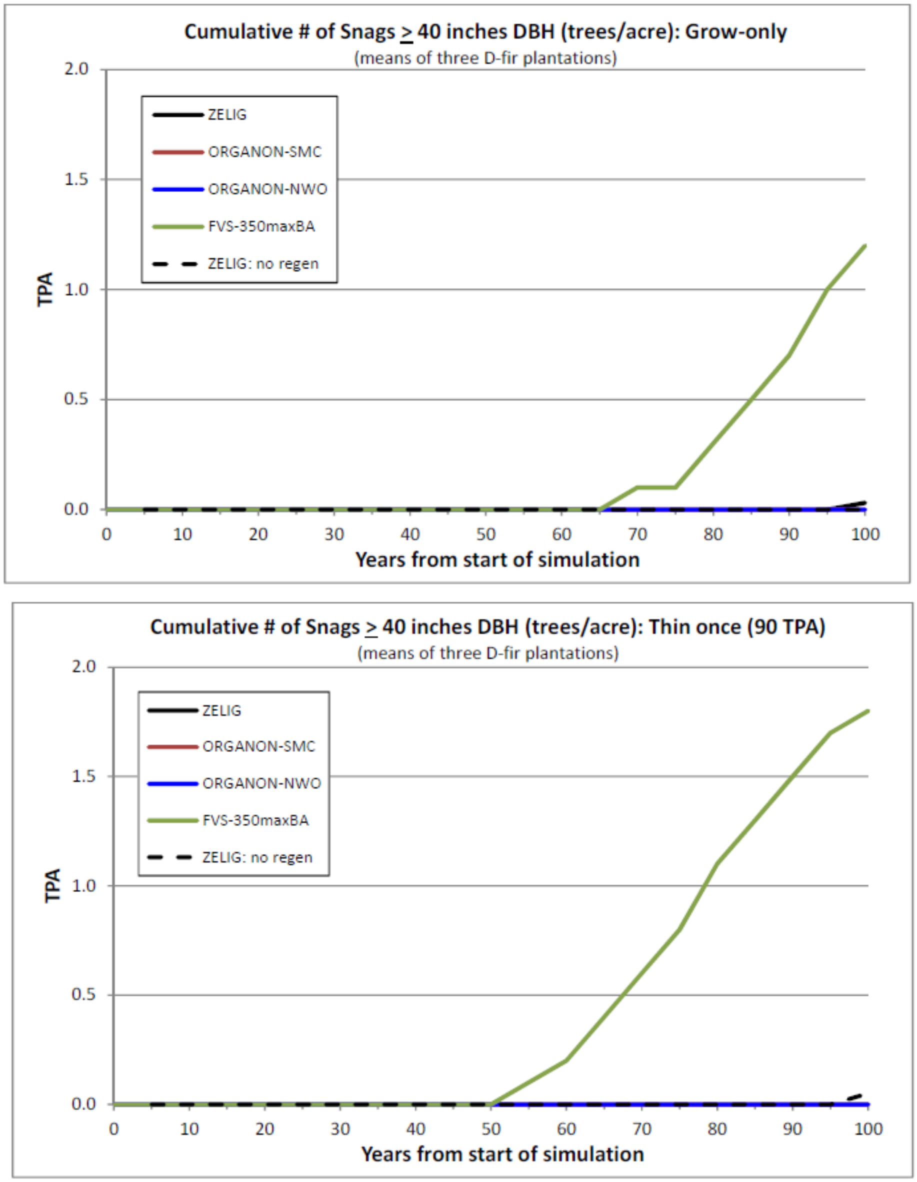

Figure 3. *Comparison of cumulative snag production for trees less than 40" dbh under a no-thin and thin once prescription for three different forest growth/succession models and their variants. See Figure 4 caption for details.*

It is difficult to say which of the models is "best" for assessing the potential effects of thinning without further evaluation of different initial stand conditions, prescriptions, and model parameterization. Based on our *preliminary* analysis, it appears that FVS and ZELIG may be the best of the three models for estimating the effects of thinning on dead wood production relative to not thinning, especially for diameters greater than 20" dbh. Of the three models, ZELIG is the only one that has been evaluated in peer reviewed literature for applications related to restoration thinning to accelerate old-growth forest structure in moist conifer forests of the Pacific Northwest (Garman et al. 2003, Pabst et al. 2008).

Managers may want to examine more than one model, but projections of levels of future dead wood production resulting from different management practices will always be uncertain, especially for the larger diameter classes and longer-time frames for which the models have not been tested. Major sources of uncertainty also include expected mortality from non-density dependent factors (e.g. windthrow, bank erosion) which will become more important over time especially for projections that extend out 50 to 100 years as most of our simulations did.

Dead Wood Production From Young Unthinned Stands

Production of dead wood from typical young, managed Douglas-fir stands in northwest Oregon (e.g. 30 to 40 years old with greater than 300 tpa of conifers) will vary over time and as a function of stand conditions, thinning regime, site productivity, and numerous other biophysical factors. Douglas-fir is a fast growing tree, and intense competition within these forests can result rapid emergence of dominant trees and senescence and death of subordinate trees. On productive sites, this period of intense competition and self thinning begins around 20 to 30 years (Franklin et al. 2002) and continues for several decades. Using our simulation models, we illustrate how dead wood production from young, unthinned Douglas-fir forests could develop over time. Dead wood gradually accumulates and produces relatively high numbers of large dead wood across a wide range of size classes (from 12” to greater than 36”) for at least a century (Figure 4). Similar patterns are seen for large wood biomass (Figure 5). Under a grow-only (no-thin) scenario (Figure 1) the cumulative number of boles of dead trees resulting from competition mortality in a young stand would be expected to be low for at least 10 years (i.e. up to age 40 or 50). During the first couple of decades (i.e. when stands are 30 to 60 years of age), all of the stand models we used showed that most dead trees would be less than 10” in diameter and there would be little or no production of dead trees greater than 20” dbh. However, the magnitude of the differences depends on the vegetation simulator used (see above) as well as initial stand conditions and other factors. For example, the cumulative production of dead trees greater than 20” dbh at 20 years (stand age ~52 yrs) ranged from 0 to 5 trees per acre for the three different models (Figure 2). For very large dead trees (greater than 40”), our simulation exercise indicated that few, if any, of these would be produced in the first 65 years (stand age ~95 yrs) (Figure 3). These outcomes for large and very large dead trees would vary by initial stand and site condition and parameter assumptions in the models.

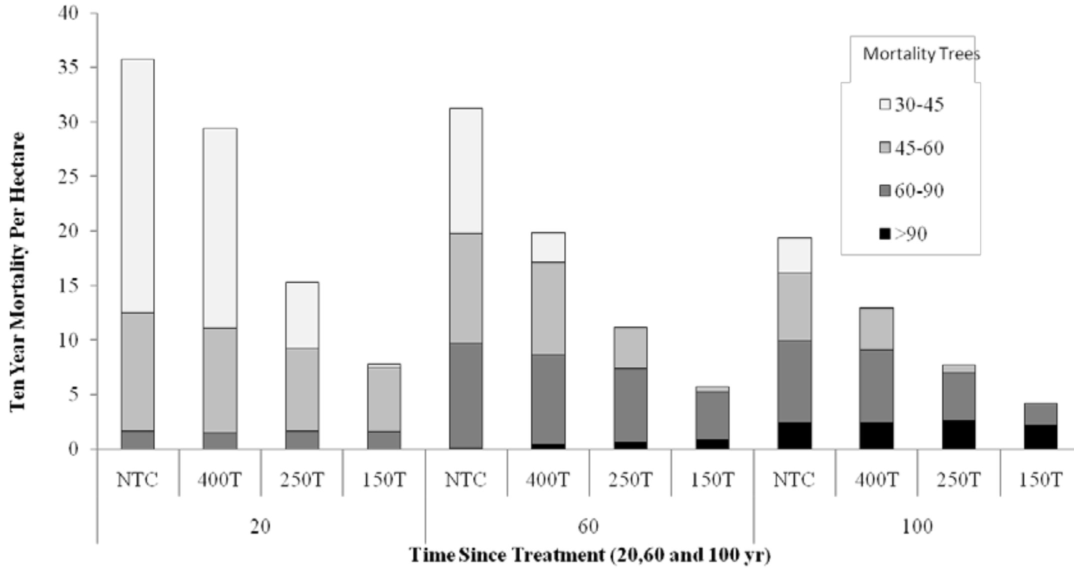

Figure 4. FVS simulation of the effects of different thinning levels on tree mortality rates for the average of seven 30 to 40 year Douglas-fir stands in northwest Oregon, with stand densities averaging about 600 tph. The figure shows the mortality rates at 20 years, 60 years, and 100 years after thinning, for a no-thin scenario (NTC), and thinning to 400 tph (162 tpa), 250 tph (101 tpa), and 150 tph 61 tpa). Four size classes of mortality trees are modeled, 30 to 45 cm (12-18"), 45-60 cm (18-24"), 60-90 cm (24-36") and greater than 90 cm (greater than 36"). Mortality rates are the number of trees dying per decade and represent the combined number of snags and downed wood produced.

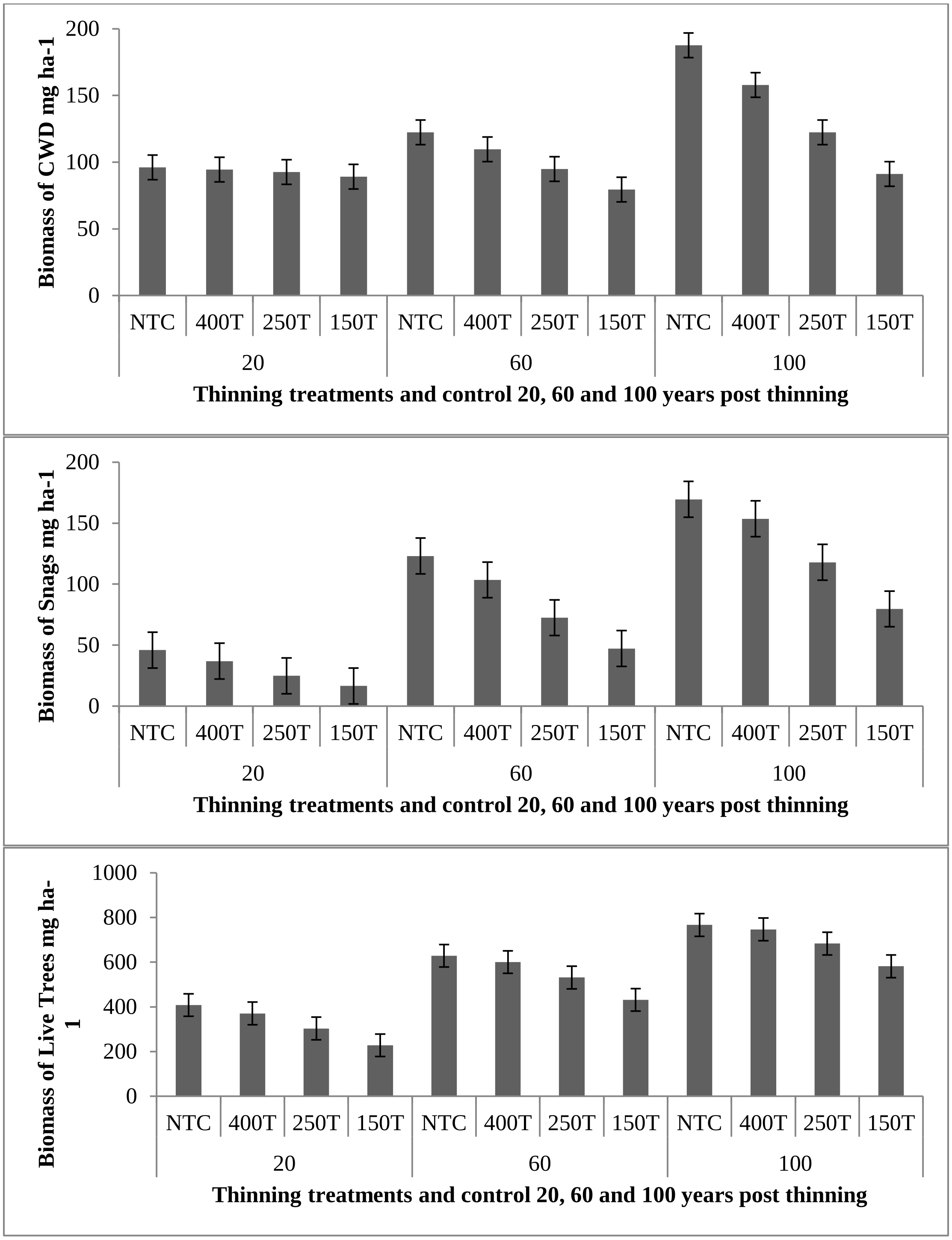

Figure 5. Comparison of average biomass (+ se) of snags, coarse woody debris and live trees, 20, 60 and 100 years post thinning of seven Pseudotsuga menziesii stands for a naturally thinned control, and silvicultural thins of 400 tph (162 tpa), 250 tph (101 tpa) and 150 tph (61 tpa)-(NTC, 400T, 250T, 150T). The FVS growth model was used to simulate tree growth and simulate dead wood biomass production. Additional details on estimating dead wood production can be found at the USFS DecAID web site (http://www.fs.fed.us/r6/nr/wildlife/decaid/).

