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Silvicultural Treatments for Enhancing Tree Value, Vigor, and Growth in 70- to 120-Year-old Stands Dominated by Noble Fir on the Warm Springs Indian Reservation:

A Synthesis of the Literature

by

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Forest Research Laboratory
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Executive Summary

This report summarizes existing knowledge about potential silvicultural treatments for enhancing tree value, vigor, and growth in dense, 70- to 120-year-old, upper-elevation, mixed-conifer forests on the Warm Springs Indian Reservation (WSIR). The primary focus of this review is on noble fir. Treatments considered include thinning, fertilization, and pruning.

There are three reasons for interest in treating such stands at this time:

- Thinning and associated treatments may generate larger-diameter, higher-value trees in the future.
- Thinning may improve tree and stand vigor and increase resistance to insect and disease pests, although such entries must be balanced against damage resulting from logging.
- Thinning will provide an immediate source of wood supply that could be used to reduce the rate of harvest of old-growth stands.

The following statements highlight findings that are presented in greater detail in the report:

1. No experiments were located that specifically addressed the response of this age of noble fir stands to density management or other silvicultural treatment. There is increasing interest in noble fir silviculture, but most research is relatively new and focused on younger stands.
2. Results from a limited number of thinning studies conducted in 100-year-old stands of Douglas-fir and other true firs document that enhanced diameter growth can occur when additional growing space is provided to selected crop trees. These results seem sufficiently positive to encourage further experimentation with local responses to silvicultural treatments by noble fir stands on the WSIR. In general, existing studies have focused on volume responses to practices, not on changes in value associated with treatment.
3. Little is known about root diseases and stem decay in these upper-elevation, mixed-conifer forests, particularly in managed stands where stem wounds and root damage may result from harvest entries. While noble fir appears to be more resistant to stem decay than other true fir species, it probably is not as resistant as more resinous species such as Douglas-fir. Interactions between stand management and disease require further research to better understand their effect on the vigor and value of residual trees, particularly in situations where stands may be managed for prolonged periods after treatment (i.e., longer rotations).
4. References in the literature state that noble fir is not a preferred host of the western spruce budworm. Therefore, thinning to improve stand resistance to budworm may be most beneficial in mixed-species stands where Douglas-fir and other true firs are likely to receive greater benefits from improved tree vigor.
5. Published mensurational information on noble fir, particularly on managed stands, is limited. This lack of data brings into question the reliability of tools used for description of current stand characteristics and prediction of future stand development. Informational needs are identified.

Executive Summary

Introduction

This literature review evaluates existing knowledge about silvicultural treatments to enhance residual tree value, vigor, and growth in 70- to 120-year-old mixed-conifer forests growing within the Pacific Silver Fir zone on the east slope of the Cascade Mountains. The Warm Springs Indian Reservation (WSIR) contains about 30,000 acres of naturally regenerated, largely unmanaged stands in this category, with species composition varying from nearly pure noble fir to mixtures of noble fir with Douglas-fir and some components of Pacific silver fir and western hemlock. The stands occur on reasonably productive sites, and large standing volumes can be found in undisturbed, adjacent, old-growth stands that are probably 200 to 400 years old. The primary focus of this review is on noble fir. Treatments considered include thinning, fertilization, and pruning.

There are three reasons for interest in treating such stands at this time:

- Thinning and associated treatments may generate larger-diameter, higher-value trees in the future.
- Thinning may improve tree and stand vigor and increase resistance to insect and disease pests, although such entries must be balanced against damage resulting from logging.
- Thinning will provide an immediate source of wood supply that could be used to reduce the rate of harvest of old-growth stands.

Framework for Evaluation

Several issues underlie this focus on growth, health, and value.

Growth

Two assumptions are key here: (1) Larger-diameter logs are more valuable; therefore, a goal of silvicultural activities is to generate large-diameter trees by thinning, which provides fewer selected crop trees with greater proportions of site resources. (2) Thinning of trees of merchantable size provides an opportunity to utilize growth on trees that will die as a result of competition, thus increasing total wood yield from the stand.

Thinning in older stands to produce large-diameter trees can result in less total stand growth than would strategies that maintain higher numbers of smaller-diameter trees. Such a result could occur because the site was not fully occupied; removal of trees in stands of this age often leaves canopy openings that are larger than remaining trees can efficiently occupy. Therefore, the criteria used to evaluate the success of silvicultural treatments must be sensitive to the management objectives; fiber production and value production are different issues. The latter is the primary focus in this review.

