For. Sci. 61(●):000–000
http://dx.doi.org/10.5849/forsci.14-194

silviculture

Overstory Development in Douglas-Fir-Dominant Forests Thinned to Enhance Late-Seral Features

Mike Newton and Liz Cole

Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*) and Douglas-fir/western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) stands were thinned at age 50 to different levels of residual stocking, with and without gaps on medium or better (McDonald) and excellent (Blodgett) sites in western Oregon. Postthinning basal areas ranged from 75 to 140 ft^2/acre in 35–80 trees/acre. The range of densities led to periodic Scribner and cubic volume growth peaking at ages 60–90 with mean annual increment peaking after age 100 based on Organon model projections. Postthinning stand growth was greatest with the highest residual basal area; percent growth was highest in the lowest densities. Projections indicated that allocating 20% of plot area in 1/6–1/4 acre gaps with stand basal areas comparable to uniform plots led to 1–10% reductions in growth. Reductions were not statistically significant. Diameter increment and average size exceeded normal yield tables at one site and were inversely related to basal area. At age 103, the difference in projected quadratic mean diameter across the densities was about 6 inches. By age 65, some tree diameters were already late-seral sizes. Crown cover increased rapidly during 15 years after thinning. Mortality has been negligible in McDonald, but windthrow has removed trees, especially hemlock at Blodgett.

Keywords: volume yield, western hemlock, mean annual increment, periodic annual increment, basal area increment

Maintenance of late-seral habitat and various indicators of increasing structural complexity are among the general goals on public forestlands requiring attention to ecosystem-level biodiversity. In the Pacific Northwest, federal forestlands have been brought under the Northwest Forest Plan (NWFP) with the objective of providing late-seral habitat to protect the northern spotted owl (*Strix occidentalis*) and other late-seral wildlife, as required by the Endangered Species Act (Thomas et al. 2006). The Organic Act and National Forest Management Act that established the National Forest System, with goal statements, and the O&C Lands Act (US Congress 1937) that designated the Oregon and California revested railroad allocations in Oregon identify the sustained yield of timber and other resources as objectives of the legislation. Thus, the need exists for planning to include early- and late-seral conditions in forests, thereby providing rural economic support while enhancing and protecting native wildlife and other natural resources.

Timing of stand harvesting has been linked to demand for wood products and maximum growth as well as late-seral environments. McArdle et al. (1961), in comprehensive studies of yields of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*) in the Pacific Northwest reported maximum net growth as occurring between ages 50–100 years of stand development, leading to maximum board-foot (BF Scribner scale, 32-ft logs) yield per acre per year at ages 90 to greater than 100; Curtis (1982) observed the same. Yields were described for each site class of commercial forestland, assuming naturally regenerated fully stocked stands with no history of density management. Growth patterns in western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) had shown similarity to those of Douglas-fir, perhaps culminating somewhat earlier (Barnes 1962). Many federal forests then adapted growth and harvest schedules with rotation ages with the greatest mean annual accumulation of merchantable timber. This approach set in motion harvesting sequences leading to roughly half of natural old stands on public lands and nearly all older stands on private timberlands being harvested over a 40- to 50-year period (Thomas et al. 2006). With continuation of this approach, stands with mature structural development were no longer being propagated except in wilderness areas or other reserves.

Harvesting at financial maturity substantially reduced mortality and therefore snags and large trees with a natural assemblage of late-seral habitat features. These features have been described by

Manuscript received October 14, 2014; accepted March 17, 2015; published online April 23, 2015.

Affiliations: *Mike Newton (mike.newton@oregonstate.edu), Oregon State University. Liz Cole (liz.cole@oregonstate.edu), Department of Forest Engineering, Resources, and Management, Oregon State University, Corvallis, OR.*

Acknowledgments: *The US Department of Interior National Biological Survey, US Geological Survey, Oregon Department of Forestry, and Bureau of Land Management have provided substantial funding for this project. The Long-Term Silviculture Research Endowment, Oregon State University Foundation, has provided sustained funding since 2004. Mary O'Dea, Thomas Brandeis, Barbara Jerra, Mark Nabel, Maciej Zwieniecki, and Richard Symons and other employees of Oregon State University forest staff have participated in layout, measuring, surveying, treeplanting, and many other aspects of this study. Craig Kintop and George McFadden have provided valuable counsel and support from within the BLM.*

Table 1. Stand descriptions for McDonald Forest, including site index, pre- and postthinning basal area, postthinning trees per acre, quadratic mean diameter, Curtis relative density index, and Scribner volumes from the initial study thinning and rethinning cut and standing post volume.

	McDonald								
	Site index 50 (ft)	Prebasal area	Postbasal area	Post-tpa	Postquadratic mean diameter (in.)	Post-Curtis relative density index[a]	Initial study thinning cut volume	Postvolume	Rethinning cut
		. . . . .(ft^2/ac)					. . . .(Scribner BF/ac)		
GAP									
LOW	124	138	76	42	18.7	17.6	9,348	16,628	0
MED	124	143	102	55	18.7	23.6	4,719	21,634	5,700
MHI	128	159	121	65	18.7	28.0	3,478	25,555	6,080
HIGH	127	157	129	80	17.4	30.9	3,583	27,296	0
UNIFORM									
LOW	126	146	81	40	19.4	18.4	10,830	18,108	0
MED	130	154	99	44	20.5	21.9	8,248	22,508	6,320
MHI	130	164	124	57	20.0	27.7	3,768	26,425	7,010
HIGH	126	144	135	85	17.0	32.7	1,057	28,146	0

[a]Relative density index from Curtis (1982).

Franklin et al. (1986) as part of the definition of old-growth. Thinning has been proposed as a means to develop late-seral habitat more rapidly than provided by natural stands (McComb et al. 1993, Cole 1996, Carey et al. 1999). Simulation runs of thinning 50-year-old Douglas-fir stands indicated that various management scenarios could result in nesting habitat for spotted owls earlier than would be expected through natural stand development (Andrews et al. 2005).