We used all three simulation models to explore how thinning prescriptions could affect dead wood production in young Douglas-fir stands. In one of our simulations using FVS, high intensity thins (e.g. 60 tpa) substantially reduced the production of dead wood in all size classes between 12” to 36” dbh for a century or more (relative to no-thin or lighter thinning scenarios) but slightly accelerated the production of dead wood greater than 90 cm (36”) dbh (Figure 4). By year 100 the unthinned stand produced 4 times as many 12” snags as the heavy thinned stand and the number of 36” snags was about the same among the treatments. Other metrics, such as biomass of snags, down wood and live trees follow similar trends. One hundred years post-thinning, live tree, snag and down wood biomass were all highest in the unthinned stands and all lowest in the high intensity thins (Figures 5).

Other simulation examples (with FVS, ZELIG and ORGANON) also show that thinning with removal of dead trees will reduce the future number of dead trees in many size classes, however, the magnitude of the differences between thinned and unthinned stands varied among the models (see discussion above). For example, a prescription of thinning young stands to 90 tpa and leaving a few dead trees reduced the cumulative production of dead trees less than 40” dbh relative to an unthinned stand (Figures 1-3). Over a 100 year period, the cumulative production of 10” to 20” dbh dead tree boles were reduced from 60 to 120 tpa down to 15 to 30 tpa, (75-85%) depending on the simulation model used (Figure 1). These prescriptions are also likely to reduce the total production of 20” to 40” dbh dead trees over 100 years but by a lesser amount than dead trees 10” to 20” (Figure 2). All the models except FVS showed little to no effect of thinning (to 90 tpa) on the production of dead trees greater than 40” dbh 100 years post thinning for three particular stands (Figure 3). In this FVS simulation, the occurrence of greater than 40” dbh dead trees (1/acre) appeared more than 15 years earlier in the thinned stand compared to the unthinned stand, but the total number of dead trees by 100 years was only slightly higher in the unthinned stand (1.8 vs. 1.2 tpa). Another FVS simulation also suggested that thinning down to 150 to 400 trees per hectare (TPH) (60 to 162 tpa) accelerates the production of very large diameter trees (greater than 90 cm /36”) from 1 to 9 years, depending on the intensity of the thin (Figure 6). A different simulation with ZELIG of conventional thinning indicated that the diameter distribution of snags produced over a 100 year period is quite different from the unthinned stand and shifted toward the larger size classes (Figure 7).

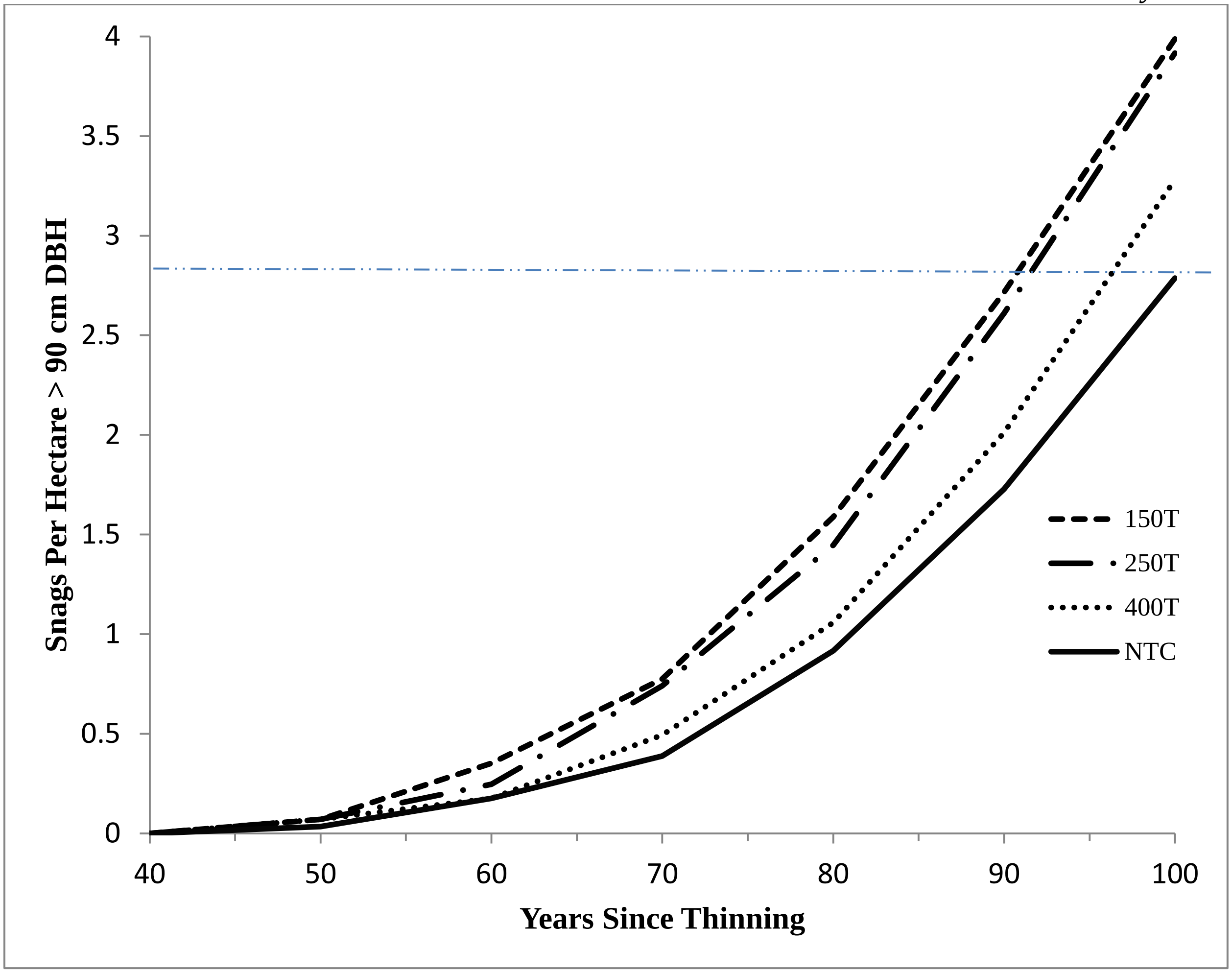

Figure 6. The effect of thinning on the average production rate of very large diameter (greater than 90 cm) snags for seven 30 to 40 year old Pseudotsuga menziesii stands for a naturally thinned control, and silvicultural thins of 400 (161 tpa), 250 (101 tpa) and 150 (60 tpa) trees per hectare (NTC, 400T, 250T, 150T) from initial stand densities averaging about 600 tph, using FVS. The heaviest silvicultural thin produces more very large snags sooner, the 250T, 400T and control lag a few years behind in the production rate of greater than 90 cm dbh snags. For example, it takes the 150T treatment 91 years to produce 2.8 greater than 90 cm dbh snags ha-1, while it takes the 250T, 400T and control, 92, 97 and 100 years to produce the same number of greater than 90 cm dbh snags (dashed horizontal line).

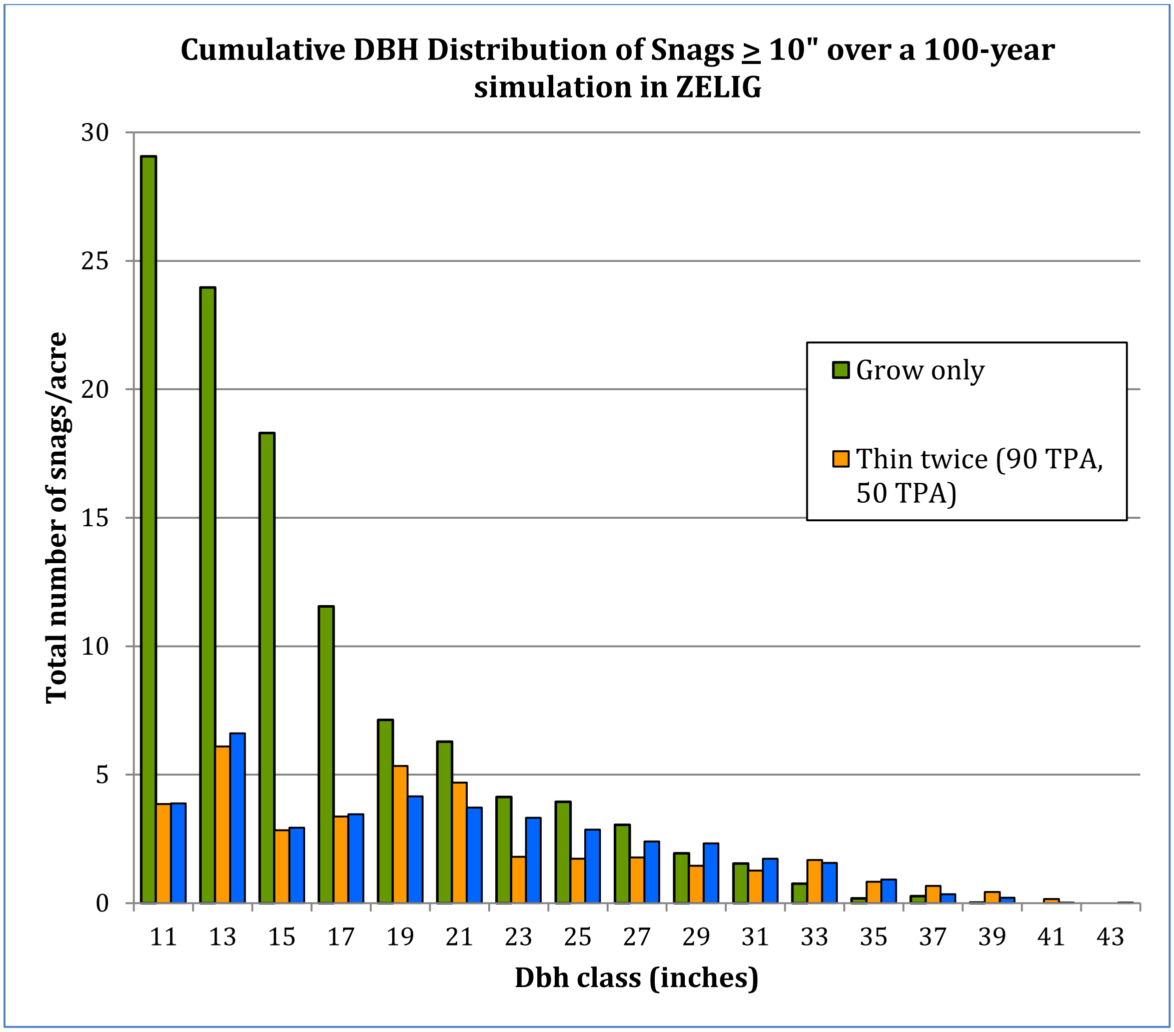

Figure 7. Mean diameter distribution of cumulative snag production over 100 years for no-thin and two thinning prescriptions based on three 31 to 35 year old Douglas-fir stands with an average density of 293 trees per acre (range 267 to 308 tpa). Simulation with ZELIG by Rob Pabst, Oregon State University. Data available upon request.

Thinning Prescriptions That Increase Dead Wood Production.

The loss of dead wood production due to thinning with removal can be offset or even reversed using thinning prescriptions where some or all of the thinned trees are left on the site and some felled into the stream. Intentionally creating many snags or felling trees into streams could strongly accelerate recruitment into streams of 10” to 20” trees during the first 10 to 50 years following treatment (Figure 8). Thinning with dead wood creation (*aka* dead wood restoration thinning) is already practiced by some managers (Stuart Johnston and Paul Anderson personal communication), has been identified as a potential restoration technique in the literature (Garman et al. 2003, Dodson et al. 2012), and could immediately reduce deficiencies in dead wood that exist in many streams and riparian areas. If trees are tipped with rootwads they may become even more stable in the stream. This prescription would produce more dead wood in riparian areas and streams in the short term than a stand that is left unthinned where dead trees slowly accumulate as a result of competition, disease, disturbance and other factors. Given the right stand conditions, such actions could have the added benefit of accelerating the future production of very larger diameter (greater than 40”) trees.

