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Forest Ecology and Management 91 (1997) 205–219

Forest Ecology and Management

# Simulated stand characteristics and wood product yields from Douglas-fir plantations managed for ecosystem objectives

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Accepted 28 June 1996

**Abstract**

Hundreds of thousands of hectares of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) plantations in coastal forests in the U.S. Pacific Northwest were established over the past 40 years. Density management regimes designed to increase structural and compositional diversity in these plantations are being tested and implemented on an operational scale. These regimes are designed to promote various tree and stand characteristics, such as trees with large limbs, stands with multi-layered canopies, and dense unthinned patches. Changes in management policy associated with these types of regimes raise questions about the potential to manage for both ecosystem values and timber production. We used state-of-the-art models to simulate stand growth and wood product yields under several silvicultural prescriptions. The results indicated that timing and intensity of early thinnings are critical in determining both stand structure and wood quality. We concluded that it should be possible to manage Douglas-fir plantations to provide a high degree of structural diversity and wood products with quality similar to that grown in many industrial plantations.

*Keywords:* Ecosystem management; Wildlife; Habitat; Silviculture; Wood properties; Wood products; Timber production

## 1. Introduction

Over the past 40 years, hundreds of thousands of hectares of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) plantations have been established in western Washington and Oregon on lands within the range of the northern spotted owl (*Strix occidentalis caurina*). The plantations were designed primarily to provide high yields of wood products, but recent shifts in public opinion and government policy have focused greater attention on protecting, restoring, or enhancing ecosystems and the ecological and economic values they provide. Toward this end, federal lands have been segregated into seven use categories, each with its own set of management objectives ranging from strict reserves to areas designated for timber production (USDA FS and USDI BLM, 1994).

An important goal of ecosystem management on federal lands is to maintain ecological integrity of forest ecosystems and resilience of social and economic systems that depend on the forest (Haynes et al., 1996). In short, this involves attempting to sustain ecological processes while providing for human

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0378-1127/97/$17.00 Published by Elsevier Science B.V.
*PII* S0378-1127(96)03873-X

needs (Hansen et al., 1995). Haynes et al. (1996) describe a set of five specific goals for ecosystem management. They include: maintaining viable populations of native species; supporting evolutionary processes and adaptation to changing biotic and abiotic conditions within robust ecological communities; accounting for the multiple spatial and temporal contexts within which ecosystems function; recognizing the human sense of "place" or the spiritual value of the forest; and managing to enhance the social and economic resiliency of human communities associated with forests.

The future management policy for young Douglas-fir plantations on federal lands will attempt to meet these goals. Specific objectives will depend on where stands happen to be located on the landscape or, for non-federal lands, the degree to which managers embrace ecosystem management or production forestry principles. In many cases, managers will attempt to use thinning or other silvicultural treatments to convert relatively large homogeneous tracts into a variety of wildlife habitat types that are distributed across the landscape over time.

In the Pacific Northwest, some species of wildlife are closely associated with late seral stage forests or are most abundant in late seral stages (Ruggiero et al., 1991). Because late seral stages are under-represented in the region (Forest Ecosystem Management Assessment Team, 1993; section IV), 30% of the federal land within the range of the northern spotted owl, about 3 million hectares, has been designated as late successional reserves (LSRs). These are intended to provide functional late-successional (old-growth-like) ecosystems. Forest management in LSR areas is limited to activities that accelerate the development of young stands and protect and enhance the functions of old-growth stands (USDA FS and USDI BLM, 1994).

Although it is unlikely that forest ecosystems will ever be understood well enough to duplicate the habitat needs of all species found in old-growth forests, substantial information now exists for plants, vertebrates, and some fungi. This knowledge can be translated into silvicultural prescriptions to develop late-seral habitats favorable to such species (Nyberg et al., 1987; Curtis and Marshall, 1993; McComb et al., 1993). For example, McComb et al. (1993) model a regime for a coastal Douglas-fir plantation that mimics many features of old-growth structure by age 115. Several studies are under way in Oregon and Washington to explore habitat development in young, managed Douglas-fir stands and test the efficacy of various density management regimes in creating desired ecosystem attributes (Cascade Center for Ecosystem Management, 1993).

But what of the objective of providing wood products? Is there a potential to simultaneously manage for ecosystem values and timber production? Does one objective necessarily preclude the other? Ecosystem management regimes may incorporate early heavy thinnings followed by underplanting to quickly produce old-growth-like structures, such as multi-storied canopies with scattered large trees. How will these regimes influence the quality of wood removed during the lifetime of the stand? Hansen et al. (1995) have recently examined the question of the economics of various ecosystem management regimes. They used wood value as a basis for economic evaluations but did not consider how changes in tree morphology that may arise under these regimes could affect wood quality.

Models developed during the past ten years (e.g. Kellogg, 1989; Sachet et al., 1989; Barrett and Kellogg, 1991; Fahey et al., 1991; Kretschmann et al., 1993; McKinley et al., 1994; Kimberley et al., 1995) that relate wood product yields from Douglas-fir trees and logs to a range of morphological characteristics, such as diameter, juvenile wood content, branch size, and stem form, might be useful for exploring this question. We used a wood product yield model, TREEVAL (Briggs, 1989; Sachet et al., 1989) and a growth and yield model, ORGANON (Hann et al., 1994) to evaluate how a range of silvicultural strategies influence lumber grade yields and stand structure in young, even-aged Douglas-fir plantations.

## 2. Methods

### 2.1. Stand management regimes

We considered seven silvicultural regimes designed to produce a range of habitat types and tree characteristics (Table 1). Management scenarios ranged from thinning to extremely low densities at a young age to more traditional regimes that maintain

Table 1
Objectives and physical descriptions of regimes

| Breast height age at thinning | Density after thinning (TPH) | Thinning strategy | Silvicultural objective | Regime identifier |
|---|---|---|---|---|
| 15 | 75 | Below | 1 | 15–75 |
| 15 | 150 | Below | 2 | 15–150 |
| 30 | 75 | Below | 1 | 30–75 |
| 30 | 150 | Below | 2 | 30–150 |
| 30 | 150 | Highl/low | 3 | 30–150HL |
| 30 | 250 | Below | 4 | 30–250 |
| no thin | 750 | None | 5 | no thin |

Silvicultural objectives:
1. Provide late seral characteristics with primary emphasis on diameter growth and secondary emphasis on canopy closure.
2. Provide mid to late seral characteristics with primary emphasis on canopy closure and secondary emphasis on diameter growth.
3. Provide diverse crown structure.
4. Maintain early to mid seral conditions with primary emphasis on fiber production and secondary emphasis on wildlife habitat.
5. Provide minimum disturbance of natural stand development.

near maximum timber volume output. The analysis treated thinning at age 15 as precommercial and thinning at age 30 as a commercial. Given rapidly changing utilization standards in the Pacific Northwest, this assumption may or may not be valid and depends on terrain, location of the stand, and market conditions.