In 1993, a long-term study that focused on patterns of commercial thinning at age 50 to enhance growth of dominant overstory trees to provide overstory and understory structural features for wildlife habitat was established in Oregon. This article describes yield and crown cover projections of overstories of longer-rotation Douglas-fir stands and mixed Douglas-fir/western hemlock forests on productive sites thinned to meet both yield and habitat expectations. It summarizes features of overstory development after various thinning treatments in previously thinned, moderately stocked stands on average to excellent Douglas-fir and Douglas-fir/western hemlock sites based on Organon projections of growth and yield to age 103 (50 years after thinning). The specific objectives of this article were to describe (1) tree size (quadratic mean diameter and their frequency by diameter class) in response to thinning at age 50, (2) the role of levels of residual stocking in thinned 50-year-old managed stands on total yield within the next 50 years, (3) periodic and mean annual increments after different patterns of thinning from below, and (4) crown cover changes after thinning.

Methods

Site Descriptions and Histories

Two sites on Oregon State University Research Forests were selected for study. The first site was established in 1993 and is located near Corvallis, Oregon (McDonald, latitude 44.83° N and longitude 123.28° W). This site was occupied by a 50- to 55-year-old stand with a mixture of planted (unknown seed source) and natural Douglas-fir with minor secondary species including grand fir (*Abies grandis* Lindl.) and bigleaf maple (*Acer macrophyllum* Pursh). This site has a dry-summer climate with moderate temperatures and about 60 in. of annual precipitation, 85% falling in the six coolest months. Soils are clay loams derived from basalts, with good drainage, moderate to deep, mostly west to northwest facing slopes of 10–50%.

The second site (Blodgett, latitude 46.07° N and longitude 123.35° W) was established in 1995 about 115 miles north of McDonald in the Coast Range. Blodgett stands were composed entirely of natural regeneration, also 50–55 years old, and varied in the percentages of western hemlock and Douglas-fir. Small amounts of western redcedar (*Thuja plicata* [D.] Don.) and red alder (*Alnus rubra* Bong.) were present in some areas. The western hemlock component varied from 4 to 81% of the postharvest basal area and overall was nearly as abundant as Douglas-fir. Rainfall distribution is similar to that at McDonald, but temperatures are cooler in summer, and annual precipitation is more than 70 inches. Soils are derived from highly weathered sedimentary rocks and are very deep.

Study Design and Layout

The study design was a randomized block split plot with three replications (blocks) at each site (Cole and Newton 2009). Blocks were divided into two whole plots that were randomly assigned one of two types of thinning: uniform thinning or thinning with gaps. Each whole plot was divided into 4 (McDonald) or 3 (Blodgett) subplots and randomly assigned a residual density. Subplots were 6.15 acres with an interior 3.6-acre measurement plot with a 60-ft buffer receiving the same density treatment. In the gap thinning, the basal area was removed in three 0.15-acre and three 0.25-acre circular gaps amounting to 20% of each subplot area including buffers, with proportional distribution in measurement area and buffer. All trees were removed within gaps. If the basal area removal in gaps was insufficient to meet target basal areas, the matrix between gaps was thinned uniformly. In the uniform plots and within the matrix areas of gap plots, trees to be removed were selected by the principles of "thinning from below" to provide residual stands of the target basal areas ranging from roughly one-third (LOW) to about 60% (HIGH) of a fully stocked stand, based on McArdle et al. (1961) for the site classes involved. Intermediate stocking levels were MED and MHI (roughly 42 and 50% of full stocking as per McArdle et al. 1961) at McDonald (Table 1) and MED at Blodgett (Table 2).

Most of the plot areas had been commercially thinned previously; McDonald had been thinned two or more times previously with the last entry at least 10 years before establishment of this study; most Blodgett stands had been thinned once about 8 years before the onset of the study. Parts of two of the highest density plots at

Table 2. Stand descriptions for Blodgett, including site indices for Douglas-fir and western hemlock, pre- and postthinning basal areas for both species, total postthinning trees per acre, quadratic mean diameter, Curtis relative density index, and Scribner volume for the initial study thinning and standing.

	Blodgett												
	Site index 50		Prebasal area		Postbasal area			Postquadratic mean	Post-Curtis relative	Initial study thinning cut volume		Postvolume	
	PSME	TSHE	PSME	TSHE	PSME	TSHE	Post-tpa	diameter (in.)	density index[a]	PSME	TSHE	PSME	TSHE
	(ft)		(ft^2/ac)							(Scribner BF/ac)			
GAP													
LOW	144	130	65	73	54	28	47	19.6	18.5	2,508	8,872	14,984	6,931
MED	143	123	82	76	73	42	51	19.3	26.2	1,995	6,571	19,958	10,013
HIGH	144	125	69	93	68	73	80	18.0	33.2	1,303	3,867	18,777	17,118
UNIFORM													
LOW	141	130	86	97	53	36	52	17.8	21.1	6,977	11,693	14,278	8,649
MED	142	124	119	92	79	40	64	18.4	27.7	9,049	10,081	20,492	9,725
HIGH	140	129	93	124	67	76	85	17.5	34.2	5,665	8,790	17,796	18,041

Western redcedar are not included. PSME, Douglas-fir; TSHE, western hemlock.
[a]Relative density index from Curtis (1982).

Blodgett had no evidence of previous entries other than the history of progressive clearcutting and natural regeneration. Yields of earlier thinnings are unknown.

Thinning to initiate this study was completed in the fall of 1993 for McDonald and the fall/winter of 1995–1996 for Blodgett. Ground and cable systems were used on both sites for thinning, depending on the slope. In year 8 of the study at McDonald, measurements of the underplanted seedlings to provide future structural features indicated they were being suppressed by the residual overstory in the higher densities. The MED and MHI densities were rethinned, returning the basal areas back to the initial study basal areas (Newton and Cole 2006). The LOW and HIGH densities at McDonald were not rethinned. Volumes from rethinning were included along with establishment harvests on those identified treatments at McDonald (Table 1). Other than the initial study thinning, no subsequent thinning had occurred at Blodgett. Table 2 describes the volumes of Douglas-fir and hemlock after establishment harvest at Blodgett; whereas traces of western redcedar were present, negligible redcedar was removed. Yield data presented here include all harvests since study initiation plus residual stand volumes. Evidence of prior thinning suggested that earlier entries at McDonald had opened the stand for understory development and probably led to trees with longer crowns than those in stands not previously thinned. No estimates of volume removed before this study were included in projections.