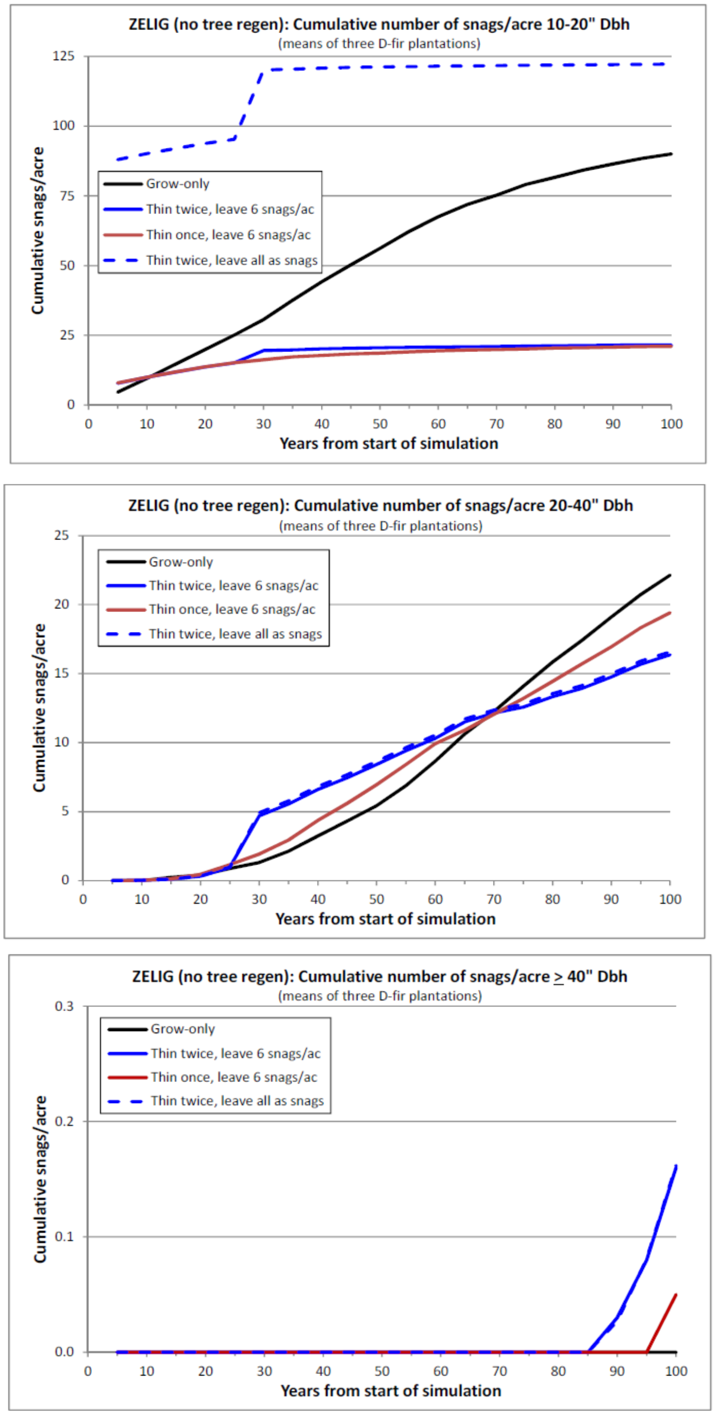

Figure 8. Simulated cumulative snag production for three different diameter classes for four thinning prescriptions including a prescription that leaves all the cut trees on the site. Curves are from an average of three 31 to 35 year old Douglas-fir plantations from the Oregon Coast Range. Simulations from ZELIG model courtesy of Rob Pabst, Oregon State University.

Landscape Scale Considerations

At the landscape level, variation in thinning regimes can create variation in the size and diameter of dead wood and live trees. A single type of thinning treatment could lead to forest structure simplification at the landscape level (Figure 9). By varying thinning prescriptions, a diversity of forest conditions can be produced that may be more reflective of the variability that occurs within unmanaged riparian areas. Using a variety of treatments is also consistent with the tenets of adaptive management in situations where the outcomes of treatments are uncertain.

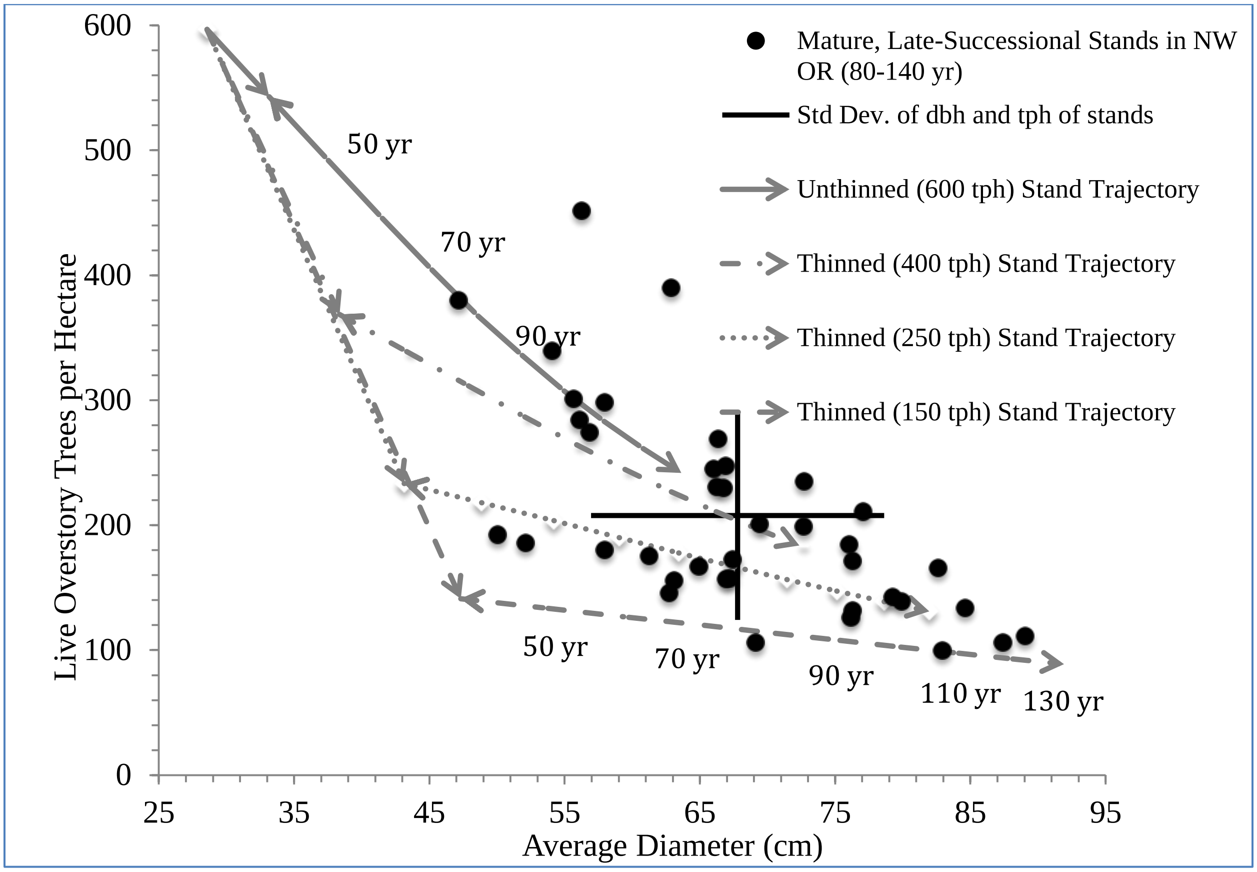

Figure 9. The projected effect of different thinning treatments on future tree density and diameter relative to undisturbed, mature (80 to 140 year old), late-successional Douglas-fir dominated forests in northwest Oregon. Trajectories are the simulated changes (using FVS) 100 years post thinning for each of the four treatments of an average of seven typical 30-40 year old (600 tph average), managed Douglas-fir stand in northwest Oregon. Each arrow head represents a 10 year interval in the simulation, ending at year 130. (a) Light, moderate and no thins options project live overstory tree densities and diameters similar to the late successional stands (i.e. within a standard deviation of the average diameter and density), but the no thin option does so at a much slower rate. Heavy thinning increases the average diameter of live trees, but densities are low relative to the late successional stands (and the light, moderate and no thin options). These data lend support to the hypothesis that young, managed Douglas-fir stands in northwest Oregon are growing at higher densities than is typical of natural stands, and that light to moderate levels of thinning will accelerate the development of live tree densities typical of mature, late-successional forests. The late-successional stands in this example were Douglas fir dominated USFS CVS plots and do not necessarily represent the diversity of stand conditions that would occur across a riparian network or within different regions of the Pacific Northwest.

Thinning And Wood Recruitment To Streams

The (Limited) Scientific Literature On Thinning And Wood Recruitment To Streams

No published empirical studies characterize the effect of thinning in riparian areas on the recruitment of wood to streams. Only one peer reviewed simulation study (Beechie et al. 2000) and two unpublished studies (Pollock et al. and Benda et al.) describe how thinning could affect wood recruitment. These studies indicate that effects of thinning on wood in the stream will be a function of stand conditions (e.g. tree size, species composition and density), thinning prescription, the location of the thinning relative to the stream and physical characteristics of the stream (e.g. size and gradient). There is general agreement on two key aspects of this issue:

- Instream wood recruitment mechanisms vary with location in the channel network
- Instream wood functions vary with the size of wood relative to the size and type of the channel

Effects Of Conventional Thinning On Near-Stream Inputs Of Dead Wood

For near-stream riparian inputs, empirical and modeling studies suggest that stream wood input rates decline exponentially with distance from the stream and varies by stand type and age (McDade et al. 1990, Van Sickle and Gregory 1990, Gregory et al. 2003) (Figure 10). For example, 95% of the total instream wood inputs in these studies came from distances that ranged between about 25 and 45 m (about 82 to 148 feet) depending on the stand conditions. Given these relationships we can assume that (all other factors being equal), increasing distance of thinning from a stream (i.e. increasing the no cut buffer width) will reduce the degree to which thinning affects instream wood recruitment over time. In general, different combinations of no-cut buffer widths and thinning intensities will have different effects relative to the unthinned condition. Figure 11 illustrates how one particular prescription affects instream delivery across a range of no-cut buffer widths—other prescriptions would have different outcomes.

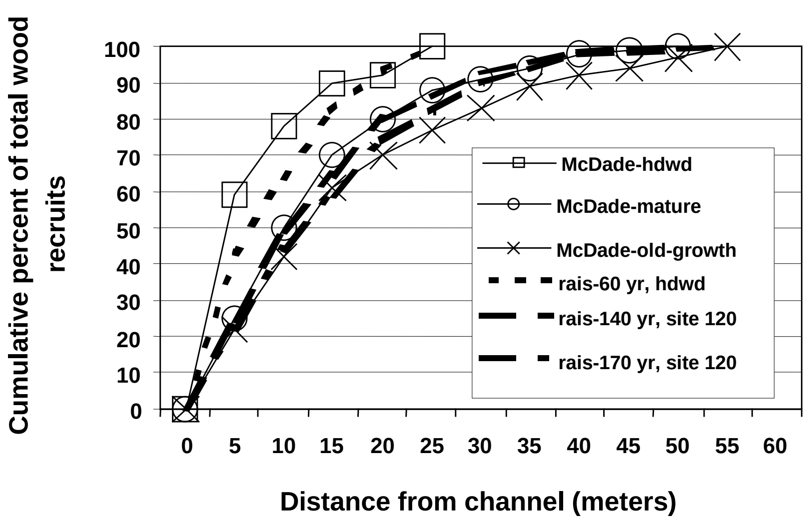

Figure 10. *Comparison of predictions of total wood accumulation with distance from channels using the Organon forest growth model and the RAIS instream wood recruitment model versus the observations of McDade et al. (1990) for streams in the Cascade mountains of Oregon and Washington. The data suggest that for old-growth forests, little*

to no instream wood is recruitment from beyond 55 m (180 ft) from the stream, while for younger (e.g. mature)forests, virtually all wood is recruited from within 40 m (131 ft) of the stream Figure from Welty et al. (2002). Note also that the simulation does not predict the total amount of wood that will be in the stream, because it does not include existing insteam wood loads, wood losses due to downstream transport, and wood delivery from upstream sources and from stands on the opposite bank. It simply predicts the relative effect of different management option on the delivery of instream wood from a stand.

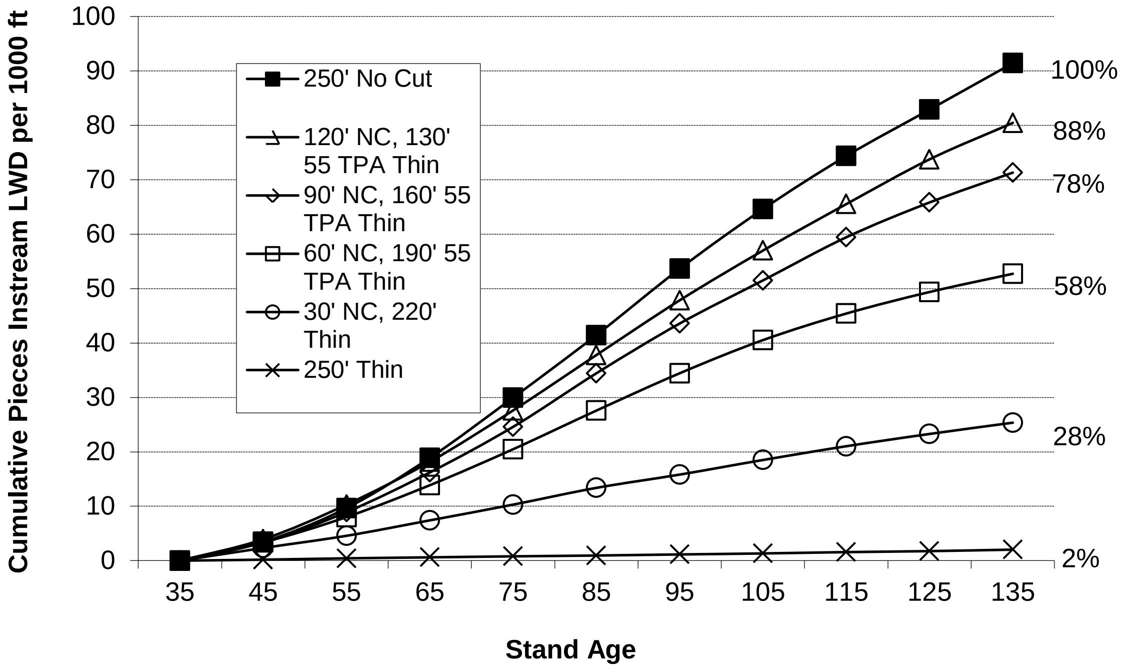

Figure 11. *Comparison of the modeled effect of various no-cut buffer width adjacent to a 55 TPA thin on cumulative large wood inputs from the modeled stand to a stream for 100 years post thinning for a young, managed Douglas-fir stand in northwest Oregon. Percentages on the right of figure are relative to a 250 foot no cut buffer, a width equal to the site potential tree height for the area. Forest growth was simulated using Organon and wood inputs were simulated using Streamwood. Stand data used in the simulation were provided by the Siuslaw National Forest and are included in their East Alsea Landscape Management Plan. The pre- and post-thin tree size and density is typical of the stands in the project where thinning is proposed. (Figure from Pollock et al., in preparation). The range of no-cut buffer widths and thinning regime examined are for comparative purposes only and is not meant to imply that they are all appropriate for meeting ACS objectives. Note also that the simulation does not predict the total amount of wood that will be in the stream, because it does not include existing insteam wood loads, wood losses due to downstream transport, and wood delivery from upstream sources and from stands on the opposite bank, It simply predicts the relative effect of different management options on the delivery of instream wood from a stand.*

Studies also show that the amount of in-stream wood is a function of the input rates and depletion rates, which results from fragmentation and movement; in general, smaller pieces and hardwood pieces have high depletion rates and larger pieces and conifer pieces, especially those with rootwads, are more stable and do not require as high a rate of input to accumulate in the stream (Kennard et al. 1998, Beechie et al. 2000, Meleason 2001, Welty et al. 2002). However, smaller pieces tend to accumulate in wood jams and perform similar functions to or enhance the functionality of larger single pieces (Bilby 1981, Bilby and Ward 1989, Bilby and Ward 1991).