Observations in some of the stands on the WSIR show that substantial crown recession has occurred on many noble fir, raising concerns about the ability of these trees to respond after thinning. Since adequate energy is required for trees to add stem diameter growth, the ability of trees to increase crown size after thinning will be important. This increase is normally accomplished by height growth or additional leaf mass on lateral branches. Understanding the height growth pattern of noble fir over time will be key to this evaluation. If height growth is relatively slow at advanced ages, treatments such as fertilization in conjunction with thinning may increase the leaf biomass on the trees.

Forest Health

There appear to be two issues to consider. (1) Stand density management to increase resistance of stands to insect attack may be beneficial, but perhaps not sufficiently so to offset the expense of increasing disease problems associated with logging damage. In addition, noble fir is apparently not a preferred host of the spruce budworm, in contrast to the substantial defoliation observed in Douglas-fir and other true firs. Therefore, density management is more likely to improve the resistance of mixed-species stands rather than pure noble fir stands to budworm attack. (2) Site-specific issues such as wind patterns have been observed to be important in some situations. Windthrow can be serious, especially where root disease is prevalent.

Value

Among the old-growth noble fir now commanding such high value on the export market, key characteristics are large diameter, fine grain (uniform, slow diameter growth), and lack of external knots. Observations show that noble fir branches are retained for some time after they die and that, although branch diameters are often not large, little clear (i.e., knot-free) wood is being produced by ages 70 to 120. If pruning of the dead branches is considered, a key issue would be the rate of branch stub occlusion; this healing process is a function of the rate of diameter growth and branch size. Diameter growth is not likely to be very rapid on these larger-diameter trees under the best of spacing regimes, and rapid diameter growth is not necessarily desirable to log graders for the export market.

Growth and Yield

Critical to our ability to develop and evaluate management regimes for these noble fir-dominated forest types will be the availability of data on growth and yield. Most information on the growth and yield of managed noble fir stands has come from European plantation management (Aldhous and Low 1974; Edwards and Christie 1981). Little information is available on potential yields from managed stands of this type in the Pacific Northwest; therefore, existing growth models appear to have limited capability to reliably predict response of stands to treatments over time.

There are three variants of the PROGNOSIS model that could have applicability to the WSIR forests: (1) the Southern Oregon/Northeast California (SORNEC) variant, (2) the Eastern Cascades (EC) variant, and (3) the new West Cascades (WC) variant (Figure 1). The species processed by the SORNEC and EC variants are shown below:

	SORNEC	EC
Western white pine	X	X
Sugar pine	X	
Ponderosa pine	X	X
Lodgepole pine	X	X
Western larch		X
Douglas-fir	X	X
Grand fir		X
White fir	X	
Subalpine fir		X
Silver fir		X
Red fir	X	
Engelmann spruce	X	X
Mountain hemlock	X	
Western redcedar		X
Incense cedar	X	

Neither of these variants includes noble fir (William R. Wykoff, personal communication, USDA Forest Service, Moscow, ID). Preliminary versions of the WC variant include diameter growth functions for all of these species and noble fir. The noble fir growth functions were developed from 1,555 observations, primarily from the Willamette and Mt. Hood National Forests in the 3,000- to 6,000-ft elevation range (George Lightner, personal communication, USDA Forest Service, Portland, OR).

The only published mensurational study on noble fir in the Pacific Northwest reported on the development of site curves for the Cascade Mountains (Herman *et al.* 1978). Data were collected by using stem analysis from stands located near Stevens Pass, Washington, south to McKenzie Pass, Oregon. The authors sampled 60 trees ranging from 10 to 260 years of age and from 60 to 180 ft in site index at 100 years.