Measurements

Before thinning, information on basal area and diameter distributions was collected on 960 (McDonald) and 720 (Blodgett) permanent sample points. Basal area was estimated using a 20 BAF prism. Diameters within a 16.4-ft radius of each point were measured for all trees greater than 2-in. dbh. After the initial thinning of whole subplots, all residual conifer trees greater than 2-in. dbh within each 3.6-acre measurement subplot were tagged and measured. Heights were recorded in a 10% sample in each 4-in. diameter class to provide information on the influence of crown position on height growth in ensuing measurements. Trees were remeasured 3 (no heights), 5, 7, 10, and 15 years after the initial measurements. A total of 5,135 numbered overstory trees in McDonald plots and 4,293 trees at Blodgett provided the data for this analysis.

Analyses

Estimates of volumes and growth projections for 50 years after thinning were derived using the Organon Stand Growth Simulator (ed. 9.1, NWO version for McDonald and SMC version for Blodgett; Hann 2005). Organon is an individual tree growth model that uses tree lists as input data to project stand development, including mortality. Organon was developed for southwest Oregon and northwest Oregon, with a version developed using the Stand Management Cooperative (SMC) at the University of Washington data for southwest British Columbia, western Washington, and northwest Oregon. For the projections, diameters for all trees greater than 10-in. dbh and height data from height subsample trees from each subplot were input into Organon, projecting growth for 50 years. Because of the rethinning at McDonald, input data varied for the projections. Measurement data (tree lists) from immediately after plot establishment were used for the HIGH and LOW treatments. The first 5 years of data for MED and MHI plots were similarly charted until rethinning and then the year 10 measurements (tree lists after rethinning) were used to develop trajectories from years 10 to 50 beyond the initial study thinning.

All statistical analyses used PROC MIXED in SAS (Statistical Analysis Systems; SAS Institute, Inc., Cary, NC) with block as a random effect. Analyses were based on Organon projections 50 years after the initial study thinning, stand age 103 years, and sites were analyzed individually. Variables included trees per acre, basal area per acre, quadratic mean diameter, crown cover, cubic foot volume, Scribner board foot volume, mean and periodic annual increment (Scribner volume), and frequency of trees greater than 30 in. and greater than 40-in. dbh. Minimum standards for old-growth conditions included trees greater than 32 in. (Franklin et al. 1986). For Blodgett, the ratio of Douglas-fir to western hemlock volume was also analyzed.

Results

Features relating to stand maturity were showing modest separation of diameters and diameter growth (Figure 1) with different residual densities, decreasing with the increase in basal area. The number of trees greater than 30- or 40-in. dbh projected to age 103 at McDonald did not vary significantly among the densities, reflecting the selection system when thinning, but the proportion of large

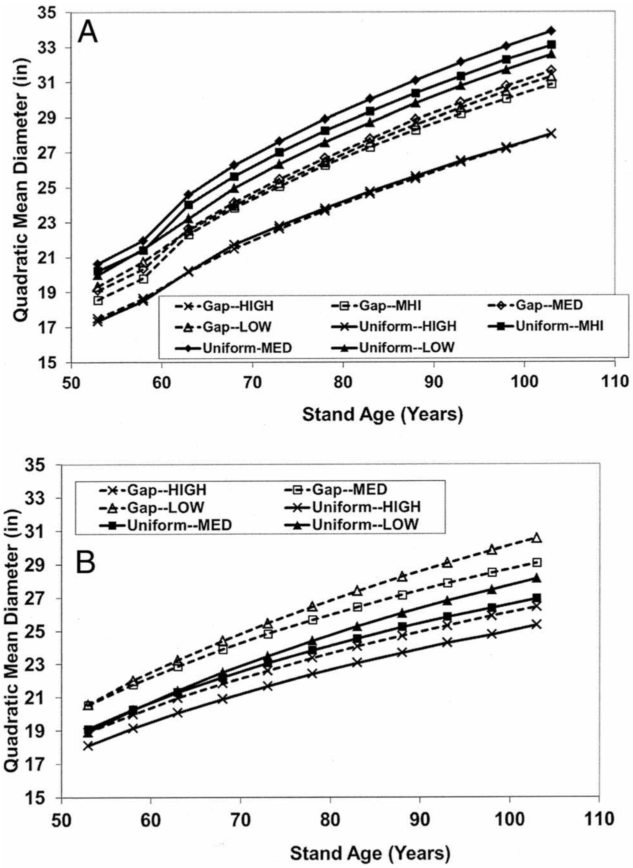

Figure 1. Quadratic mean diameter for overstory trees as a function of residual basal area after thinning, from age 53 to 103 with and without 20% of plot area in gaps for McDonald (A) and Blodgett (B), based on Organon projections.

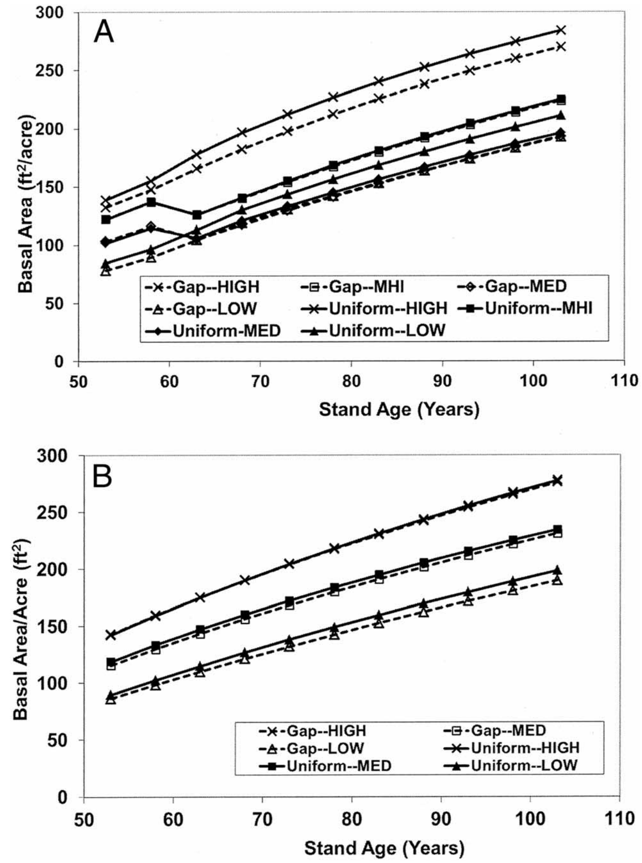

Figure 2. Basal area of overstory trees after thinning to various densities with and without 20% of each plot area in gaps for McDonald (A) and Blodgett (B), based on Organon projections to age 103.