Because most instream wood recruitment models (e.g. Streamwood, RIAB and RAIS) use the mortality outputs from forest growth models, estimates of potential instream wood recruitment are dependent on the forest growth model used. It is essential to assess the effects of thinning on instream wood recruitment on a relative scale (e.g. percentages, as illustrated in Figure 11). Caution should be exercised in comparing absolute outputs between different forest growth or instream wood recruitment models (e.g. see above section on forest growth models).

We used some of our forest growth and mortality simulations (see Figures 1-3) as input to a instream wood recruitment model (Figure 12). The pattern of recruitment of small and medium sized pieces were similar using ORGANON and ZELIG; there were declines in recruitment of smaller pieces as a result of thinning. However, the magnitude of the differences were greater with ORGANON. The pattern differed for the larger size categories. Very few pieces in either category were recruited under ORGANON (see model discussion section). For the large size pieces (24" to 30"), the volume from thinned stands was slightly higher than unthinned from 30 to 80 years but by 100 years there was less recruitment under this thinning prescription. Thinning slightly increased the instream volume of the largest diameter class (greater than 30") category.

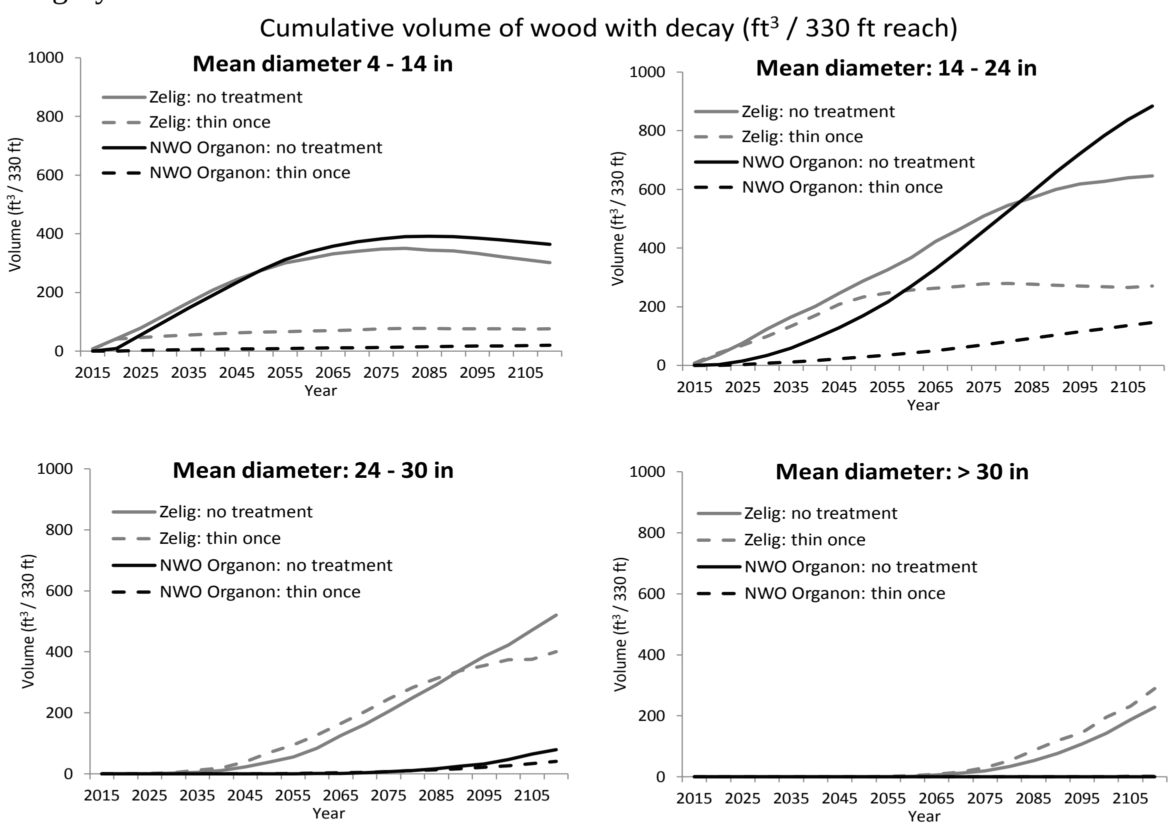

Figure 12. *Comparison of model results of potential wood recruitment to the channels using Zelig and NWO ORGANON. The thinning scenario modeled was thinning 31 to 35 year old Douglas-fir stand from 400 tpa to 90 trees/acre and leaving 6 dead snags per acre. The wood recruitment model was a modified version of Streamwood (Meleason et al. 2003) that is in NetMap. Simulations from S. Leichart and L. Benda, Earth Systems Institute. (see Figure 1 for stand modeling details)*

Using FVS in conjunction with a stream wood recruitment model, Beechie et al. (2000) showed that the effect thinning on wood recruitment and pool formation was a function of the size of trees at the time of thinning relative to the size of wood desired for a specific instream functions (Figure 13). That study focused on floodplains and gently sloping low terraces on relatively productive sites (site II) in Washington. It examined the size of wood that independently (i.e. not in conjunction with other obstructions such as boulders, bedrocks, channel constrictions, other wood, etc.) form pools in a stream of a given width. The general result was that thinning increased the supply of pool-forming wood for those stream conditions (5 to 30 m wide) when the average diameter of trees in the stand was smaller than the average minimum diameter of pool-forming wood, and that when trees were already at the pool-forming size, thinning simply reduced the amount of pool-forming wood recruited to a stream. This study also found that red alder could perform the same function as smaller sized conifers in creating pools, but that alder wood abundance decreased rapidly after 70 years. When production of larger instream wood such as key pieces (Abbe et al. 1996, Montgomery et al. 1996, Fox and Bolton 2007) is targeted, thinning stands with larger trees will be consistent with that goal, provided that the size of the trees in the stand is smaller than the target size of the key pieces. Although Beechie et al. (2000) did not examine scenarios that included no-cut buffers adjacent to the streams, the same principle still applies when no-cut buffers are present: *If the stand to be thinned already has trees that are large enough to have the desired function if they fall into a stream, then thinning is not going to increase the abundance of "functional" trees (unless some of the thinned trees are felled and left onsite, as illustrated in Figure 14).* More generally, as thinning operations move away from the edge of the stream, the opportunities for thinning treatments to increase the amount of pool-forming wood (or any size class of instream wood) diminishes.

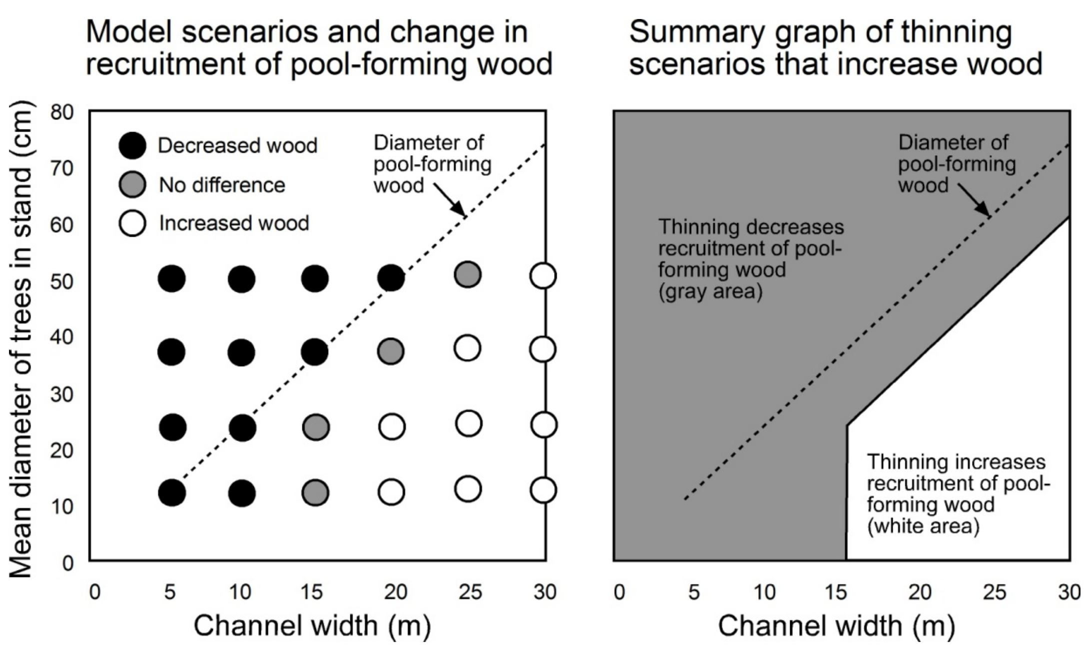

Figure 13. *Example of combinations of size of trees and channel widths where Douglas fir thinning enhances recruitment of pool-forming wood (left panel). Each dot represents a model run for a particular channel width and quadratic mean diameter of trees in the riparian stand at time of thinning, and dot shading represents the change in recruitment of pool-forming wood over a 100 year simulation (adapted from Beechie et al 2000). The dashed line shows the minimum diameter of pool-forming wood by channel width. The right panel is the summary graph illustrating combinations of stand diameter and channel width for which thinning can increase recruitment of pool-*

forming wood over 100 years (Beechie et al. 2000). For the thinning regimes examined, combinations of stand diameter and channel width in the shaded area represent cases where thinning will reduce recruitment of pool-forming wood, and combinations in the unshaded area will increase recruitment of pool-forming wood. In general, when trees in the riparian zone are large enough to form pools thinning simply removes potential pool-forming wood. Where trees are too small to form pools, thinning can increase growth rates and increase recruitment of pool-forming wood. Douglas-fir stands modeled for this figure had a 100 year site index of 52 m (170 ft), pre-thin average diameters of 12-51 cm (5 to 20"), pre-thin stand densities ranging from 420 to 1065 trees/ha (170 to 431 tpa) and post thin densities ranging from 220-370 trees/ha (93 to 150 tpa). Stands were modeled up to 100 years of age using Forest Vegetation Simulator. Additional details can be found in Beechie et al 2000).

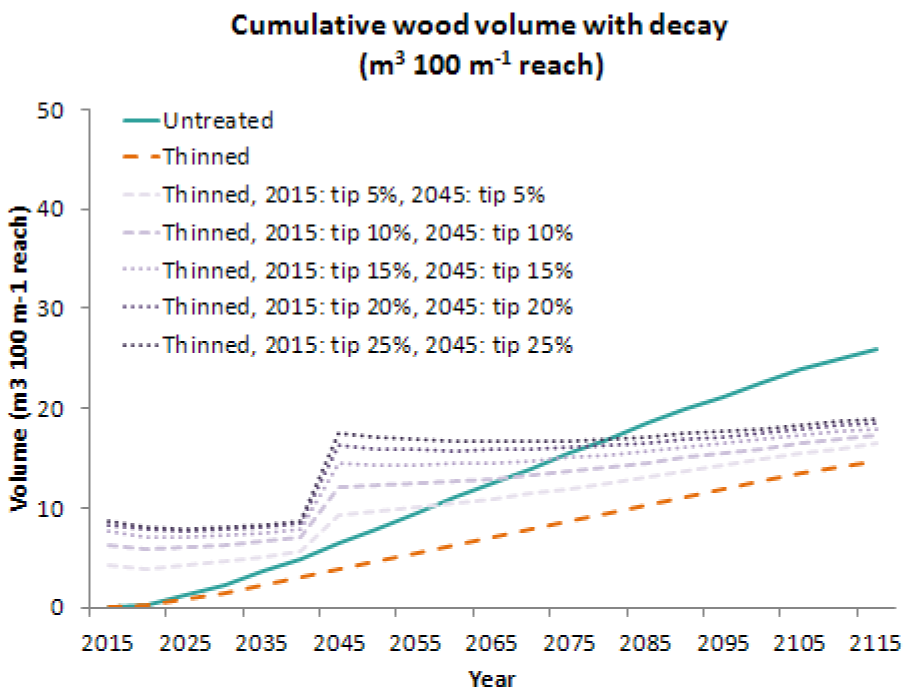

Figure. 14. *Simulation (using the forest growth model, Zelig) of the estimated volume of in-channel wood (m^3/100 m) under different options for directionally falling or tipping of wood during thinning operations. The modeled stand was a xx year old Douglas-fir stand thinned from 400 to 90 trees/acre and there were two entries. Wood input from only one bank was considered.*

If instream wood goals focused on key-sized pieces, the intensity of thinning and range of stand conditions where thinning would be appropriate would likely increase. However, the effects of management on key pieces has not been studied to date, and we are not yet able to quantify the range of potential outcomes on total wood recruitment and function. Regardless of the range of large wood sizes targeted, site-specific information on forest stands on both banks and stream conditions, in conjunction with forest growth and stream wood recruitment models, are required to estimate the site-specific effect of thinning on instream wood loads.