Regimes are named following the convention of $x$–$y$ where $x$ is the age of the thinning treatment and $y$ is the density in trees per hectare (TPH) of the residual stand just after thinning. Given this convention, the regime designated 15–75 involves a thinning at stand age 15 to a residual stand density of 75 trees per hectare.

The 75 and 150 TPH regimes are intended to promote late seral characteristics. By opening the overstory canopy, these regimes allow the development of understory conifers and hardwoods and encourage development of large overstory trees with deep crowns. Although wood quality analyses were performed to cover the spectrum of responses, extremely heavy thinnings, such as the 75 TPH regimes, may be most useful in areas where further overstory manipulation is not desired. Development of the understory was not considered in this analysis since ORGANON does not project growth of grasses, shrubs and forbs.

The 150 TPH regimes may provide greater flexibility to create snags and downed coarse woody material or to remove trees for commercial use later in stand development than 75 TPH regimes. The 150 TPH regime leaving the 75 largest and 75 smallest trees (30–150HL) is designed to create diversity in crown structure and wood properties by leaving a range of trees that will develop at different rates. This regime was an attempt to stimulate development of deep overstory crown structure and a variety of stem sizes.

The 250 TPH regime was designed to maintain early to mid seral conditions with primary emphasis on fiber production and secondary emphasis on wildlife habitat. The 750 TPH (no thin) regime was intended to provide undisturbed, dense stand development and high timber volume production.

We used the Willamette Valley version of ORGANON (Hann et al., 1994) to project stand growth and wood quality attributes. The stand data for the model were taken from both plantations and managed second growth stands. ORGANON is an individual-tree, distance-independent growth model that enables simulation of various density and tree size distributions but does not allow for variation in tree spacing or small openings. The wood quality version of the model predicts juvenile wood core diameter and limb size for each tree (Maguire et al., 1991).

All the management scenarios were simulated by using a single stand initiation condition. The sample stand data used in the simulation were from a stand management cooperative plot (Snellgrove and Chappell, 1988) in western Washington of a medium King's site index of 125 (King, 1966). The initial density was 750 trees per hectare (TPH) at breast height, age 10 years and a total stand age of 15 years. Crown ratios were about 90%. No provision was made for self pruning in the simulated stands because published data suggests that self pruning will not occur before about age 80 (Paul, 1947) and may be delayed as long as 140 years in more widely spaced natural stands (Finnis, 1954).

### 2.2. Analysis

Simulated thinnings were done from below (removing trees with the smallest diameters), except for

Table 2
Average stand characteristics for all regimes

| Regime | Age 15 or 30 | | Age 40 | | Age 60 | | Age 80 | | Age 100 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | *Diameter mean and range* (cm) | | | | | | | | | |
| 15–75 | 16.3 | (15–20) | 54.6 | (51–61) | 81.5 | (76–86) | 97.8 | (91–107) | 109.0 | (97–117) |
| 30–75 | 34.5 | (30–41) | 45.7 | (41–51) | 70.9 | (66–76) | 89.2 | (981–97) | 101.6 | (91–112) |
| 15–150 | 15.5 | (10–20) | 51.8 | (46–51) | 66.5 | (61–86) | 81.0 | (66–97) | 91.7 | (71–112) |
| 30–150 | 33.3 | (30–41) | 43.7 | (41–51) | 63.2 | (56–71) | 75.4 | (61–86) | 83.8 | (66–102) |
| 30–150HL | 28.4 | (15–41) | 37.1 | (20–51) | 57.4 | (36–76) | 71.4 | (41–86) | 81.0 | (51–107) |
| Low | * | * | 26.2 | (20–30) | 41.4 | (36–46) | 51.1 | (41–51) | 57.9 | (56–66) |
| High | * | * | 45.7 | (36–46) | 68.6 | (61–76) | 84.3 | (71–86) | 96.0 | (86–107) |
| 30–250 | 32.3 | (25–41) | 41.4 | (36–51) | 55.9 | (46–66) | 64.8 | (46–81) | 71.6 | (51–97) |
| No thin | * | * | 33.8 | (20–46) | 55.9 | (20–66) | 50.5 | (20–76) | 58.7 | (25–86) |
| | *Trees per hectare* | | | | | | | | | |
| 15–75 | 74 | | 72 | | 72 | | 69 | | 67 | |
| 30–75 | 72 | | 69 | | 69 | | 69 | | 69 | |
| 15–150 | 148 | | 141 | | 133 | | 126 | | 121 | |
| 30–150 | 141 | | 138 | | 136 | | 133 | | 131 | |
| 30–150HL | 133 | | 126 | | 121 | | 119 | | 116 | |
| Low | * | | 57 | | 52 | | 49 | | 47 | |
| High | * | | 69 | | 69 | | 69 | | 69 | |
| 30–250 | * | | 230 | | 220 | | 210 | | 198 | |
| No thin | * | | 615 | | 383 | | 378 | | 296 | |
| | *Height* (m) | | | | | | | | | |
| 15–75 | 9.4 | | 30.5 | | 41.1 | | 49.1 | | 55.2 | |
| 30–75 | 22.9 | | 30.2 | | 41.1 | | 49.1 | | 54.9 | |
| 15–150 | 9.4 | | 29.9 | | 40.8 | | 48.5 | | 54.6 | |
| 30–150 | 22.3 | | 29.3 | | 40.2 | | 48.2 | | 53.9 | |
| 30–150HL | 21.0 | | 28.0 | | 39.0 | | 46.9 | | 53.0 | |
| Low | * | | 25.6 | | 36.6 | | 44.2 | | 50.0 | |
| High | * | | 30.2 | | 41.1 | | 48.8 | | 54.9 | |
| 30–250 | 22.3 | | 29.6 | | 39.9 | | 47.5 | | 53.3 | |
| No thin | * | | 27.7 | | 38.1 | | 45.1 | | 50.9 | |
| | *Crown ratio* (%) | | | | | | | | | |
| 15–75 | * | | 98 | | 81 | | 67 | | 60 | |
| 30–75 | * | | 78 | | 72 | | 65 | | 57 | |
| 15–150 | * | | 88 | | 64 | | 52 | | 47 | |
| 30–150 | * | | 76 | | 57 | | 46 | | 40 | |
| 30–150HL | * | | 67 | | 60 | | 49 | | 43 | |
| Low | * | | 54 | | 49 | | 38 | | 32 | |
| High | * | | 78 | | 68 | | 56 | | 50 | |
| 30–250 | * | | 62 | | 44 | | 36 | | 31 | |
| No thin | * | | 40 | | 35 | | 26 | | 25 | |
| | *Percentage juvenile wood* | | | | | | | | | |
| 15–75 | * | | 62 | | 34 | | 26 | | 20 | |
| 30–75 | * | | 75 | | 37 | | 25 | | 19 | |
| 15–150 | * | | 72 | | 45 | | 33 | | 28 | |
| 30–150 | * | | 76 | | 43 | | 32 | | 25 | |
| 30–150HL | * | | 77 | | 41 | | 28 | | 22 | |
| Low | * | | 81 | | 43 | | 30 | | 23 | |
| High | * | | 74 | | 39 | | 27 | | 21 | |