trees did vary among the densities. The lower proportion of trees greater than 30 in. (37%) in the HIGH density compared with that in the other densities (62–68%) reflected the presence of smaller trees in the residual stands retained to meet basal area targets. Differences were not significant for the 40-in. trees, but only a small portion of trees (less than 10%) was greater than 40 inches. As at McDonald, the number of trees with projected diameters greater than 30 or 40 in. at age 103 did not vary among the densities at Blodgett. However, the proportion of trees greater than 30 in. differed among the HIGH (24%), MED (31%), and LOW (40%) densities. Proportions of trees greater than 40 in. were low (less than 3%) in all densities and did not differ. For trees per acre and quadratic mean diameter, the HIGH density had significantly more trees with smaller average diameters than the other densities while retaining the same number of trees greater than 30 inches.

Basal area increments were consistently greater in HIGH density treatments than in LOW (Figure 2), but the percent growth was higher in LOW associated with slightly higher diameter growth rates on the larger stems resulting from thinning from below. The rate of basal area increment decreased with age, whereas volume per square foot of basal area increased with increments of tree height (data not shown). The proportion of the basal area in Douglas-fir in the mixtures with western hemlock and western redcedar at Blodgett decreased significantly from ages 53 to 103, dropping from 57 to 51% (data not shown).

Volume increments and standing crops after thinning, whether Scribner board foot (Figure 3) or cubic foot volumes (Figure 4), exhibited almost linear patterns up to age 103 years. Both sites illustrated some divergence in board-foot yield among residual stand densities. The two rethinned stands at McDonald did not show obvious decreases in slopes of volume curves despite the loss of growing stock from an extra entry. At McDonald, standing volumes in the LOW and MED densities were similar, reflecting the similarity of growing stock after rethinning, but volumes were significantly different among the other densities. Volumes for all densities were significantly different from each other at Blodgett.

The increase in board-foot volume with age in all stands was somewhat greater proportionally than that of cubic feet, reflecting the increase in volume/basal area ratio as trees gained in size. This allowed a near-linear increase in Scribner yield associated with the decreasing rate of basal area increment, when the net increment of both scales was influenced by stocking. Mean annual board-foot increment (MAI) in these thinned stands (Figure 5) differed significantly among the densities at age 103 at both sites. MAI had not culminated at either site at age 103; periodic annual board-foot increment (PAI) had reached near maximum between ages 60 and 90 (Figure 6), well above the MAI, leading to a continued increase in MAI. At McDonald, the HIGH and MHI densities and the LOW and MED densities formed two groups for mean and periodic annual increment (Figures 5 and 6). Small differences in MAI associated with gaps were nonsignificant ($P > 0.05$).

When volumes removed to establish initial basal areas and yields from rethinning (McDonald only) were included in total yield,

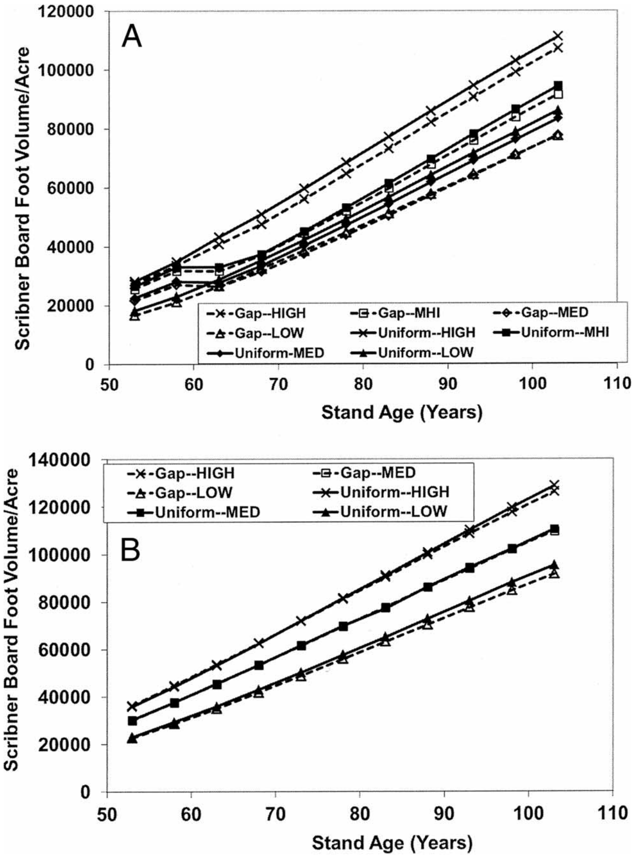

Figure 3. Scribner board foot volume after thinning to various densities with and without 20% of plot areas in gaps for McDonald (A) and Blodgett (B), based on Organon projections.