Non-Conventional Thinning Prescriptions That Increase Instream Dead Wood

As we identified in the thinning section above, it is possible to increasing dead wood delivery to streams when thinning. This is accomplished by actively dropping tree boles into the stream during thinning operations. Such dead wood restoration thinning would immediately increase the amount of wood in the channel, which should provide benefits to fishes and other aquatic organisms.

We explored this management option by modeling the amount of instream wood that would result from directionally falling or pulling over trees in the stand and compared this to the amount of wood that would be expected to be found in the stream without thinning the stand (Figure 14). The amount of wood increased above the “no thin” level immediately after the entry in all of the options of wood additions. However, the cumulative total amount of wood expected in the stream over 100 years relative to the unthinned stand varied depending on the amount of wood delivered (Table 1). Adding less than or equal to10% of the wood that would be removed during thinning produced less wood in the channel than the unthinned option. When less than or 15% of the thinned trees were tipped at each entry, the total amount of dead wood in the channel exceeded the unthinned scenario. This analysis of tree-felling into streams during thinning is very preliminary and needs further examination.

Table 1. *Percent difference in the volume of in-channel wood between an unthinned stand and one in which varying percent of trees were directionally felled or tipped into the channel (See Figure 14). The modeled stand was thinned from 400 to 90 trees/acre and there were two entries (year 2015 and year 2045). Wood input from only one bank was considered.*

Percent of trees felled or tripped into the stream	Time period (simulation year) when wood volume production curves for treated untreated stands cross in Figure 14.	Percent difference in total volume of wood produced relative to the unthinned stand
Thin, no tip	N/A	-43
5	2055-60	-17
10	2065-70	-4
15	2070-75	7
20	2075-80	14
25	2080-85	18

Large Diameter Trees And Distance From Stream

While the importance of large diameter wood to stream and riparian ecosystems has been well established (Harmon et al. 1986), creating additional very large diameter trees may also be important because recruitment of large wood into streams depends on bole diameters at heights that correspond to the distance of the tree from the stream. For example, to deliver a 20” diameter bole (the minimum pool forming diameter for a 60 foot wide stream) from a 160 foot tall tree that is 60 feet away from a stream would require a tree greater than 30” dbh. Thinning with dead wood creation can meet short-term needs and accelerate production of very large diameter (greater than 40” dbh) dead wood. This could be important near larger streams where conifers are separated from a stream by a band of alders or shrubs and large conifer bole inputs must come from trees that are 30 to 50 or more feet away from the stream.

Instream Wood Recruitment From Sources Outside The Thinned Stand

The relative effects of thinning a stand on instream wood recruitment should be assessed with knowledge of wood in the stream and recruitment from the opposite bank as well as upstream sources (see Landscape section below). Unless both banks have the same initial vegetative conditions and slope features, the wood delivery potential will vary between the banks. Most, if not all, of the current assessment of thinning effects have only considered impacts from one bank. Conclusions about the effects of thinning on instream wood recruitment at a site may not accurately reflect the potential impacts of thinning unless both banks have similar conditions and are treated the same. Assessing the relative effect of riparian thinning on instream wood loads at the site and over the long term requires an estimation of the likely wood recruitment that will occur from the opposite bank, the wood recruitment that will occur from upstream transport, and the rate of decay and downstream transport of wood from the site. Tools such as the model Streamwood can be used in combination with a forest growth model to make such assessments and predict the relative effect of a riparian thinning treatment. However, the model is data intensive, requiring knowledge of stand conditions and planned future silvicultural treatments for riparian forests at and upstream of the site (Meleason 2001, Meleason et al. 2003). The model also requires estimates of stream size, gradient, existing wood load, and flood frequency. Though data intensive, such modeling would provide a strong analytical justification for evaluating proposed riparian thinning relative to management objectives.

Overview Of Instream Wood Recruitment Processes And Functions

General Mechanisms And Pattern of Wood Recruitment To Streams

Wood recruitment to streams occurs either from near-stream tree mortality events (e.g. bank erosion, windthrow or windsnap) or from upstream landslides and debris flows. At a watershed scale, near-stream inputs are relatively regular in space and time while landslides and debris flows are episodic, adding large amounts of wood to low-gradient streams, but also removing large amounts of wood from higher gradient streams. Upslope, episodic delivery can account for a substantial portion (up to 80%) of the large wood in small to mid-sized streams (Reeves et al. 2003, Bigelow et al. 2007) in mountainous setting. Near-stream recruitment is the dominant source (up to 100%) in low gradient streams with floodplains. Topographic features of a watershed influence the relative contribution of upslope sources of wood. Steeper, more highly dissected watersheds will likely have a greater proportion of wood coming from upslope sources than will watersheds that are less dissected or steep (Martin and Benda 2001). However, in any watershed only a small subset of the upslope channels will deliver wood to valley floors and fish-bearing streams via debris flows.

It is not possible to fully understand or predict the effects of riparian forest management on wood delivery without considering both near-stream and episodic (upslope) processes. The wood found in forested streams in coastal areas of the Pacific Northwest originates from both sources and either source may be dominant depending on physiographic setting and location in the channel network. However, the spatial distribution of wood from these two sources is substantially different as is the function. Near-stream wood recruitment tends to be more evenly distributed throughout a drainage network, whereas episodic landslides tend to create large concentrations of wood at tributary junctions, which contributes to habitat complexity and ecological productivity (Bigelow et al. 2007). The presence of large wood in debris flows slows the speed of the flow and reduces the run-out distance of debris flows on the valley floors (Lancaster et al. 2003). Stream-side sources of wood can provide the largest key pieces to streams, and contribute to gravel storage that converts bedrock reaches to alluvial reaches, and create smaller, more numerous pools, and create habitat complexity (Montgomery et al. 1996, Bigelow et al. 2007). Both types of wood delivery are necessary for functioning and productive stream ecosystems.

The variable sources and delivery processes of dead wood to streams has implications for assessing the effects of thinning on wood delivery to fish-bearing streams. The magnitude of the effects of streamside silviculture (either positive or negative) relative to amount and size of wood delivered to streams will vary depending on stream type and location in a drainage network. For example, wood delivered to most streams that are high in the drainage network will not ultimately be delivered to fish-bearing streams that are low in the drainage network. However, some small and intermittent streams will be key sources of wood to larger streams. It is not possible to characterize the effects of thinning on delivery of wood to fish-bearing streams from nonfish-bearing streams without knowledge of stream type and stream network context as well as the condition of the vegetation where thinning is proposed. Potential impacts of riparian thinning on anadromous fish habitats are much less in forests along headwater streams that have a low potential to deliver wood and sediment to fish-bearing streams. Thinning in such riparian forests could focus on achieving other Aquatic Conservation Strategy (ACS) goals (e.g. see Table 2).

Table 2. *Potential ecological outcomes of Riparian Thinning in Relation to Aquatic Conservation Strategy Objectives (See NWFP, 1994).*

Aquatic Conservation Strategy Objectives for Forest Service and BLM-administered lands within the range of the northern spotted owl will be managed to:	Range of outcomes	
1. Maintain and restore the distribution, diversity, and complexity of watershed and landscape-scale features to ensure protection of the aquatic systems to which species, populations and communities are uniquely adapted.	Where landscapes are dominated by dense, young conifer stands (e.g. Douglas-fir plantations), thinning can help increase the long-term diversity of forest patch types by accelerating the development of variable density stands with large diameter trees	Where landscapes already have a diversity of stand types, thinning can decrease landscape-level stand diversity by creating stands that are all the same (i.e. low density stands of large diameter trees).
2. Maintain and restore spatial and temporal connectivity within and between watersheds. Lateral, longitudinal, and drainage network connections include floodplains, wetlands, upslope areas, headwater tributaries, and intact refugia. These network connections must provide chemically and physically unobstructed routes to areas critical for fulfilling life history requirements of aquatic and riparian-dependent species.	If young, high density conifer stands interfere with the movement of riparian-dependent species, then thinning can improve connectivity between habitats of riparian-dependent species. Thinning that increases wood loads to streams can improve connectivity for aquatic species.	Thinning that reduces snag and down wood abundances of a size that are important to species (e.g. see Table 4) may interfere with both the movement of species and the utilization of riparian and aquatic habitat by certain species (e.g. salmonids). If thinning alters microclimates it may interfere with the movement of species sensitive to temperature and humidity (e.g. herpetofauna).
3. Maintain and restore the physical integrity of the aquatic system, including shorelines, banks, and bottom configurations.	Thinning that increases wood loads to streams can help maintain and restore the physical integrity of stream beds.	Removal of trees adjacent to shorelines and banks and construction/maintenance of roads used to access thinning sites can affect the integrity of aquatic systems and their shorelines and banks. Thinning that reduces wood loads to streams can delay recovery of the physical integrity of stream beds.
4. Maintain and restore water quality necessary to support healthy riparian, aquatic, and wetland ecosystems. Water quality must remain within the range that maintains the biological, physical, and chemical integrity of the system and benefits survival, growth, reproduction, and migration of individuals composing aquatic and riparian	Thinning adjacent to streams may reduce shade and increase stream temperatures which can improve growth of instream organisms such as benthic invertebrates and fishes	Thinning can increase stream temperatures beyond a level that supports healthy aquatic and riparian ecosystems.

communities.		
5. Maintain and restore the sediment regime under which aquatic ecosystems evolved. Elements of the sediment regime include the timing, volume, rate, and character of sediment input, storage, and transport.	Thinning that increases dead wood loads to streams can help maintain and restore natural sediment regimes in aquatic systems	Thinning that reduces wood loads in streams can reduce sediment storage and affect transport rates.
6. Maintain and restore in-stream flows sufficient to create and sustain riparian, aquatic, and wetland habitats and to retain patterns of sediment, nutrient, and wood routing. The timing, magnitude, duration, and spatial distribution of peak, high, and low flows must be protected.	Thinning that increases dead wood loads to streams, riparian areas and wetlands can help sustain such habitat.	Thinning that reduces dead wood loads in both low- and high-gradient streams can delay recovery of natural patterns of sediment and wood storage and transport and nutrient processing.
7. Maintain and restore the timing, variability, and duration of floodplain inundation and water table elevation in meadows and wetlands.	Thinning that increases dead wood loads to streams can increase floodplain inundation, by creating jams and other instream obstructions	Thinning that reduces wood loads in low-gradient streams can lead to channel incision and reduced floodplain inundation.
8. Maintain and restore the species composition and structural diversity of plant communities in riparian areas and wetlands to provide adequate summer and winter thermal regulation, nutrient filtering, appropriate rates of surface erosion, bank erosion, and channel migration and to supply amounts and distributions of coarse woody debris sufficient to sustain physical complexity and stability.	Thinning can increase the diversity and biomass of understory plants. If shade-tolerant tree species become established, this helps increase structural diversity by creating a multi-tiered canopy. Thinning that increases dead wood loads in streams and riparian areas can help to sustain physical complexity	Thinning can reduce the future supplies of snags and large dead down and decomposing wood on the forest floor and in aquatic systems and thus delay the recovery of physically complex aquatic, riparian and terrestrial habitat. A lack of large wood in streams can also reduce channel migration and potentially lead to channel incision and habitat simplification. Thinning can affect the forest microclimate and the thermal regime of aquatic systems

9. Maintain and restore habitat to support well-distributed populations of native plant, invertebrate, and vertebrate riparian-dependent species.	Thinning can increase the biomass and diversity of understory vegetation. Thinning can create stands of variably spaced overstory trees with thick limbs that are used for nesting by marbled murrelets and can provide habitat for a diverse arboreal, epiphytic community	Thinning can reduce the future supplies of snags and large dead down and decomposing wood on the forest floor and in aquatic systems and thus delay the recovery of habitat essential to numerous aquatic, riparian-dependent and terrestrial vertebrates, invertebrates, plants and fungi. Also, the roads used to access thinned stands may provide access routes for diseases, exotic species and other undesirable species

Wood Size And Function In Streams

Studies of sizes and functions of wood of in Pacific Northwest streams have examined three key attributes: (1) minimum diameter of wood needed to independently form a pool (Beechie et al. 2000), (2) median diameter of pieces in unlogged Coast Range streams in SW Washington (which coincidentally is similar to the median diameter of pool-forming pieces in second growth forests) (Bilby and Ward 1989), and (3) key piece sizes; those that are unlikely to move during a flood and are needed to anchor wood jams (Figure 15) (Abbe et al. 1996, Montgomery et al. 1996, Fox and Bolton 2007). The size of wood increases with channel width for each functional attribute. Hence, judging the effects of thinning on recruitment of wood to streams depends in part on the size of the stream next to the thinned riparian stand, as well as the size of future instream wood being targeted. In general, more wood creates more pools in streams, up to a point at which pool formation is maximized and additional wood does not increase pool area or numbers (Montgomery et al. 1995, Beechie and Sibley 1997) (Figure 16). Rosenfeld and Huato (2003) found a similar relation for streams in coastal streams in British Columbia. The relation between wood and pools was statistically significant but wood only accounted for 11% of the variation in pool spacing, suggesting that other factors likely also influence pool abundance. Previous studies show that this relationship holds in both low and moderate gradient streams but that it is stronger in moderate gradient streams (Montgomery et al. 1995, Beechie and Sibley 1997).