Table 2 (continued)

| Regime | Age 15 or 30 | Age 40 | Age 60 | Age 80 | Age 100 |
|---|---|---|---|---|---|
| 30–250 | * | 76 | 51 | 38 | 31 |
| No thin | * | 80 | 56 | 45 | 36 |
| | *Largest branch* (cm) | | | | |
| 15–75 | * | 5.3 | 7.6 | 9.4 | 11.1 |
| 30–75 | * | 6.9 | 6.9 | 8.9 | 10.6 |
| 15–150 | * | 5.3 | 7.1 | 8.6 | 9.9 |
| 30–150 | * | 4.6 | 6.6 | 7.9 | 9.4 |
| 30–150HL | * | 3.6 | 5.8 | 7.4 | 8.6 |
| Low | * | 3.0 | 4.6 | 5.6 | 6.6 |
| High | * | 4.3 | 6.9 | 8.6 | 10.1 |
| 30–250 | * | 4.6 | 5.8 | 7.1 | 8.1 |
| No thin | * | 3.6 | 5.1 | 5.3 | 6.6 |

the 30–150HL regime where the 75 largest trees and 75 smallest trees were retained after thinning. Regimes were projected to ages 40, 60, 80, and 100 years. ORGANON estimated the branch index (LLAD; Fahey et al., 1991) and percentage of juvenile wood for the average tree in each 5 cm diameter class. Juvenile wood was estimated as the volume encompassed in the first 20 rings from the pith. TREEVAL simulated the bucking of trees to a nominal log length of 4.9 m and a minimum small-end diameter of 13 cm. Volumetric lumber grade recoveries were estimated for each log by using the TREEVAL model (Briggs, 1989; Sachet et al., 1989). Individual log data were summed to obtain tree data, which were in turn summed to provide stand totals. Volumes reported are lumber yields and not standing volumes. Chip and sawdust volumes are not reported.

The raw data for lumber grades are multi-dimensional (incorporating age, regime, and grading system), which makes them difficult to interpret either directly or graphically. To simplify analysis, we converted volume recovered in each grade to a percentage of the total volume for that regime. The original volumes can be recreated by dividing the percentage of lumber volume by 100 and multiplying the resulting fraction by the total lumber volume for the regime at the desired age.

Percentage of yields for visually graded lumber are reported by grade but because of the complexity of the grading system and the methods used to make projections, this was not possible for machine stress rated (MSR) lumber. Instead, results are grouped by "quality classes," which roughly approximate several North American MSR grades. The quality classes for MSR lumber are not grades because, even though they are based on estimates of edge knot size and stiffness, they do not include estimates of other physical properties incorporated into true MSR grades (Western Wood Products Association, 1991; West Coast Lumber Inspection Bureau, 1995). Even if all properties were known, the presence or absence of wane or other visual characteristics is important in determining the type of product for which a given piece of lumber is suitable (e.g. MSR laminating stock). The predicted quality classes are, however, a good indication of the differences in potential properties of lumber manufactured from trees with different morphological features. They are also a good indication of the inherent properties of the wood, because stiffness measurements, used in deriving the quality classes, are related to density, microfibril angle, and other basic wood properties (Mark, 1967).

## 3. Results

### *3.1. Stand characteristics of 75-tree regimes*

The characteristics of stands simulated under the 15–75 and 30–75 regimes are quite different at age 40 but are essentially identical by age 80 except for diameter (Table 2). At 80 years, the average diameter and maximum diameter of the trees grown under the 30–75 regime are about 10% smaller than those in the 15–75 regime. By 100 years, those differences decreased to 7% and 4.5%, respectively, and would presumably converge over time. The 15–75 regime may, however, support greater woody understory plant diversity and have a more complex canopy system, but these features are not predicted by ORGANON.

### 3.2. Stand characteristics of 150-tree regimes

As with the 75-tree regimes, the age at thinning made little difference in the ORGANON calculation of average stand characteristics at stand ages of 80 and 100 years, although the 15–150 regime maintained a slightly higher crown ratio than and the 30–150 regime (Table 2). Average values for the 30–150HL regime differed only slightly from those for the 15–150 and 30–150 regimes. The bimodal diameter distribution imposed in the 30–150HL regime by the treatment was, however, maintained throughout the analysis period (Table 2). Thus, we report separate results for the high segment, or large trees, and the low segment, or small trees. When stand characteristics for the 30–150HL regime are split into the high and low segments, differences between this regime and the two other 150–tree regimes are evident. Distinctions between the sets of characteristics were retained throughout the simulation period. The low segment had crown ratios comparable to the 30–250 regime with branches about the same size as those in the no-thin treatment. Stand characteristics for the high segment were consistently intermediate between the 75- and 150-tree regimes.