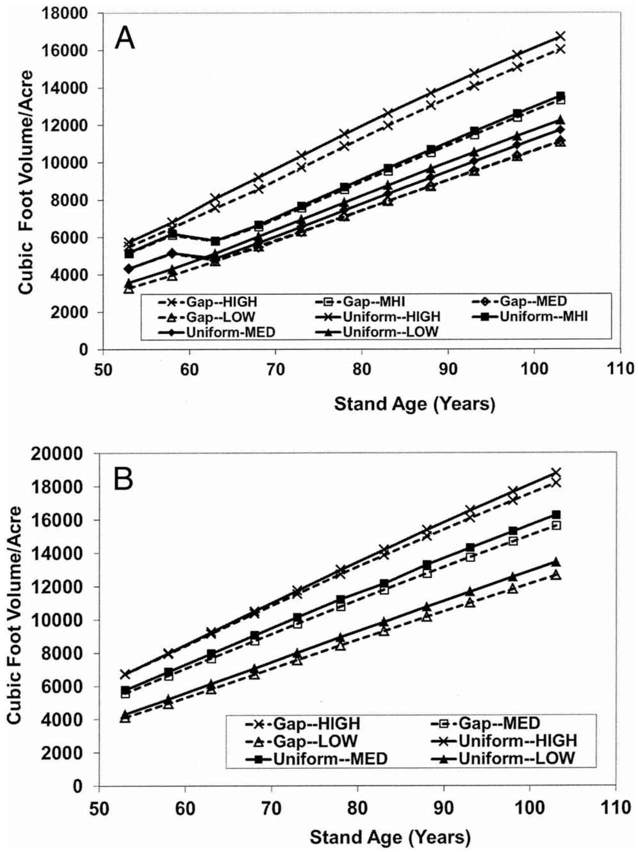

Figure 4. Cubic foot volume after thinning to various densities with and without 20% of plot areas in gaps for McDonald (A) and Blodgett (B), based on Organon projections.

there was relatively little difference between the totals of all increments at both sites, except in the lowest density residual stands, where there was evidence of decreased stand growth through age 103. A small degree (nonsignificant) of divergence with time suggested a slightly greater increment with HIGH residual densities than with LOW, in postthinning curve projections.

In the establishment of the study, removal of volume to calibrate residual stands as uniformly as possible led to differences in removals between uniform and gap treatments and differences in contributions of thinning harvest to total yield between the two sites and two approaches to residual stand distributions. Analysis of covariance evaluating the possible role of correlation between the initial harvest targets and preharvest volumes indicated a nonsignificant relationship of prior stocking on postthinning growth ($P > 0.11$).

The dynamic features of these overstories even with major reductions in canopy with thinning treatments resulted in a relatively steady return of the canopy cover after thinning (Figure 7). Differences in crown cover among densities were significant after thinning and continued to be significant at age 103, based on Organon projections.

Discussion

As expected, differences among the densities of these experimental stands were maintained in projections for 50 years after thinning. Although trends from projections indicated that there might be some differences in growth rates of stands between those with uniform stem distributions and thinning with gaps when growth was projected to age 103, differences were not statistically different. We did not account for yield from plantings or natural regeneration within gaps.

Much has been written describing growth and yield of Douglas-fir-dominated forests (Munger 1911, 1955, Worthington and Staebler 1971, Curtis 1995, Curtis et al. 1998). Curtis (1995) described growth of Douglas-fir in extended rotations as nearing maximum accretion in stands approaching a century in age, and perhaps beyond, possibly reflecting the tendency for low densities in early regeneration to grow to maturity with abundant space to expand, as observed by Tappeiner et al. (1997). Curtis et al. (2007) reported that density control early in the life of a stand offered opportunities for increasing both total yield and size of timber if held for rotations longer than the available data from levels of growing stock studies. Curtis et al. (2007), in summarizing studies of older stands, indicated that culmination of annual increment was apparently later than commonly thought. After "high grading," even-aged Douglas-fir stands ages 50–70 down to 30 trees/acre (tpa), Douglas-fir stands were growing at 1,000 board feet (BF)/acre/year at ages 120–140 (Newton and Cole 1987). Reukema (1961), Williamson (1982) and Williamson and Price (1971) have also shown significant positive growth in released Douglas-fir thinned at ages 70–150. Mean annual increments in all treatments in our study rose at a decreasing rate through age 103, at which time PAI was still projected to be higher than MAI, delaying the onset of maximum MAI by a decade or two beyond projected yields.

One of the prominent features of late-seral habitat is the presence of large trees (Franklin et al. 1986, Tappeiner et al. 1997). All

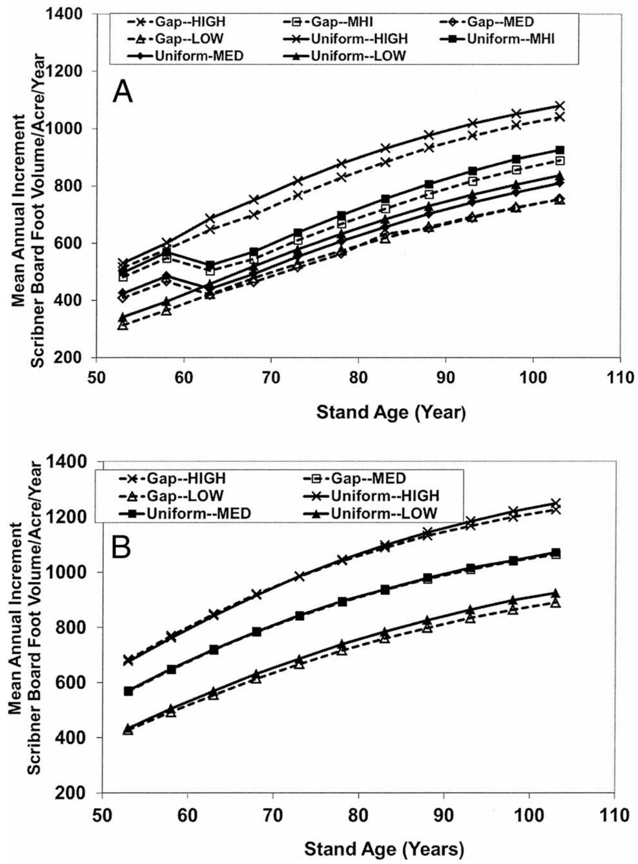

Figure 5. Mean annual increment in Scribner board foot volume after thinning to various densities with and without 20% of plot areas in gaps for McDonald (A) and Blodgett (B), based on Organon projections.