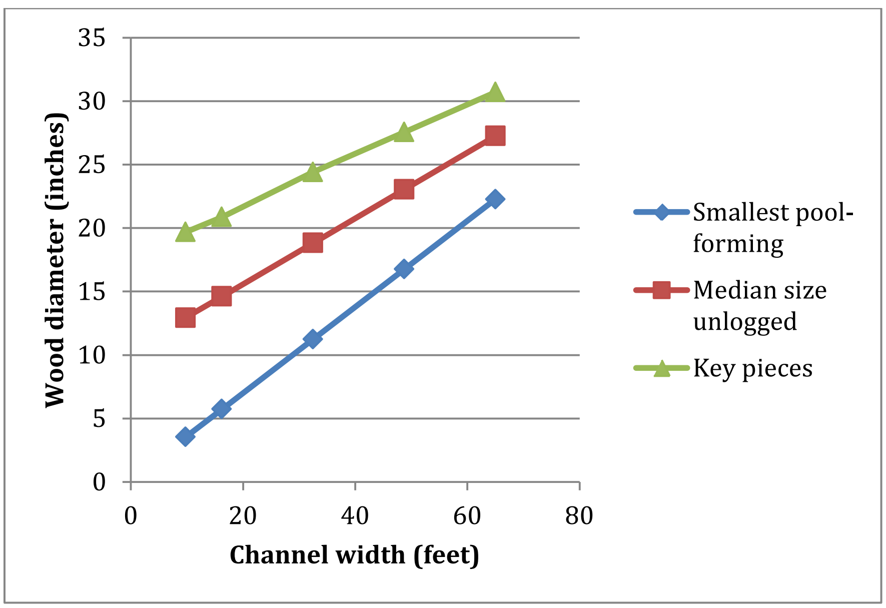

Figure 15. *Examples of variation in functional wood sizes as a function of channel width (based on data in Bilby and Ward (1989) for median size of wood in unlogged streams Beechie and Sibley (1997) for smallest pool-forming, and Washington Forest Practice Board (1995) for key pieces.*

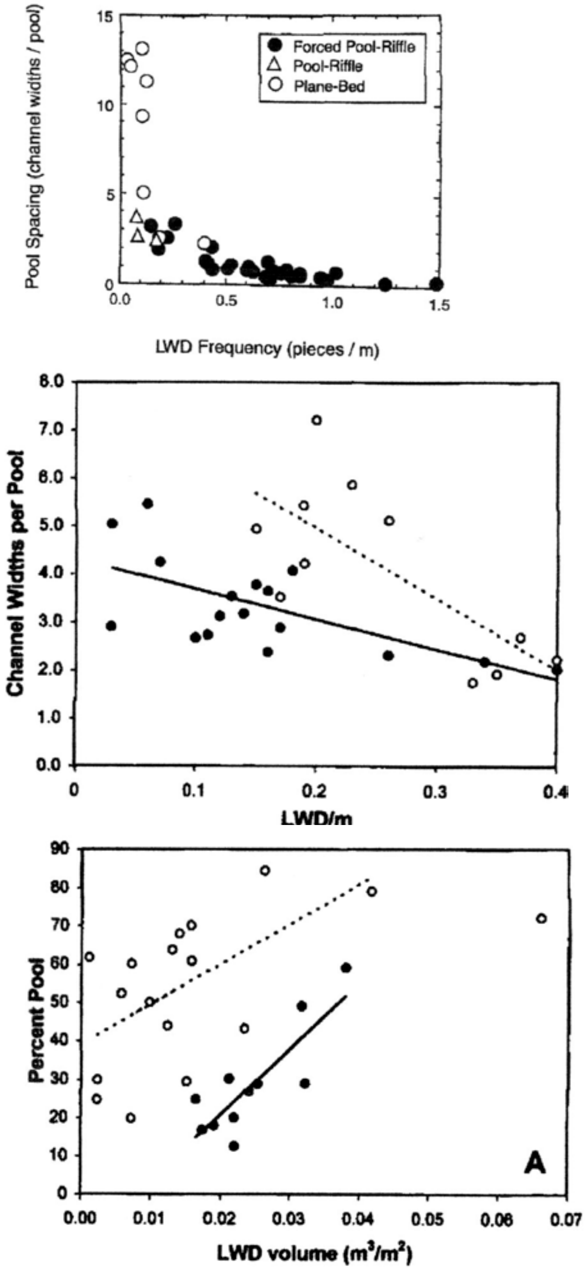

Figure 16. *Pool formation by wood in low and moderate gradient channels. Upper panel from Montgomery et al 1995, lower and middle panels from Beechie and Sibley 1997. Upper panel illustrates strong relationship between wood and pools up to about 0.5 pieces/m, and little influence at wood abundance greater than 0.5 pieces/m (Montgomery et al 1995). Middle panel illustrates difference between pool spacing in low and moderate gradient channels, and lower panel illustrates difference between percent pool in low and moderate gradient channels (Beechie and Sibley 1997). Open circles are moderate gradient channels and filled circles are low gradient channels. Note difference in x-axis scales between upper and middle panels.*

The size of wood that can create a pool is directly related to stream size but the potential to form pools in a channel of a given size increases with piece size (Rosenfeld and Huato 2003). For example, Rosenfeld and Huato (2003) found that on average only 6% of the pieces of wood 6-12” (15-30 cm) in diameter formed pools in smaller streams in British Columbia, but 42% of pieces greater than 24” (61 cm) in diameter formed pools (Figure 17). They also modeled pool abundance as a function of number and sizes of wood pieces and found that the removal (from the stream) of the largest pieces (larger than 24” or 61 cm) caused the greatest decrease in pool abundance compared to removal of smaller pieces (Figure 18). Thus, assessments of the impact of thinning should consider the range of sizes of wood that will be delivered.

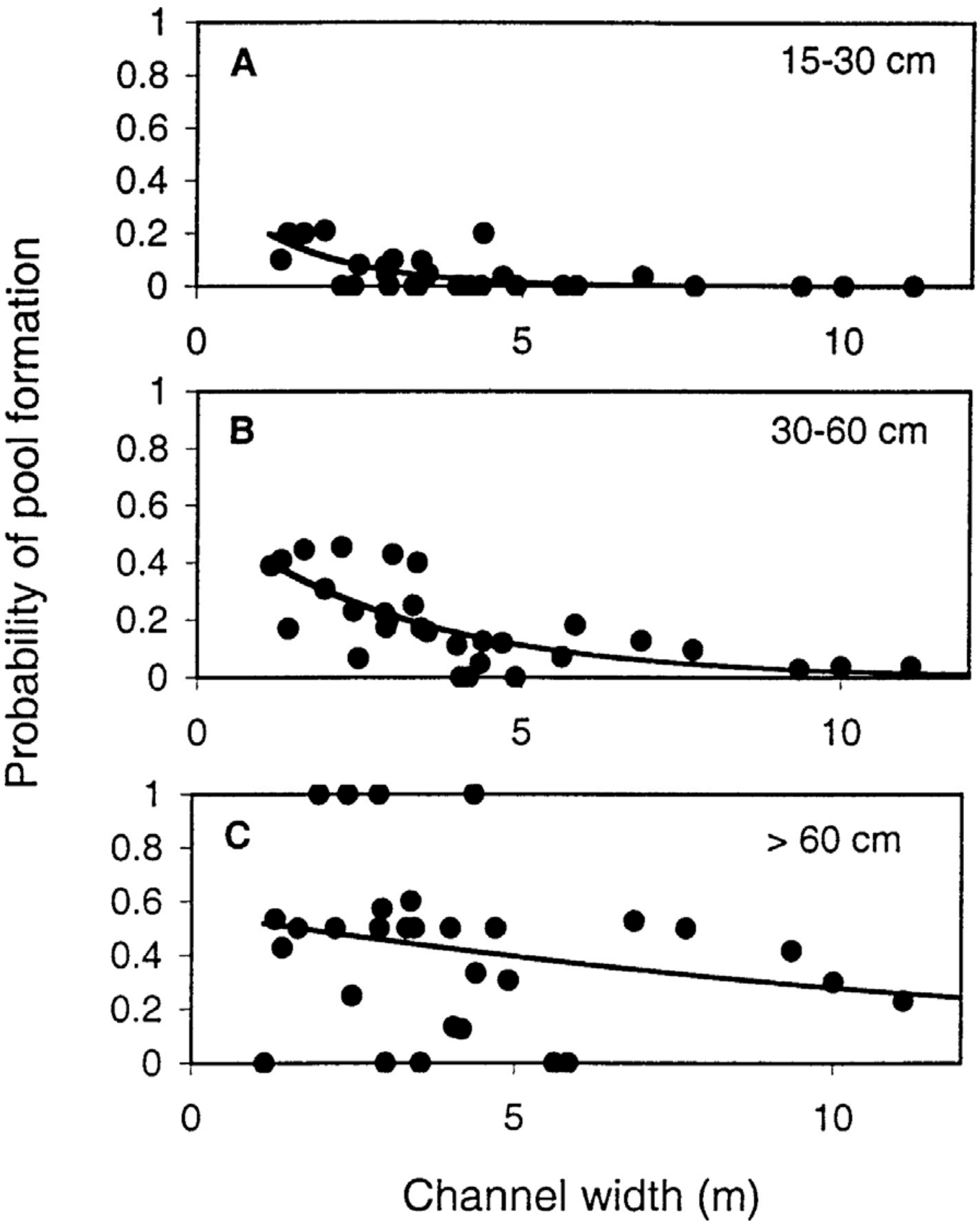

Figure 17. *Probability of pool formation as a negative exponential function of bank-full channel width for LWD of the following diameters: (A) 15 to 30 cm (P 5 0.42 3 2.71(–0.69 · width)), (B) 30 to 60 cm (P 5 0.57 3 2.71(–*

0.33 · width)), and (C) greater than 60 cm (P 5 0.56 3 2.71(–0.07 · width)). Solid lines represent the fitted functions. (From: Rosenfeld and Huato 2003.)

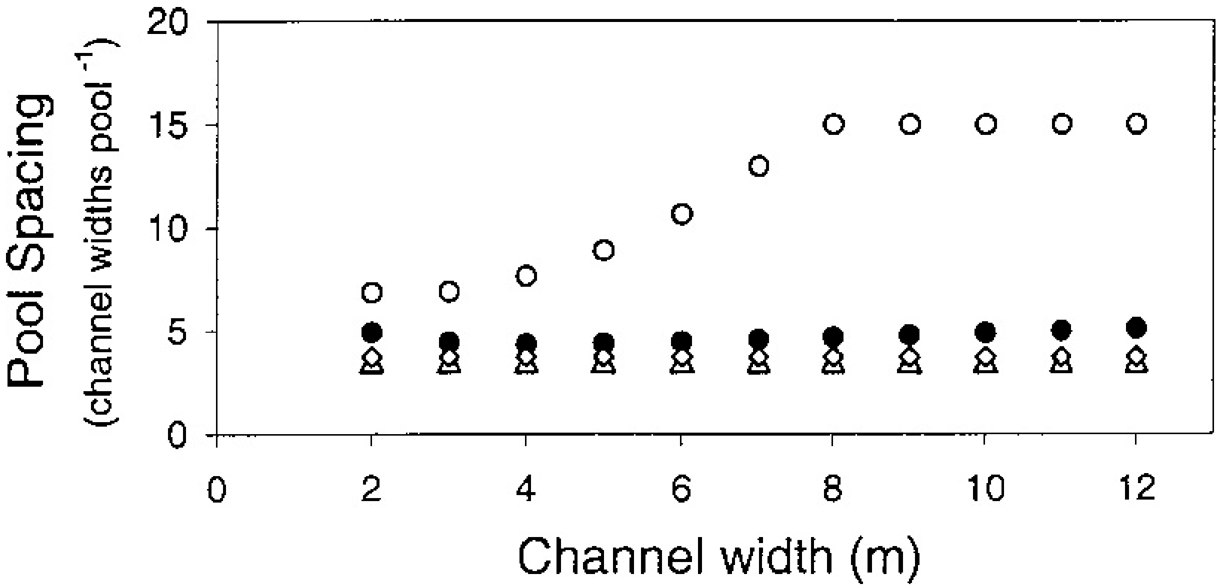

Figure 18. *Modeled pool spacing plotted against channel width, where pool spacing was calculated as a power function of total LWD abundance (pool spacing 5 2.67 3 (LWD/m)20.33) either with all diameter classes included (triangles) or with the largest diameter class removed (diamonds). The solid circles show the pool spacing predicted by the diameter-specific probability model (equation 1 in text) with all diameter classes of LWD included; the open circles show the predicted pool spacing with the largest diameter class (greater than 60 cm) removed. (From: Rosenfeld and Huato 2003.)*

Wood of a size that can independently form pools is not the only ecologically important size of wood in streams. Larger pieces can serve as stable key members that create instream obstructions and form wood jams by racking up numerous smaller pieces of wood that are mobile during high flows. Such wood jams typically consist of a wide range of wood sizes, with the larger sizes creating stability, and the smaller sizes filling the interstices of the jam, helping to store sediment and forcing water over the tops of jams, creating plunge or scour pools (Bilby and Ward 1989, May and Gresswell 2003, May and Gresswell 2004). Sediment stored above wood jams creates areas of stable vegetated surfaces along the channel (Jackson and Sturm 2002). The latter may also be areas of hyporheic flows, which can help to cool streams and may provide other important ecological functions, as has been observed for larger streams (Stanford and Ward 1988, Jackson and Sturm 2002, Johnson 2004). Wood jams containing a range of wood sizes, particularly in small streams, provide for other functions including sediment sorting, energy dissipation, habitat for benthic organisms, nutrient and organic material retention and cycling and the creation of low-gradient alluvial habitat in otherwise steep, bedrock-dominated reaches (Bilby 1981, Bilby and Ward 1989, Montgomery et al. 1996).