### 3.3. Stand characteristics of 250 and no-thin (750-tree) regimes

The 250-TPH and no-thin regimes produced much smaller trees with shorter crowns and smaller branches than did the 75-TPH and 150-TPH regimes. As with other regimes, tree size at 100 years was influenced more by stand density than by thinning age.

### 3.4. Stand characteristics of cross-density comparisons

Average diameters for the 75-tree regimes were 34–42% larger than those in the 30–250 regime at stand age 100. Average diameters of trees in the 75-tree regimes were 73–86% larger than those in the no thin regime at stand age 100. By comparison, the 75-tree regimes produced trees about 18–20% larger in diameter than the corresponding 150-tree regimes at 100 years. At the same stand age, the 15-year thinnings produced trees about 7–9% larger in diameter than the corresponding 30-year thinnings. So residual stand density, not treatment age, seemed to be more important in determining tree size at 100 years.

Other differences included crown ratio and mortality rates (Table 2). The differences in crown ratio between the 30-tree and 100-tree regimes were enough to create important variation in structural diversity between the treatments. The level of mortality also could contribute to natural snag formation and generation of coarse woody debris. In the 75- and 150-tree regimes, only a few trees per hectare died during the simulation period. In the no-thin regime, 52% of the trees died by age 100.

### 3.5. Lumber grade yield prediction

The no-thin regime produced the most lumber volume throughout the 100-year modelling period, and the 30–75 regime produced the least. The total lumber volume also declined roughly in order of increasing intensity and stand age when thinned (Table 3). The heavier thinning regimes produced less volume because they failed to fully use the site.

Our simulations did not consider underplanting in these widely spaced stands, therefore, the volume gain associated with the resulting understory trees is not reported. The heavy thinning regimes also may increase the risk of windthrow, but OGRANON does

Table 3
Volumetric yield by age and regime in cubic meters

| Age | 15–75 | 30–75 | 15–150 | 30–150 | 30–150HL | 30–250 | No thin |
|---|---|---|---|---|---|---|---|
| 30 | [a] | 37 | [a] | 30 | 34 | 24 | [a] |
| 40 | 30 | 22 | 54 | 37 | 25 | 43 | 107 |
| 60 | 100 | 76 | 153 | 124 | 94 | 167 | 219 |
| 80 | 180 | 153 | 253 | 223 | 180 | 269 | 308 |
| 100 | 250 | 228 | 340 | 313 | 260 | 361 | 376 |

[a] No volume removed at time of thinning for 15-year regimes; volume shown for 30-year regimes is thinned volume.

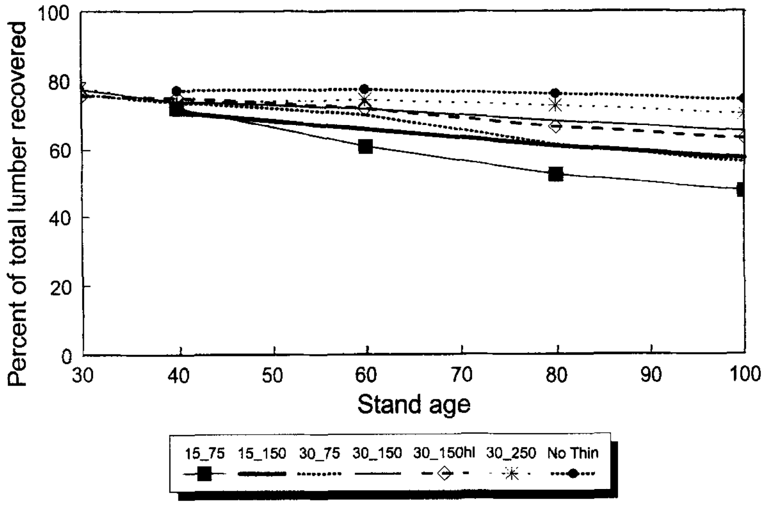


Fig. 1. Percentage of yield of visually graded No. 2-and-Better by regime.

not account for this in its volume calculations. Regimes involving more frequent, lighter thinnings may produce higher lumber volumes and achieve the same tree size and spacing objectives, but the goal here was to model a set of fairly simple regimes and establish the bounds of wildlife and wood quality outputs.

Much of the visually graded dimension lumber sold in North America is marketed as No. 2-and-Better (combined grades No. 2, No. 1, and Select Structural). Grouping results in this way simplifies initial comparisons of the regimes (Fig. 1). Differentiation among regimes begins at age 60 and increases with stand age. Stands that were older when thinned or those thinned to higher densities yield more No. 2-and-Better. This results from TREEVAL responding to the decline in knot size with increasing thinning age and stand density (Table 2).

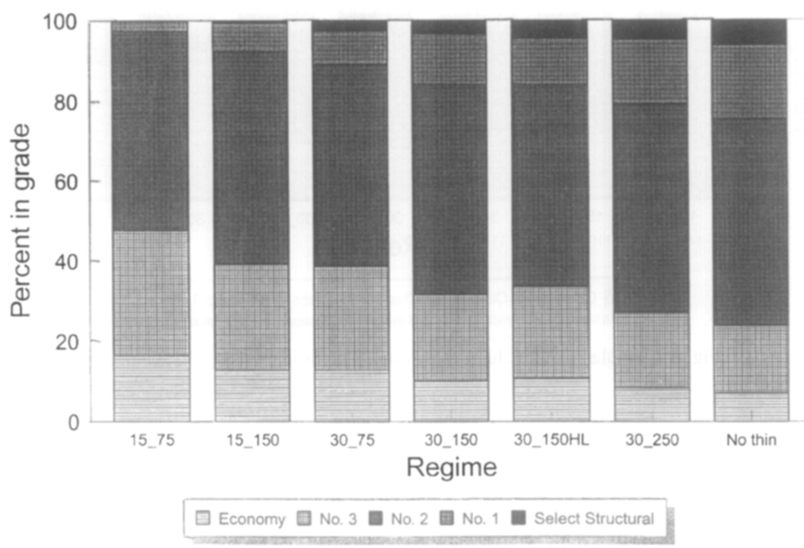


Fig. 2. Cumulative visual grade recovery in 80-year-old stands.