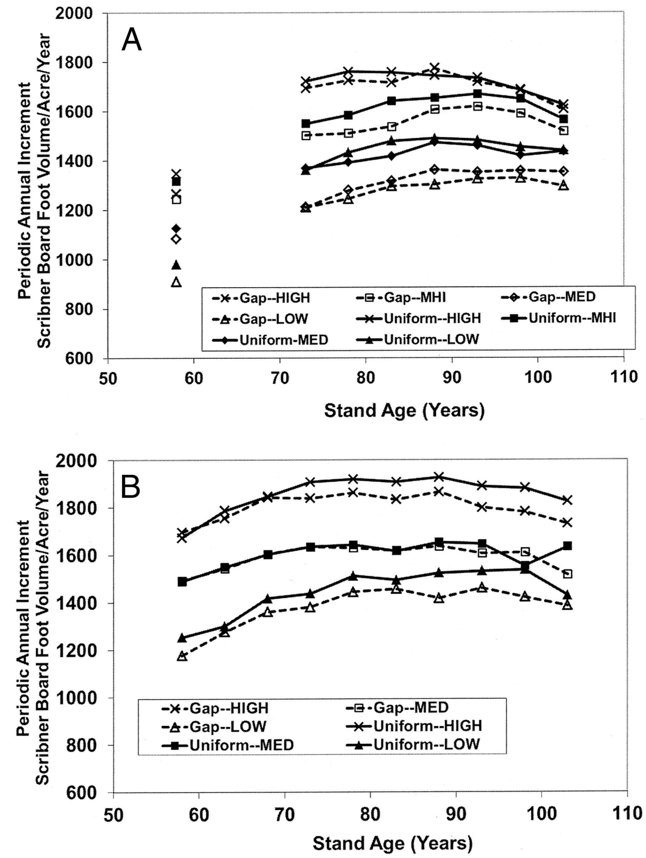

Figure 6. Periodic annual increment in Scribner board foot volume after thinning to various densities with and without 20% of plot areas in gaps for McDonald (A) and Blodgett (B), based on Organon projections.

densities and thinning types already had led to some trees greater than 30-in. dbh by age 65, having increased space available for virtually all preexisting large trees. Although the number of large trees per acre did not differ among the densities, having been thinned from below, the proportions varied at both sites, reflecting the greater number of small trees in the stands of higher densities. At age 100, McArdle et al. (1961) estimated that unthinned site II (site $\text{index}_{100} = 160–180$ ft) stands would have 9 tpa greater than 30 in. and 0 tpa greater than 40 in. at age 100. Our stands at McDonald were projected to have greater than 20 tpa greater than 30 in. and at least 2 tpa greater than 40 in. at age 103. Rather than the 123 tpa in the McArdle et al. (1961) stands, our stands would range from 33 to 66 tpa, resulting in stands with characteristics different from those of the natural, unmanaged stands that McArdle et al. studied. This difference in trees per acre would result in a higher projected periodic annual increment (1,300–1,600 BF/acre/year from our study compared with 900–980 BF/acre/year from McArdle et al. 1961). Projected MAI at age 103 from our study ranged from 750 to 1,080 BF/acre/year among the densities and ranged from 900 to 1,140 BF/acre/year based on McArdle et al. (1961). As with MAI, volume projections ranged from higher to lower than normal yields, and a reduced population of trees would lead to larger average diameters.

Normal yields at 100 years for hemlock-dominant stands (146,000–155,000 Scribner BF/acre) (Barnes 1962) were higher than those predicted at Blodgett, which ranged from 100,000 to 138,000 Scribner BF/acre in the mixed stands of Douglas-fir and hemlock. PAI from our stands ranged from 1,380 to 1,825 Scribner BF/acre/year, whereas stands from Barnes (1962) had PAI of about 800 Scribner BF/acre/year at ages 100–110 after peaking at greater than 3,000 Scribner at age 60. Thus, the short-term gain by hemlock in young mixed stands may be predictable, perhaps declining later when stands were still dominated by Douglas-fir. Barnes (1962) did not provide diameter distributions. Site I (site $\text{index}_{100} = 190–210$ ft) estimates of Douglas-fir diameters from McArdle et al. (1961) indicated that 27 tpa would be greater than 30 in. and 4 tpa would be greater than 40 in. at age 100. The numbers of trees greater than 30 in. at Blodgett ranged from 16 to 20 tpa and less than 2 tpa would be greater than 40 in., which were fewer than projected for McDonald even though the site index was higher at Blodgett. Although trees per acre immediately postthinning was similar between the sites, trees per acre at age 103 was higher for the MED and HIGH densities at Blodgett than at McDonald. That, combined with the proportion of hemlock in the stands, resulted in fewer trees greater than 30 inches. Volumes at Blodgett were higher than at McDonald because of the projected differences in height and greater trees per acre.

The question of leaving openings in which light-demanding species might develop islands of habitat raised the question of whether this affected yields. Our study allocated 20% of plot areas in gaps of 1/6–1/4 acre. Organon projections (Figure 3) indicated that volume in stands with gaps was 1–10% less than volume in stands with uniform thinning when averaged over the blocks. This did not result

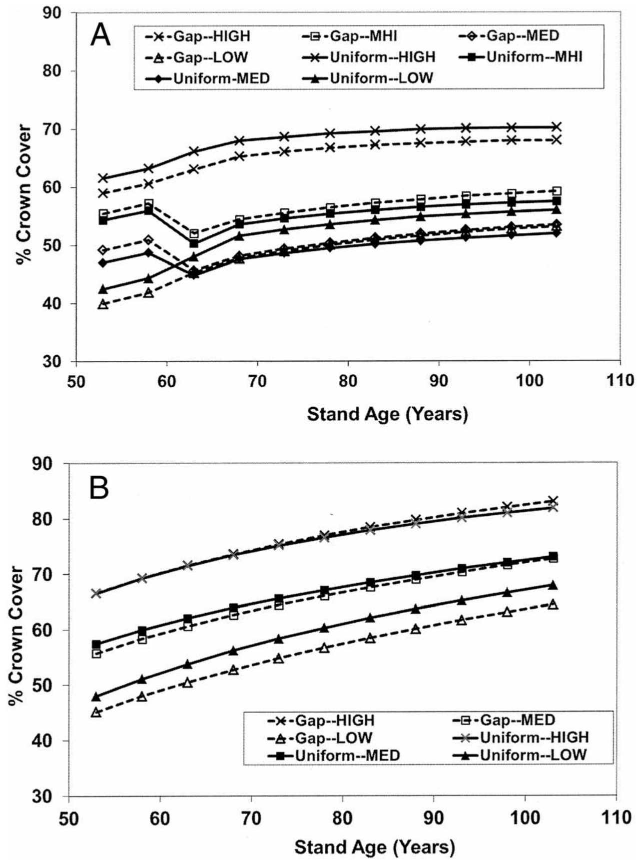

Figure 7. Crown closure after thinning to various densities with and without 20% of plot areas in gaps for McDonald (A) and Blodgett (B), based on Organon projections.