Effects Of Tree Species Composition On Instream Wood Quality And Quantity

Hardwood trees, such as red alder and big leaf maple are common components of riparian zones in western Oregon and other parts of the Pacific Northwest (Nierenberg and Hibbs 2000, Hibbs and Bower 2001). In the Pacific Northwest, hardwoods do not achieve the combination of diameter, length, strength, longevity and rootwad size of the conifers (Alden 1995, Alden 1997) but they can, nonetheless, provide wood that can create habitat in streams and riparian areas over the short-term, up to 70 years (Andrus et al. 1988, Beechie et al. 2000). In smaller streams, they may form accumulations by serving as the key piece, and like all pieces of instream wood, are most stable when they have root wads attached rather than being broken or bucked into pieces (Abbe et al. 1996, Braudrick and Grant 2000, Abbe and Montgomery 2003). Their effectiveness in forming pools is directly related to bole size relative to both the size of the stream and position within the stream (Bilby and Ward 1989, Abbe et al. 1996). Hardwoods can also be important components of coarse wood accumulations in larger streams, particularly when coniferous key pieces are present (Hyatt 1998, Collins et al. 2002). However, hardwood longevity is limited because they deteriorate more quickly than conifers, particularly when exposed to air (Harmon et al. 1986, Bilby et al. 1999, Bilby 2003). Thus, they may be important in the short-term for improving instream habitat, but conifers are needed for longer-lasting, long-term improvements.

Watershed-Scale Perspectives

Much knowledge about vegetation manipulation and aquatic and landscape ecology has been developed since the Northwest Forest Plan was enacted in 1994, and alternative approaches for designing management of riparian areas are emerging (Harris 1999, Rot et al. 2000, Reeves et al. 2003, Hughes et al. 2005). The management of a particular location depends on the "context" of that location (Kondolf et al. 2003, Montgomery and Bolton 2003) and many restoration efforts fail because of the reliance on "off-the-shelf" and one-size-fits all concepts and designs rather than on an understanding of specific features and capabilities of the location of interest (Kondolf et al. 2003). Recent scientific advances suggest that effective aquatic conservation practices should be tailored to the specific features and characteristics of the location of interest as illustrated in Table 3 (Beechie et al. 2010).

Table 3. *This table illustrates how the ecological consequences of wood recruitment are expected to vary with physiographic setting and stream type. Thinning with bole removal will likely reduce total wood recruitment to streams, but could reduce the time required to get greater than 40" dead trees by approximately a decade (see Figures 1-3). While simulated thinning effects on dead wood production are the same regardless of setting, the ecological consequences to streams vary depending on stream characteristics. Note that in this example, we are not considering effects on temperature, riparian or terrestrial ecosystems. Nor are we considering potential ecological effects of road systems that are needed to support the management actions.*

Physiographic Setting	Ecological effects for instream wood at the site	Ecological effects for wood recruitment in coho salmon streams
Coho salmon stream with low wood abundance	Pool-forming wood and key pieces for small streams (i.e., <50 feet wide) are typically 17-28 inches (Figure 15), so heavy thinning could delay recruitment of wood large enough to form pools for a century or more if both banks are treated similarly.	Same as for wood recruitment at the site
Small, steep headwater streams that have been scoured to bedrock by debris flows.	Wood sizes required to store sediment and remain stable in small steep streams such as these are typically >36 inches, so decreased time to recruitment of >36 inch wood may hasten	Where delivery of large wood to coho streams by debris flow is possible, the eventual increase in large wood may alter delivery rates of large wood and sediment to downstream coho salmon habitats

	recovery of sediment storage (though the recruitment of very large wood will still likely be 60 to 100 years away even with thinning, depending on the model used to predict recovery time).	for several decades at some point in the future.
Small, steep headwater streams without debris flow potential	Thinning may decrease recruitment of <36 inch wood in small streams could will likely delay accumulation of stored sediments (< 36 inch wood can store sediment in small streams). However, thinning and leaving some boles could accelerate recruitment of wood.	By definition, these streams have a low potential to deliver wood to coho streams so thinning in these headwaters streams will likely have little influence on wood loads in coho streams.

It is now widely recognized that variation in geomorphic setting of the stream or reach supports fish species habitat diversity (Benda et al. 2004, Burnett et al. 2007, Beechie et al. 2010). Variation depends on channel gradient and size, and the ratio of the valley width relative to the size of the active channel. Intrinsic potential (IP) is a measure of the capability of a given stream or stream segment to potentially provide suitable habitat for a given fish species (Burnett et al. 2007).

A watershed-scale perspective on wood recruitment is needed to restore wood loadings in streams in the Oregon Coast Range. Small, headwater streams can be important sources of wood that can be in key components of fish habitat in fish-bearing streams (Reeves et al. 2003, Bigelow et al. 2007). The model NetMap (http://www.netmaptools.org/taxonomy/term/21) is capable of identifying the streams that are the most likely sources of wood. Figure 19 illustrates how management of riparian reserves might vary, depending on the context of the particular location. Factors to consider in determining the specific management scheme could include the intrinsic potential (see Burnett et al. 2007) and potential for thermal loading and erosion at the location. Areas of management option 1, which correspond to the first row of Table 3, are ecologically productive or sensitive areas. Management activities in these areas could be relatively conservative to maintain or enhance the key ecological processes that affect the quantity and quality of aquatic habitat. Areas of management option 2 are portions of the fish-bearing network that are less ecologically productive (e.g. low intrinsic potential for any fish species) or less sensitive (e.g. not likely to warm because of topographic shading or orientation). A greater range of ACS-related management activities could occur here.

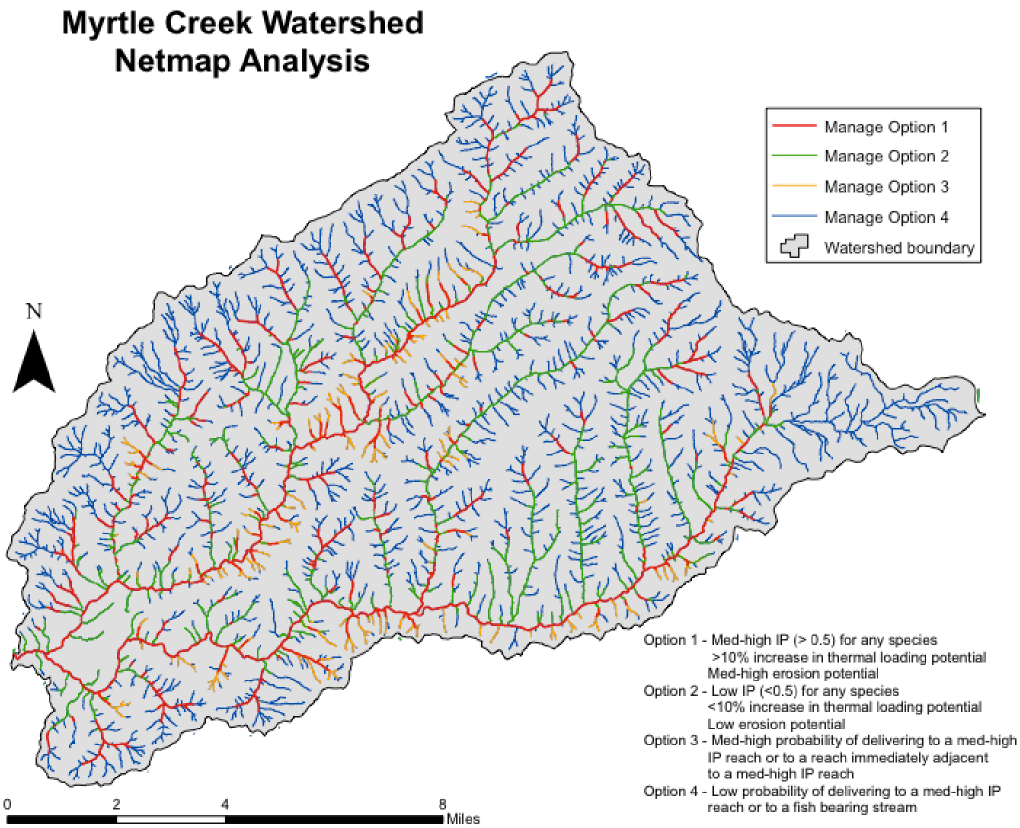

Figure. 19. *An example of potential strata of areas of varying relative ecological sensitivity and productivity in which options for riparian management could be developed. See the text for more detail.*

Streams with management options 3 and 4 in Figure 19 are in the non-fish bearing portions of the stream network. Those in option 3 represent the second row in Table 3 and are potential sources of large wood and sediment for the fish-bearing portion of the network. Riparian management could be directed towards the development of large key pieces of dead wood to help form jams that could store sediment (Montgomery et al. 1996), and smaller pieces of wood in the channel for eventual delivery to fish-bearing streams when debris flows occur (May and Gresswell 2003, May and Gresswell 2004). Streams in option 4 are not as strongly connected to the fish-bearing portion of the network but could be sources of cold-water inputs to larger streams, sites of storage and processing of organic material, or habitat for amphibians and other aquatic organisms.

A decision support framework that recognizes the inherent variation in stream networks and riparian areas, and identifies appropriate management actions for a specific set of circumstances could be developed to guide management. Such an approach is illustrated in Figure 19. This approach would require identification of the selected characteristics of a site, and the application of a given set of management options that are specific to that site. Site features could include intrinsic potential, thermal loading potential, the location of headwater streams that have a strong potential to deliver wood to the location of interest, riparian stand condition and the species for which the stream and riparian areas are being managed. The first three parameters could be determined using NetMap.

Overview of Dead Wood Functions in Terrestrial Environments and the Effects of Thinning

Use Of Large Dead Wood By Terrestrial Species

There is voluminous literature on the role of dead wood in terrestrial ecosystems. Dead wood in the form of snags or down wood is utilized by numerous plants, animals and fungi and its presence is a signature feature of late-successional forests. Different species prefer different sizes, densities and decay classes of snags and down wood. Comprehensive information on the size and density of snags and down wood utilized by different species are available at the USFS DecAID web site (http://www.fs.fed.us/r6/nr/wildlife/decaid/) and other sources. Below we briefly summarize what is known about dead wood use by terrestrial species including fauna, flora and fungi.

The literature available from DecAID, suggests that relations between snag size and use has been documented for a number of species, particularly cavity nesting birds and bats. DecAID uses the density of snags greater than 25 cm and greater than50 cm as important metrics for assessing the suitability of snag habitat for numerous species. Studies relating down wood and species use (e.g. herpetofauna or small mammals) usually measure down wood as a percent of the cover on the forest floor, and relations between species use and a specific size of large wood are less clear. DecAID suggests that wood cover of about 20% will be sufficient for most species, and that the down wood should generally be at least 30 cm to 50 cm in diameter, or larger. The process of tree fall can be important too. As trees fall, they break branches and scar the boles of nearby trees. This creates structural irregularities which can provide important habitat such as nesting and roosting platforms and nesting cavities.

Numerous terrestrial vertebrates are associated with large dead wood, ranging in size from 13 cm to greater than 200 cm diameter, however, the average diameter of dead wood used ranges from 53 cm to 123 cm. Table 4 provides examples of specific sizes of dead wood and live trees associated with vertebrate species found in older forests (cf. Bunnell et al. 1999, Bunnell and Houde 2010). A number of forest vertebrates are also positively associated with the percent cover of all dead wood on the forest floor, often defined as logs greater than 10 cm or greater than 30 cm diameter (Marcot et al. 2010). Large diameter snags or down wood are used in a number of ways that vary by species (Table 4). Such uses include nesting, denning, resting, foraging and roosting. Several small mammals, such as the northern flying squirrel form the prey base for the Endangered Species Act (ESA) listed spotted owl and are among the species associated with abundant large dead standing and down wood. This presumably, is why spotted owls prefer to forage in stands with abundant standing and fallen dead wood (Table 2, North et al. 1999). The fruiting bodies of hypogeous fungi are a food source of northern flying squirrels and are also associated with down logs, suggesting that there are complex, indirect paths through which dead wood supports spotted owls (Amaranthus et al. 1994, Carey 2000).