Table 4
Percentage of recovery of visually graded lumber by age and regime

| Age | 15–75 | 30–75 | 15–150 | 30–150 | 30–150HL | 30–250 | no thin |
|---|---|---|---|---|---|---|---|
| *Select structural* | | | | | | | |
| 30 | [a] | 2.5 | [a] | 2.9 | 2.2 | 3.2 | 0.0 |
| 40 | 1.5 | 2.8 | 1.3 | 2.8 | 3.3 | 2.7 | 4.0 |
| 60 | 0.1 | 3.2 | 0.8 | 3.9 | 4.6 | 5.1 | 6.3 |
| 80 | 0.1 | 2.6 | 0.6 | 3.3 | 4.5 | 4.8 | 6.2 |
| 100 | 0.1 | 2.2 | 0.5 | 2.9 | 4.2 | 4.1 | 5.9 |
| *No. 1* | | | | | | | |
| 30 | [a] | 16.2 | [a] | 17.5 | 15.8 | 18.1 | 0.0 |
| 40 | 12.9 | 14.7 | 11.9 | 14.8 | 15.8 | 14.5 | 17.8 |
| 60 | 5.0 | 12.3 | 9.0 | 14.4 | 14.0 | 16.5 | 18.7 |
| 80 | 2.5 | 8.3 | 7.0 | 12.6 | 11.4 | 15.9 | 18.1 |
| 100 | 2.1 | 7.0 | 6.0 | 11.2 | 10.5 | 14.5 | 17.2 |
| *No. 2* | | | | | | | |
| 30 | [a] | 57.2 | [a] | 56.9 | 57.5 | 56.5 | 0.0 |
| 40 | 57.7 | 56.8 | 57.5 | 56.3 | 55.8 | 56.2 | 55.4 |
| 60 | 55.6 | 54.7 | 56.1 | 53.7 | 53.5 | 52.8 | 52.5 |
| 80 | 49.9 | 50.5 | 53.4 | 52.5 | 50.7 | 52.3 | 51.9 |
| 100 | 45.7 | 47.0 | 50.8 | 51.2 | 48.5 | 51.9 | 51.4 |
| *No. 3* | | | | | | | |
| 30 | [a] | 17.7 | [a] | 16.7 | 18.0 | 16.3 | 0.0 |
| 40 | 20.3 | 19.3 | 21.2 | 19.0 | 18.2 | 19.2 | 16.7 |
| 60 | 27.6 | 21.3 | 24.1 | 19.9 | 19.9 | 18.1 | 16.1 |
| 80 | 31.3 | 26.0 | 26.4 | 21.6 | 22.7 | 18.7 | 16.7 |
| 100 | 31.7 | 27.4 | 27.4 | 22.6 | 23.6 | 19.7 | 17.4 |
| *Economy* | | | | | | | |
| 30 | [a] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0.0 |
| 40 | 7.6 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 6.1 |
| 60 | 11.7 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 6.3 |
| 80 | 16.2 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 7.0 |
| 100 | 20.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 8.1 |

[a] No volume removed [illegible] ne.

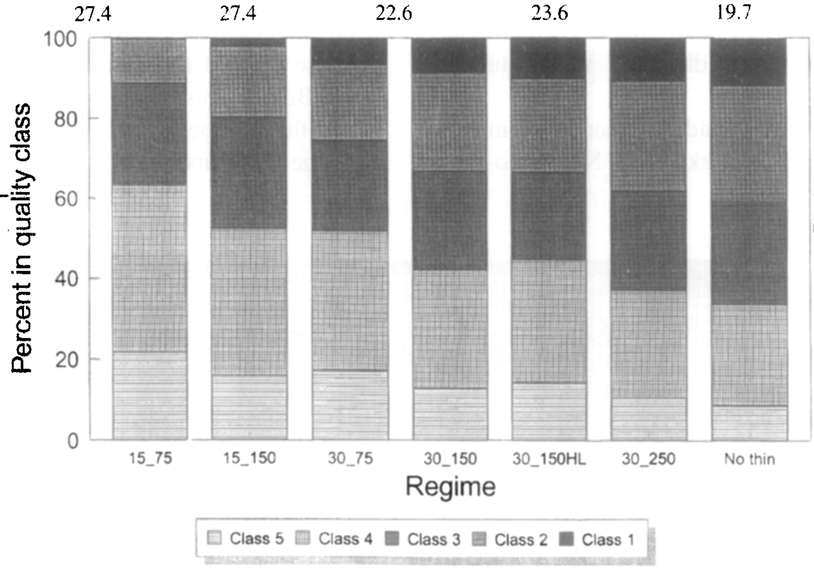


Fig. 3. Cumulative MSR lumber by quality class in 80-year-old stands.

Table 5
Percentage of recovery of machine stress rated (MSR) lumber by quality class by age and regime