in statistically significant differences even though in most instances, the uniform stands had higher volumes than the corresponding gap stands within a block. However, there were instances when the gap stands had higher volumes than the uniform stands within a block and that variability resulted in the overall effect of gap being nonsignificant. Douglas-fir exhibited greater growth per tree around gaps in previous studies (Davis et al. 2007, Dodson et al. 2012). Growth for the first 5 years after gap creation for a number of western conifer species was at least 10% greater within 33 ft of the gap edge than in surrounding stands (Roberts and Harrington 2008, York and Battles 2008). York and Battles (2008) did not find an effect related to orientation of gaps and trees and speculated that belowground resources and/or stem development to accommodate greater winds was more important than light in explaining the increased growth. The extent to which greater growth around gaps would compensate for the presence of gaps probably depends on gap size, site quality, rotation age, soil, and species.

The recovery of overstory crown cover after thinning of middle-aged stands, as seen here, would reflect the role of shade tolerance in the persistence of released trees. The reduction of crown cover associated with the thinning treatments clearly had an influence on the probability that Douglas-fir seedlings underplanted in these stands would persist and develop substantial crown cover or stratification in understories (Brandeis et al. 2001, Cole and Newton 2009, Shatford et al. 2009, Nabel et al. 2013). Shade-tolerant species, including western hemlock, grand fir, and browse-protected western redcedar can offer possibilities for understory structure. Franklin et al. (1986) considered these species to be essential parts of old-growth structures and their definitions. The extent that the increasing crown cover decreases opportunities for developing understory structure is under investigation (Cole and Newton 2009, Nabel et al. 2013).

In the first 15 years after thinning, the major cause of mortality in these stands has been windthrow, with greater windthrow at Blodgett than at McDonald. Although some windthrow was seen along gap edges, windthrow occurred throughout the stands, and the ratio of windthrow was similar in gap and matrix areas at both sites. Mortality was included in Organon projections. Mortality rates from our stands through 15 years after thinning were within 3% of those projected in Organon, with the exception of mortality after a windthrow event at Blodgett that occurred along exposed edges after an adjacent stand was clearcut. We did not include mortality from this event in model projections. Organon runs of basal area and volume indicated that the shade-tolerant hemlock portion of the Blodgett stands was increasing despite the dominance of large Douglas-fir. Although the overall change was significant, the change in percentage varied only from 57 to 51%. Hemlock trees were affected by windthrow proportionally more than Douglas-fir trees. Windthrow events could eventually affect the long-term species composition in mixed stands.

None of the studies of long-term growth, including this one, have addressed quality considerations for trees widely spaced in early years so as to provide late-seral habitats. Providing very large trees quickly can involve long, broad crowns, the expansion of which entails large knots and hence abundant stem defects (Maguire et al. 1991). Greater space per tree can affect taper, which results in lower board-foot to cubic-foot ratios and therefore lower value per ton. Thus, volume growth, tree dimensions, log quality, and habitat develop simultaneously. The need for these properties to develop together appears to necessitate longer rotations than those with maximum return on investment. The internal rate of return with long rotations is reduced compared with that for short rotations with no thinning, but the total value of products on a per acre per year basis can be very high. There is a need to evaluate wood quality, yield, wood products, economic costs and returns, and habitat to identify the trade-offs when considering managing for late-seral features.

Natural late-seral stands include a component of large snags and downed wood (Franklin et al. 1986). The thinning patterns we investigated here were unlikely to provide large snags until later in the rotation than would be observed in natural stands, unless provisions for large snags (e.g., Brandeis et al. 2002) were made during the thinning process.

Conclusions

Thinning Douglas-fir at ages 50–55 allowed development of some large diameter trees by the age of 65. Projected volume yields to age 103 varied among the densities, with projections for gap stands ranging from 1 to 10% less than those in uniform stands. Differences between gap and uniform stands were not statistically different. The periodic annual increment peaked around ages 60–90, but the mean annual increment was projected to peak beyond age 100. Long rotation even-aged management with thinning provided an option for developing some features of late-seral habitat.

Literature Cited

ANDREWS, L.S., J.P. PERKINS, J.A. THRAILKILL, N.J. POAGE, AND J.C. TAPPEINER II. 2005. Silvicultural approaches to develop northern spotted owl nesting sites, Central Coast Ranges, Oregon. *West. J. Appl. For*. 20(1):13–27.

BARNES, G.H. 1962. *Yield of even-aged stands of western hemlock.* USDA For. Serv., Tech. Bull 1273, Washington, DC. 52 p.

BRANDEIS, T.J., M. NEWTON, AND E.C. COLE. 2001. Underplanted conifer seedling survival and growth in thinned Douglas-fir stands. *Can. J. For. Res.* 31:302–312.

BRANDEIS, T.J., M. NEWTON, G.M. FILIP, AND E.C. COLE. 2002. Habitat development in artificially made second-growth Douglas-fir snags. *J. Wildl. Manage.* 66(3):625–633.

CAREY, A.B., B.R. LIPPKE, AND J. SESSIONS. 1999. Intentional systems management: Managing forests for biodiversity. *J. Sustain. For.* 9(3/4):83–125.

COLE, E.C. 1996. Managing for mature habitat in production forests of western Oregon and Washington. *Weed Tech.* 10(2):422–428.

COLE, E.C., AND M. NEWTON. 2009. Tenth-year survival and size of underplanted seedlings in the Oregon Coast Range. *Can. J. For. Res.* 39:580–595.

CURTIS, R.O. 1982. A simple index of stand density for Douglas-fir. *For. Sci.* 28(1):92–94.

CURTIS, R.O. 1992. A new look at an old question—Douglas-fir culmination age. *West. J. Appl. For.* 7:97–99.