Table 4. *Examples of species of Pacific coastal forests use of large diameter dead wood and live trees in aquatic and terrestrial habitats, with an emphasis on ESA-listed species (salmonids, the northern spotted owl (and its prey base) and the marbled murrelet). Size range numbers refer to bole diameter breast height (dbh), unless otherwise noted (cf. Bunnell et al. 1999, Bunnell and Houde 2010).*

Species	Wood Type	Function	Size Range	Avg diam (cm)	Avg L or Ht (m)	References
Onchorynchus, *Salmo*, and *Salvelinus* (salmonids) and other aquatic species	Instream CWD	Forms pools independently, in the absence of other wood or obstructions	0.15-0.75 m diameter for streams with bankfull widths between 4-23 m according to the equation: Diameter = 0.028*BFW + 0.0057	-	-	Beechie and Sibley 1997
salmonids and other aquatic species	Instream CWD	Independently stable during large floods. "Key" piece forms jams	Varies with stream size: wood piece volumes from 1.0-10.8 m3 for streams 1-100 m wide.	-	-	Fox and Bolton 2007
salmonids and other aquatic species	Instream CWD	Independently stable during large floods. "Key" piece forms jams	Varies with stream size: wood diameters from 40-70 cm and lengths from 8-24 m for streams 1-20 m wide.	-	-	WFPB 1995
salmonids and other aquatic species	Instream CWD	Stablize valley spanning jams in high gradient channels	60-200 cm diameter	-	-	Montgomery et al. 1996
salmonids and other aquatic species	Instream CWD	accumulates on larger “key” pieces to form debris jams	> 10 cm dbh, 2 m length	-	-	Bilby 1980, Bilby and Ward 1989,
Strix occidentalis (northern spotted owl)	CWD	Preferred foraging areas	foraging positively related to all CWD volumes, and big log (dbh >50 cm and L > 8m) volumes and densities	-	-	North 1999
G. sabrinus (northern flying squirrel), *Neotamias townsendii* (Townsend's chipmunk)	CWD	Preferred habitat for NSO prey species	12% cover of large wood	-	-	Carey 1995
Myotis lucifugus (little brown myotis)	CWD	Roosting	-	55	8	Bunnell and Houde 2010
Martes pennanti (fisher)	CWD	Resting	50-200	95		Zielinski et al. 2004
Martes americana (marten)	CWD	Denning	-	53	-	Ruggerio 1998

M. americana	CWD	Resting	-	66	17	Bull and Heater 2000
Ursus americanus (black bear)	CWD	Denning	-	108	17	Bull et al. 2000
U. americanus	CWD	Denning	-	123		Davis 1992
Ensatina eschscholtzii	CWD	General habitat	0-800 m3/ha, density=0.11*(CWD Volume)^0.66	-	-	Butts and McComb 2000
Ensatina eschscholtzii	CWD	General habitat	91% of observations related to CWD	-	-	Bury and Corn 1988
Aneides ferreus (clouded salamander)	CWD	General habitat	84% of observations related to CWD	-	-	Bury and Corn 1988
Batrachoseps wrightorum (slender salmander)	CWD	General habitat	64% of observations related to CWD	-	-	Bury and Corn 1988
S. occidentalis	Snags	Preferred foraging areas	vol > 142 m3/ha, 70% of snag volume was from snags > 50 cm dbh. 15 large snags >50 cm/ha in medium and high use areas	86	-	North 1999
G. sabrinus (northern flying squirrel), *Neotamias townsendii* (Townsend's chipmunk)	Snags	Preferred habitat for NSO prey species	23 large (>50 cm) snag/ha	-	-	Carey 1995
Myotis californicus (California myotis)	Snags	Roosting	-	56	27	Brigham et al. 1997
Myotis volans (Long-legged myotis)	Snags	Roosting	95% CI = 83-110	97	38	Ormsbee and McComb 1998
Myotis thysanodes (Fringed myotis)	Snags	Roosting	58.5-167	121	41	Weller and Zabel 2001
M. americana	Snags	Denning	-	55	-	Ruggerio 1999
M. pennanti	Snags	Resting	66-200	119		Zielinski et al. 2004
Colaptes auratus (common flicker)	Snags	Cavity nesting	36-112 cm	61	11	Mannan et al. 1980
Dryocopus pileatus (pileated woodpecker)	Snags	Cavity nesting	46-172 cm	78	15	Mannan et al. 1980
Picoides villosus (hairy woodpecker)	Snags	Cavity nesting	48-172 cm	92	18	Mannan et al. 1980
Sphyrapicus varius (sapsucker)	Snags	Cavity nesting	56-216 cm	101	17	Mannan et al. 1980

Sitta canadensis (nuthatch)	Snags	Cavity nesting	74-185 cm	118	28	Mannan et al. 1980
Oecile rufescens (chickadee)	Snags	Cavity nesting	53-160 cm	103	18	Mannan et al. 1980
C. auratus	Snags	Foraging	19-167 cm	95	23	Mannan et al. 1980
D. pileatus	Snags	Foraging	20-185 cm	103	30	Mannan et al. 1980
P. villosus	Snags	Foraging	13-173 cm	62	20	Mannan et al. 1980
S. occidentalis	Live trees	Platform nesting	36-179 cm dbh	106	42	Forsman 1984
S. occidentalis	Live trees	Cavity nesting	74-205 cm dbh	135	38	Forsman 1984
S. occidentalis	Live trees	Roosting	Range of means: 15-115 cm, varies with location and weather	83	-	Forsman 1984
S. occidentalis	Live trees	Dispersal habitat	> 40% canopy cover of trees > 28 cm dbh	-	-	USFS 2010
Brachyramphus marmoratus (marbled murrelet)	Live trees	Platform nesting	large trees > 82 cm dbh comprising > 10% of the canopy cover	-	-	Meyer and Miller 2002
B. marmoratus	Live trees	Platform nesting	dominated by conifers > 50 cm dbh	-	-	Ripple et al. 2003
B. marmoratus	Live trees	Platform nesting	mean dbh of trees > 77 cm (OR) or > 91cm (CA)	-	-	Meyer et al. 2002
B. marmoratus	Live trees	Platform nesting	> 70% crown closure from trees > 53 cm dbh (WA)	-	-	Raphael 2002a
B. marmoratus	Live trees	Platform nesting	key predictors of nest sites: total # trees > 90 cm	-	-	Perez-Comas and Skalski 1996
B. marmoratus	Live trees	Platform nesting	high density of trees > 80 cm within 50 m of nest	-	-	Rodway and Regehr 2002
B. marmoratus	Live trees	Platform nesting	-	110	32	Hamer and Meekins 1999
B. marmoratus	Live trees	Platform nesting	49-533 cm dbh, range of means, varies with location	116-278	51-73	Hamer and Nelson 1995
M. americana	Live trees	Resting	-	61	25	Bull and Heater 2000
M. pennanti	Live Trees	Resting	35-205	125		Zielinski et al. 2004
U. americanus	Live Trees	Denning	-	112	24	Bull et al. 2000
U. americanus	Live Trees	Denning	-	159		Davis 1992

Though species association with specific sizes of large dead wood are known (Table 4), mechanistically speaking, the reasons why a particular species is associated with a particular size class of dead wood are not always well understood (cf. Bunnell et al. 1999). Potential functions provided by large dead terrestrial wood that would not occur in smaller dead wood includes temperature (hot and cold) and humidity refugia (Ruggiero et al. 1998, Kluber et al. 2009), large internal cavity volumes for nests and dens (Bull et al. 2000, Zielinski et al. 2004), cavities between the bark and bole (Bunnell et al. 2002), and sustained structural integrity, particularly during advanced stages of decay (Mannan et al. 1980). For some species, the size of the dead wood may not matter so much as the mechanism by which the tree died and what happened to the tree while it was alive. As an example, the slow death of a tree by heart rot creates a large cavity that is useful as a denning site for several species (e.g. black bear, fisher and marten *M. americana*), suggesting that variation in the mechanisms of tree death is another consideration for the maintenance of biodiversity (Bunnell and Houde 2010).

Dead wood also affects plant composition, successional dynamics, and forest structure. The light gap formed when the tree falls allow understory vegetation to grow, including shade-tolerant trees, which helps to form a multi-tiered canopy. As the fallen bole decays it creates an elevated organic substrate (i.e. a “nurse” log), which is an important establishment site for conifer species such as Sitka spruce and western hemlock (Harmon and Franklin 1989). This function is especially important for maintaining a conifer component in moist, hardwood and shrub dominated riparian forests. Thus, large diameter wood recruitment into stream-adjacent alder forests may be essential to ensure that these forests can re-establish a conifer component over the long-term, which in turn can become an important source of large diameter coniferous wood to streams.

Many nonvertebrate species in forest ecosystems are associated with dead wood. Though size preferences are not well understood for most of them, many are associated with dead wood across a wide range of sizes, including wood less than 30 cm diameter. Species groups that utilize dead wood include fungi, lichen, bryophytes, mosses, invertebrates and vascular plants (reviewed in Bunnell and Houde 2010). Within these groups are hundreds of species that are dead wood obligates or are predominantly found on dead wood. The loss of dead wood in managed forests has been associated with a decline in biological diversity for many of these species groups (Jonsson et al. 2005, Davies et al. 2008, Bunnell and Houde 2010). In terms of considering management options for the purpose of maintaining and restoring biological diversity, it would be helpful to better understand how such species are affected by the size, abundance and quality of dead wood, and in particular, which species prefer large diameter dead wood.

Dead wood can affect soil moisture and is important for fungi. Down wood has a high pore volume and thus can serve as moisture reservoirs and provide persistent microsites that aid in forest recovery after prolonged drought or fire (Amaranthus et al. 1989). For example, in one study in southwest Oregon, down logs provided considerable rooting and mycorrhizal activity, and mean moisture content (157%) was 25 times greater than mean soil moisture (6%) (Amaranthus et al. 1989). In forests of western North America, decomposing wood occurs in the organic humus horizon of soils and, indeed, throughout the entire soil horizon (Harvey et al. 1976a, Harvey et al. 1976b). Down wood is also a major source of mychorrizal fungi (Amaranthus et al. 1996). In dry environments, decaying wood retains moisture and serves as important reservoirs of such fungal activity during dry summer months (Harvey et al. 1976a, Harvey et al. 1976b).

Thinning And Development Of Structurally Complex Forests With Large Dead Wood

Biodiversity declines in conifer forests have led to experimental and management efforts to accelerate the development of old forest structure, especially large live and dead wood in young, simplified stands that are a legacy of past commercial harvest activities (Davis et al. 2006, Puettmann et al. 2009, Bauhus et al. 2010). The approaches (e.g. active vs. passive management) for restoring dead wood and the structural complexity for terrestrial and aquatic biodiversity are a subject of ongoing discussion and active research (Beechie et al. 2000, Puettmann et al. 2009, Bauhus et al. 2010, Bunnell and Houde 2010, Marcot et al. 2010). Several researchers have proposed that restoration in young stands be done with variable density thinning (Carey 2006) and ecological forestry (Franklin et al. 2007). Variable density thinning is being applied in many plantations in national forests in Oregon (Stuart Johnston personal communication). The rationale for such thinning is that it will accelerate the development of large live trees and create structural and compositional heterogenity that fosters increased biodiversity in homogeneous young stands (Muir et al. 2002, Garman et al. 2003, Davis et al. 2006). Thinning young forests with variable density thinning creates canopy gaps, another structural attribute of older forests that is often missing in dense young stands (Spies 1989). If active management can accelerate the development of old forest structure, then the restoration of biologically diverse aquatic and terrestrial communities could also be accelerated (Puettmann et al. 2009, Bauhus et al. 2010).

It is well established in the literature that thinning young Douglas-fir stands can increase the diameter growth rates of the remaining live trees (Tappeiner et al. 2007). In one of the longest experiments in the region, a 35 year study of thinning effects, the average growth of surviving trees in thinned plots was 165% greater than in unthinned plots (Marshall and Curtis 2002). However, the increases in diameter growth from thinning may not apply equally to all individuals, especially for the largest trees in the stand which may be under less competition from neighbors. (e.g. Davis et al. 2006). Although we may have a relatively good understanding of the effects of thinning on the growth of surviving trees in young stands, that is not the case for the effects of thinning on dead wood dynamics. Currently, there are few long-term (e.g. greater than 50 years) data sets with which to assess the long-term impacts of thinning on snag and down wood dynamics (Bunnell and Houde 2010, Marcot et al. 2010). Forest growth models can be used to assess the long-term effects of thinning on deadwood production in terrestrial ecosystems but only one study by Garman et al. (2003) has examined effects of thinning on dead wood (see page 3). The simulations and state of knowledge that we presented earlier in the report for riparian forests (see pages 3-4) are also relevant to understanding the effects of thinning on dead wood in terrestrial forests and we do not repeat them here.

Additional Considerations

As stated in the introduction, the amount and recruitment of dead wood in forests and streams is difficult to predict and function of many factors. We have attempted to answer the wood recruitment question that was posed to us and discuss some of these factors that affect this answer. However, there are other important aspects restoring habitat for salmonids that we do not address including:

- Recognizing how the inherent dynamics of forests and streams affect habitat quality and ecosystem functions over time
- Characterizing how management effects vary with spatial and temporal scale—we have focused primarily on stand/site-level effects in this summary
- Putting wood recruitment into a broader ecological context, e.g. its role in stream habitat relative to other factors (e.g. boulders).

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