| Age | 15–75 | 30–75 | 15–150 | 30–150 | 30–150HL | 30–250 | no thin |
|---|---|---|---|---|---|---|---|
| Quality class 1(1/6 edge knot 12.4 GPa E) | | | | | | | |
| 30 | [a] | 0.0 | [a] | 0.0 | 0.0 | 0.0 | 0.0 |
| 40 | 2.6 | 1.7 | 2.4 | 1.5 | 1.6 | 1.3 | 2.3 |
| 60 | 0.5 | 7.8 | 2.5 | 8.7 | 9.9 | 9.0 | 8.7 |
| 80 | 0.2 | 6.7 | 2.1 | 8.6 | 10.2 | 10.6 | 11.5 |
| 100 | 0.2 | 5.7 | 1.8 | 7.8 | 9.5 | 10.0 | 12.4 |
| Quality class 2 (1/4 edge knot 10.3 GPa E) | | | | | | | |
| 30 | [a] | 11.4 | [a] | 11.9 | 11.2 | 12.0 | 0.0 |
| 40 | 20.4 | 19.0 | 19.3 | 18.8 | 19.7 | 18.1 | 20.2 |
| 60 | 15.6 | 24.3 | 20.0 | 25.5 | 25.8 | 26.4 | 26.9 |
| 80 | 10.9 | 18.9 | 17.6 | 24.5 | 23.3 | 27.5 | 29.0 |
| 100 | 8.9 | 16.1 | 15.7 | 22.8 | 21.6 | 26.5 | 29.3 |
| Quality class 3 (1/3 edge knot 9.0 GPa E) | | | | | | | |
| 30 | [a] | 31.2 | [a] | 32.2 | 30.9 | 32.6 | 0.0 |
| 40 | 31.5 | 33.3 | 30.7 | 33.5 | 34.3 | 33.3 | 34.3 |
| 60 | 29.7 | 26.4 | 29.9 | 26.2 | 25.0 | 27.2 | 29.3 |
| 80 | 25.6 | 22.8 | 28.1 | 24.6 | 21.9 | 24.9 | 25.7 |
| 100 | 22.0 | 20.0 | 25.8 | 23.2 | 20.0 | 23.7 | 23.3 |
| Quality class 4 (1/3 edge knot 6.9 GPa E) | | | | | | | |
| 30 | [a] | 53.3 | [a] | 51.9 | 53.6 | 51.6 | 0.0 |
| 40 | 38.2 | 39.8 | 40.0 | 40.1 | 38.5 | 41.2 | 38.1 |
| 60 | 39.8 | 31.0 | 36.1 | 30.2 | 29.6 | 29.2 | 28.4 |
| 80 | 41.6 | 34.5 | 36.3 | 29.4 | 30.4 | 26.5 | 25.0 |
| 100 | 39.5 | 34.2 | 35.6 | 29.3 | 29.8 | 26.2 | 23.8 |
| Quality class 5 (> 1/3 edge knot < 6.9 GPa E) | | | | | | | |
| 30 | [a] | 4.1 | [a] | 3.9 | 4.2 | 3.8 | 0.0 |
| 40 | 7.3 | 6.2 | 7.5 | 6.1 | 5.9 | 6.0 | 5.2 |
| 60 | 14.5 | 10.5 | 11.5 | 9.4 | 9.7 | 8.1 | 6.7 |
| 80 | 21.6 | 17.1 | 15.9 | 12.8 | 14.2 | 10.5 | 8.7 |
| 100 | 29.4 | 24.1 | 21.0 | 16.9 | 19.1 | 13.6 | 11.2 |

[a] No volume removed at time of thinning for 15-year regimes; volume shown for 30-year regimes is thinned volume.

The complete visual grade breakdown for each regime at 80 years, the oldest age at which thinning is currently allowed in federal late successional reserves (USDA FS and USDI BLM, 1994), is illustrated in Fig. 2. The different regimes produced a relatively consistent amount of No. 2-grade lumber. The increase in the yield of Select Structural- and No. 1-grade lumber for the later or lighter thinnings corresponds to a reduction in No. 3 and Economy grades in the earlier or heavier thinnings (Table 4).

The distribution of MSR quality classes (Fig. 3; Table 5) has a different shape than the distribution of visual grades (Fig. 2; Table 4). A higher percentage of the MSR lumber is classified into the two highest and two lowest quality classes. From 35 to 60% of the MSR lumber volume falls into the two lowest classes and 10–40% into the two highest. In contrast, only 25–45% of the lumber volume falls into the two lowest visual grades and 5–25% in the two highest.

## 4. Discussion

### 4.1. Stand characteristics

Our simulations suggest that thinning young Douglas-fir stands at age 15 or 30 holds promise for accelerating the development of aspects of stand structure found in late-seral stage forests such as tree diameter, crown depth, and limb diameter. Preliminary studies indicate that populations of some wildlife species will show rapid, favorable responses to thinning. For example, Hagar (1992) found that the

Hammond's flycatcher (*Empidonax hammondii*), a species sometimes considered to be an old-growth associate (Sekai and Noon, 1991), was absent in unthinned stands but occurred in thinned stands. This species sometimes moves into stands within weeks of thinning (Hayes et al., unpublished data). Populations of several other bird species, including brown creepers (*Certhia americana*), dark-eyed juncos (*Junco hyemalis*), and hairy woodpeckers (*Picoides villosus*), were more abundant in thinned stands (Hagar, 1992). Development of larger crowns as a result of thinning may benefit other species, such as the red tree vole (*Arborimus longicaudus*), which nest and forage in Douglas-fir foliage (Maser, 1965; Gillesberg and Carey, 1991).

Simply accelerating tree growth and increasing spacing will not, however, provide the structural characteristics necessary for all species of wildlife. Many wildlife species respond to the amount and size of coarse woody debris on the forest floor (Hayes and Cross, 1987; Tallmon and Mills, 1994; Carey and Johnson, 1995), density and size of snags (Mannan et al., 1980; Raphael and White, 1984; Carey, 1995), and multi-storied stand structure (Carey and Johnson, 1995). Mechanisms such as windthrow, mortality resulting from logging or natural causes, and natural regeneration may provide some of these structural characteristics in thinned stands. These mechanisms may be most effective in stands thinned to relatively low densities (such as the 75-TPH regimes), but because of the lack of empirical studies in heavily thinned stands, estimates of the efficacy of natural mechanisms to create these structures are speculative.

Stands left at higher densities for extended periods produce large numbers of small snags plus large quantities of coarse woody debris, but at the expense of structural diversity. Stands thinned to low density will have great vertical habitat diversity with multi-layered vegetation, but will require active management to create snags.

Direct manipulation and active management may help to create habitat structure in some thinned stands. Underplanting in stands thinned to densities of 150 TPH or lower is likely to accelerate development of multi-storied stands. Hardwood species should be included in these plantings, as several species of birds are associated with hardwoods (Brown, 1985; Huff and Raley, 1991; Hagar, 1992). Creating snags and coarse woody debris may be necessary to supplement natural recruitment. Large-diameter snags and coarse woody debris meet the habitat requirements of more species and are used more frequently than those with smaller diameters (McClelland et al., 1979; Mannan et al., 1980; Hayes and Cross, 1987; Schreiber and de Calesta, 1992). Large-diameter snags also survive longer while standing than the smaller diameter snags (Morrison and Raphael, 1993). As a consequence, in some cases it may be advantageous to wait until tree diameters are larger before creating snags and coarse woody debris in stands. In situations where snags for nesting and foraging are limited, creation of small-diameter snags at the time of initial thinning may be beneficial.