CURTIS, R.O. 1995. *Extended rotations and culmination age of coast Douglas-fir: Old studies speak to current issues.* USDA For. Serv., Res. Pap. PNW-RP-485, Pacific Northwest Forest Research Station, Portland, OR. 49 p.

CURTIS, R.O., D.S. DEBELL, C.A. HARRINGTON, D.P. LAVENDER, J.B. ST. CLAIR, J.C. TAPPEINER, AND J.D. WALSTAD. 1998. *Silviculture for multiple objectives in the Douglas-fir region.* USDA For. Serv., Gen. Tech. Rep. PNW-GTR-435, Pacific Northwest Research Station, Portland, OR. 123 p.

CURTIS, R.O., D.S. DEBELL, R.E. MILLER, M. NEWTON, J.B. ST. CLAIR, AND W.I. STEIN. 2007. *Silvicultural research and the evolution of forest practices in the Douglas-fir Region*. USDA For. Serv., Gen. Tech. Rep. PNW-GTR-696, Pacific Northwest Forest and Range Experiment Station, Portland, OR. 172 p.

DAVIS, L.R., K.J. PUETTMANN, AND G.F. TUCKER. 2007. Overstory response to alternative thinning treatments in young Douglas-fir forests of western Oregon. *Northw. Sci*. 81(1):1–14.

DODSON, E.K., A. ARES, AND K.J. PUETTMANN. 2012. Early responses to thinning treatments designed to accelerate late successional forest structure in young coniferous stands of western Oregon, USA. *Can. J. For. Res*. 42:345–355.

FRANKLIN, J.F., F. HALL, W. LAUDENSLAGER, C. MASER, J. NUNAN, J. POPPINO, C.J. RALPH, AND T. SPIES. 1986. *Interim definitions for old growth Douglas-fir and mixed-conifer forests in the Pacific Northwest and California*. USDA For. Serv., Res. Note 447, Pacific Northwest Forest and Range Experiment Station, Portland, OR. 5 p.

HANN, D.W. 2005. *ORGANON user's manual*, ed. 8.0. Oregon State University Department of Forest Resources, Corvallis, OR. 129 p.

MAGUIRE, D.A., J.A. KERSHAW, AND D.W. HANN. 1991. Predicting the effect of silvicultural regime on branch size and crown wood core in Douglas-fir. *For. Sci.* 37:1409–1428.

MCARDLE, R.E., W.H. MEYER, AND D. BRUCE. 1961. *The yield of Douglas-fir in the Pacific Northwest*. USDA For. Serv., Bull. 201, Washington, DC. 72 p.

MCCOMB, W.C., T.A. SPIES, AND W.H. EMMINGHAM. 1993. Douglas-fir forests: Managing for timber and mature-forest habitat. *J. For.* 91(12): 31–42.

MUNGER, T.T. 1911. *Growth and management of Douglas-fir in the Pacific Northwest*. USDA For. Serv., Circ. 195, Washington, DC. 34 p.

MUNGER, T.T. 1955. Fifty years of research in the Pacific Northwest. Portland, OR. *Ore. Hist. Q*. 56(3):236–247.

NABEL, M.R., M. NEWTON, AND E.C. COLE. 2013. Abundance of natural regeneration and growth comparisons with planted seedlings 10–13 years after commercial thinning in 50-year-old Douglas-fir, Douglas-fir/western hemlock, Oregon Coast Range. *For. Ecol. Manage*. 292:96–110.

NEWTON, M., AND E.C. COLE. 1987. A sustained-yield scheme for old-growth Douglas-fir. *West. J. Appl. For.* 2(1):22–25.

NEWTON, M., AND E.C. COLE. 2006. Harvesting impacts on understory regeneration in two-storied Douglas-fir stands. *West. J. Appl. For.* 21:14–18.

REUKEMA, D.L. 1961. *Response of individual Douglas-fir trees to release*. USDA For. Serv., Res. Note 208, Pacific Northwest Forest and Range Experiment Station, Portland, OR. 4 p.

ROBERTS, S.D., AND C.A. HARRINGTON. 2008. Individual tree growth response to variable-density thinning in coastal Pacific Northwest forests. *For. Ecol. Manage*. 225(7):2771–2781.

SHATFORD, J.P.A., J.D. BAILEY, AND J.C. TAPPEINER. 2009. Understory tree development with repeated stand density treatments in coastal Douglas-fir forests of Oregon. *West. J. Appl. For*. 24(1):11–16.

TAPPEINER, J.C., D. HUFFMAN, D. MARSHALL, T.A. SPIES, AND J.D. BAILEY. 1997. Density, ages and growth rates in old-growth and young-growth forests in coastal Oregon. *Can. J. For. Res.* 27:638–648.

THOMAS, J.W., J.F. FRANKLIN, J. GORDON, AND K.N. JOHNSON. 2006. The Northwest Forest Plan: Origins, components, implementation experience and suggestions for change. *Conserv. Biol.* 20:277–287.

US CONGRESS. 1937. *Public Law No. 405.* Oregon and California Revested Railroad Lands Act, approved by the 75th Congress, Aug. 28, 1937.

WILLIAMSON, R.L. 1982. *Response to commercial thinning in a 110-year-old Douglas-fir stand*. USDA For. Serv., Res. Pap. PNW-296, Pacific Northwest Forest and Range Experiment Station, Portland, OR. 18 p.

WILLIAMSON, R.L., AND F.E. PRICE. 1971. *Initial thinning effects in 70 to 150-year-old Douglas-fir—Western Oregon and Washington.* USDA For. Serv., Res. Pap. PNW-117, Pacific Northwest Forest and Range Experiment Station, Portland, OR. 21 p.

WORTHINGTON, N.P., AND G.R. STAEBLER. 1971. *Commercial thinning of Douglas-fir in the Pacific Northwest*. USDA For. Serv., Tech. Bull. 1230, Washington, DC. 124 p.

YORK, R., AND J. BATTLES. 2008. Growth response of mature trees versus seedlings to gaps associated with group selection management in the Sierra Nevada, California. *West. J. Appl. For.* 23(2):94–98.