ORGANON can provide guidelines for such an approach. For example, a portion of a stand could be thinned to 150 TPH at age 30 and underplanted with shade-tolerant conifer species, such as western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) and western redcedar (*Thuja plicata* Donn ex D. Don), and deciduous trees, such as bigleaf maple (*Acer macrophyllum* Pursh.). At ages 60–80, as the overstory canopy closes, another entry could be made to remove some trees for commercial harvest and for creation of snags and coarse woody debris. Our results indicated that average tree diameters will be between 60 and 75 cm DBH at this age (Table 2). Entries at ages 60–80 would create large-diameter snags and coarse woody debris to provide habitat for more species than would have been possible at age 30. Other benefits from multiple entries could be maintenance of an open understory for further development of a multi-storied stand, economic returns to the community, and a source of funds for continued habitat enhancement. Thinning understory trees also may be possible at these entries. Such a management regime may leave a stand with 30 large overstory trees, a complement of created snags and coarse woody debris, as well as significant understory crown development. Characteristics of overstory trees would probably be intermediate between projections for 75- and 150-TPH regimes.

The 30–150HL regime was designed to promote diverse crown structure by leaving a range of trees to develop at different rates. We hypothesized that this regime also would provide a wide variety of trees from small-limbed suppressed and intermediate trees to fast-growing dominant trees with larger limbs. Our results suggest that this regime will succeed in producing stands with more varied overstory structure than the thin-from-below regimes. Our simulations indicate that mortality will be greater in the small-diameter class. The high and low stand segments maintain very different characteristics through the analysis period and show no signs of converging at stand age 100 (Table 2).

The choice of a regime should be made with knowledge of the composition of the surrounding landscape. Even though some of the regimes described may benefit some wildlife species, they may have negative consequences for others. For example, predation on marbled murrelet (*Brachyramphus marmoratus*) nests seems to be higher for less concealed nests and for nests closer to habitat edges (Nelson and Hamer, 1995). Heavy thinning of stands adjacent to known marbled murrelet nest sites could increase risk of predation on eggs and chicks. Large gaps between crowns also could promote heavy shrub layers in the understory or increase susceptibility to windthrow in the residual stand.

### 4.2. Juvenile wood

ORGANON predicted that trees grown at wider spacings would produce a smaller percentage of juvenile wood, as a proportion of tree volume, than those grown in more dense stands (Table 2). This result is counterintuitive. According to accepted theory, the transition from juvenile to mature wood occurs at the approximate base of the live crown (Larson, 1969; Di Lucca, 1989). Trees grown under lower density regimes have larger crowns (Table 2), which take longer to close than in the higher density regimes. Trees from low-density regimes, therefore, should contain more juvenile wood than those grown under higher density regimes.

For this analysis, juvenile wood was defined as rings 1–20 from the pith. This definition is appropriate for stands grown under regimes with several hundred trees per hectare (Di Lucca, 1989; McKinley et al., 1995) but may not be appropriate for the heavy early thinning regimes modelled here.

Estimating juvenile wood content from the base of the live crown gave a considerably different result (Table 6). The differences will be examined, by the senior author and others, as part of ongoing work to improve the modelling system. The lumber yield prediction equations were, however, derived by using the 20-ring transition definition (Fahey et al., 1991) so that is the only appropriate definition for predicting lumber yields with the Fahey et al. (1991) yield equations.

Juvenile wood in Douglas-fir can have densities much more in line with low density, and consequently weaker, softwoods (Jozsa et al., 1989). This could have major implications for the production of structural composites and engineered wood products from trees grown under the regimes with earlier thinnings or stands thinned to very low density over the age range modelled here (Table 6).

### 4.3. Lumber grade yield prediction

On average, the lumber industry in western Washington and Oregon produces 85% or more No. 2-and-Better lumber from Douglas-fir (Western Wood Products Association, 1994). Although this range is typical, actual percentages fluctuate because the production of low-grade lumber is related to chip prices as well as to wood quality.

The no-thin and the 30–250 regimes approached the level of No. 2-and-Better reported by Western

Table 6
Juvenile wood content calculated as a percentage of total tree volume by using the fixed number of rings and crown recession methods for selected regimes

| Regime | Age 40 | | Age 60 | | Age 80 | | Age 100 | |
|---|---|---|---|---|---|---|---|---|
| | Fixed ring | Crown death | Fixed ring | Crown death | Fixed ring | Crown death | Fixed ring | Crown death |
| 15–75 | 62 | 100 | 34 | 98 | 26 | 89 | 20 | 73 |
| 30–150 | 76 | 82 | 43 | 64 | 32 | 56 | 25 | 51 |
| No thin | 80 | 56 | 56 | 49 | 45 | 41 | 36 | 37 |

Wood Products Association (1994) but none of the other regimes did. Mills relying heavily on materials from stands managed under the more severe thinning regimes might find it difficult to produce a sufficient quantity of No. 2-and-Better to survive in the current commodity market. This will depend on market conditions, but the ability of mills to deal with a 150–250% increase in the volume of low grade material (No. 3 and Economy) is questionable (Table 3).

Although displaying lumber grade yield as a percentage of No. 2-and-Better helps to illustrate how these regimes compare with one another, it fails to show finer differences among regimes. The ability to understand these potential differences may be important in setting policy or evaluating manufacturing options. The economic analyses used in developing the present regulations for managing federal lands in the coastal US Pacific Northwest (USDA FS and USDI BLM, 1994) assume that the timber industry will alter manufacturing processes in response to changes in timber supply from federal lands (Forest Ecosystem Management Assessment Team, 1993). The Forest Ecosystem Management Assessment Team predicted that increases in the production of composite products and certain types of secondary manufactured products will offset some job losses in other segments of the forest products industry (Forest Ecosystem Management Assessment Team, 1993; section VI, pp. 39–42). This outcome requires a resource with technical properties adequate to manufacture the new products. Some of these products will require fiber, small particles, strands, or other types of highly modified wood that cannot be modelled with the existing version of TREEVAL. Others, such as laminating stock for gluelam beams, components for trusses, solid lumber flanges for wood I-beams, and fingerjointing stock, are manufactured from dimension lumber. Results presented in Tables 4 and 5 give some indication of the potential for manufacturing these types of products.

Our projections for 80-year-old stands (Fig. 2) are compared to the industry average data in Table 7 (Western Wood Products Association, 1994). All the proposed regimes produce a higher proportion of low-grade lumber than is currently being manufactured from the existing resource. The recovery of higher grades, however, increases with thinning age and stand density. It is encouraging that the lower grades, not the middle, decrease as the upper grades increase, because the economic viability of a resource often has both as much to do with the amount of low-grade material as the proportion of higher grades.

The heavier and earlier thinning regimes generate almost no high-grade lumber and substantially more low-grade lumber than the regional average. Our results also suggested that even technological improvements, such as MSR grading, that minimize the importance of visual defects and emphasize the inherent physical properties of the wood may have difficulty finding value in trees grown under the earliest, heaviest thinnings.

Mechanical grading can be substituted for visual grading on only part of the production because there currently is no market for MSR lumber in the two lowest quality classes. Manufacturers probably would want to sell this material as visually graded lumber. Under the existing grading rules, this material is likely to qualify only as No. 3 and Economy. Thus, high proportions of these grades would be produced under either mechanical or visual grading systems.

As with visual grades, improvements in the higher quality classes come at the expense of the lowest classes and not those in the middle (Fig. 3). Our

Table 7
Comparison of simulated 80-year-old stands with WWPA's index log for coastal Douglas-fir (Western Wood Products Association, 1994); data shown as percentage of yield by grade group

| Grade | WWPA | | Simulated regimes at 80 years | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1985–1986 | 1992–1993 | 15–75 | 15–150 | 30–75 | 30–150 | 30–150HL | 30–250 | no thin |
| No. 2 and Better | 85 | 89 | 53 | 61 | 62 | 69 | 67 | 73 | 76 |
| No.3 and Economy | 15 | 11 | 48 | 39 | 39 | 32 | 33 | 27 | 24 |

No. 2 and Better includes all selects, shops, select structural and No.1 dimension and timbers for all thicknesses, Str. and Btr commons, No. 2 dimension, timbers, and studs.
No. 3 and Economy includes all other grades reported by Western Wood Products Association (1994).

results may, however, present a best case scenario for MSR lumber. Like visual grades, the change in quality class yields are probably due to decreasing limb size with increasing stand density (Table 2). The use of a fixed ring count method for predicting juvenile wood content limits the effect of juvenile wood, which is known to be of major importance in determining MSR lumber yield (Barrett and Kellogg, 1991; Fahey et al., 1991).

In areas where revenues from future thinnings are needed to finance continued habitat improvement, the heavier earlier thinnings should be applied with caution. However, the unique habitat and structural characteristics, such as large branches, long crowns, and opportunities for understory development, offered by these treatments may outweigh concerns about their wood product potential. The cost of establishing such treatments in younger stands may, however, make it essential to understand the balance between the costs of and revenues from the initial thinning and benefits of habitat development. More complex treatments involving multiple entries may allow growth of higher quality trees and more desirable habitat characteristics than the single-entry regimes modelled here.

### 4.4. Structural composites and engineered products

Although no models exist to estimate potential yields of composite or engineered products, information available from existing models is useful for this purpose. Wood-based structural composite products manufactured today generally require raw materials with similar mechanical properties to the solid wood products they replace. The difference is that they use smaller pieces of this high-quality material. For example, gluelam beams have largely replaced solid sawn beams for architectural uses, but the grading rules for laminating stock are some of the most restrictive applied by the industry (Western Wood Products Association, 1991). As solid joists are replaced by wood I-beams, the material used in the flanges – whether solid lumber, finger jointed lumber, or laminated veneer lumber – is also of very high quality but much smaller in size than the joist.

Even under the conservative definition of juvenile wood used here, some of the modelled regimes would be poor sources of raw materials for a structural composites or engineered wood products industry. Additional experimental work is required to determine if the low-grade lumber from the simulated regimes is suitable for existing value-added processing. For example, when low stiffness results from grain deviation around knots, then crosscutting to remove knots followed by fingerjointing might make sense. If low stiffness results from high juvenile wood content, then fingerjointing will not improve stiffness.

There are, however, emerging technologies to combine wood with other materials to enhance the mechanical properties of composite products or to improve wood particle orientation and adhesion. These processes may make many fiber sources suitable for structural composites (Rowell, 1992). These products will undoubtedly appear someday in the market place, but their commercial introduction is probably many years in the future. This makes it impossible to anticipate what type of raw material they will require. For the present and some time into the future, entrepreneurs will want to find ways to recover the most value from the available resource through existing technologies or incremental changes in existing composite products. Those technologies will probably continue to require wood with inherently high mechanical properties.

### 4.5. Limitations in the modelling system

The applicability of any model is limited by the range of empirical data used in its development. Our results are clearly at the edge, and in some cases probably exceed the abilities of the ORGANON and TREEVAL modelling system to accurately predict stand characteristics and wood quality. Some of the scenarios, such as thinning to 75 TPH and the 150 TPH high-low thin, have rarely or never been implemented operationally, and empirical studies to examine their ecological ramifications are only now being established. Our analyses do, however, help generate ideas for approaches to the management of young stands. Working hypotheses resulting from this process must be tested through empirical studies. Conclusions from such studies may be many years away, but decisions must be made today on how to manage these stands. Any decision, even one to not act, will have implications for a long time to come. It is therefore useful to employ the available tools to weigh up the possible outcomes of policy decisions made today. These tools should be continuously improved and decisions revisited as new empirical data become available.

## 5. Conclusions

The results of our simulations suggest that silvicultural manipulations of Douglas-fir plantations can accelerate development of stands with multi-storied structures and large-diameter overstory trees at relatively young ages. This can be accomplished through a combination of early heavy thinning and underplanting. By delaying thinning until a stand is 30 years of age and increasing residual stand density from 75 to 150 trees per hectare, it may be possible to grow stands with multi-storied structure, abundant large snag-candidate trees (in excess of 85 cm DBH at 100 years), and sufficient residual stems to carry out a second thinning to recover moderate quality wood. This wood should have characteristics comparable to wood grown in commercial plantations. The final thinning could be timed between stand ages 60 and 80 to capture the maximum value from the trees based on the products recovered.

## Acknowledgements

The authors would like to thank the following people for reviewing and commenting on this manuscript during various stages of its development: Andy Carey (USDA FS, PNW Station, Wildlife Biologist) Dave Marshall (Oregon State University, Biometrician), Bob Gale (USDA FS Siuslaw National Forest, Wildlife Biologist/Silviculturist), Bill Emmingham (Oregon State University, Silviculturist), Alex Clark (USDA FS, Southern Station, Wood Products Specialist) Sue Willits (USDA FS, PNW Station, Wood Products Specialist), and Richard Haynes (USDA FS, PNW Station, Economist).

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