Harrington and Murray (1982) compared height growth of true firs with that of Douglas-fir in Washington and found that Douglas-fir generally grew better than noble fir on higher-quality Douglas-fir sites but that noble fir grew better on poor-quality Douglas-fir sites. They also found that noble fir performed relatively better as age increased, as is borne out in our comparisons of published data on noble fir and Douglas-fir (Figures 2 and 3). Our comparisons in Figure 2 were made with King's (1966) Douglas-fir site curves for western Washington, for which about 90 percent of the data were collected at elevations of less than 2,000 ft. The Curtis *et al.* (1974) site curves for Douglas-fir at

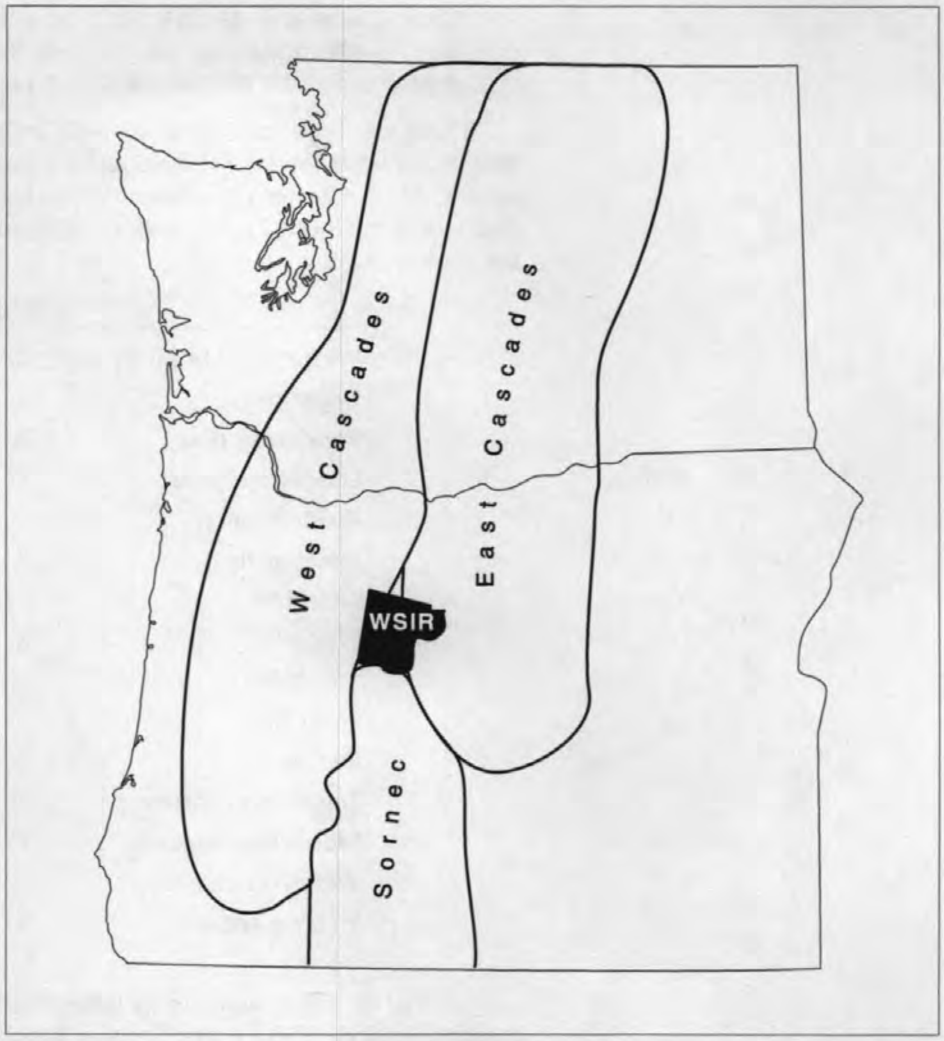

Figure 1. Approximate range of applicability of the three variants of the PROGNOSIS model. Note location of WSIR.

higher elevations show slower juvenile height growth but more prolonged height increment after 100 years (Figure 3). When we compared published data on height growth of site trees from high-elevation stands of Douglas-fir and noble fir, we found that growth at higher elevations is more comparable for the two species (Figure 3). While noble fir grows slower than Douglas-fir at young ages on high- and medium-quality sites, the two species grow similarly at older ages. On lower-quality sites, the two species grow similarly at young ages, but noble fir grows better at older ages.

No published tree-volume or taper equations are available for noble fir (Hann 1994), although its high form factor is well known (Franklin 1982). Its cylindrical shape allows noble fir trees of a given diameter and height to produce greater volumes than can any of the species associated with it.

In spite of slow juvenile growth, the long-term productivity of noble fir may be superior to that of Douglas-fir at upper elevations (Harrington and Murray 1982). When nine plant associations in the Pacific Silver Fir zone were analyzed on the Mt. Hood and Willamette National Forests, the site indexes for Douglas-

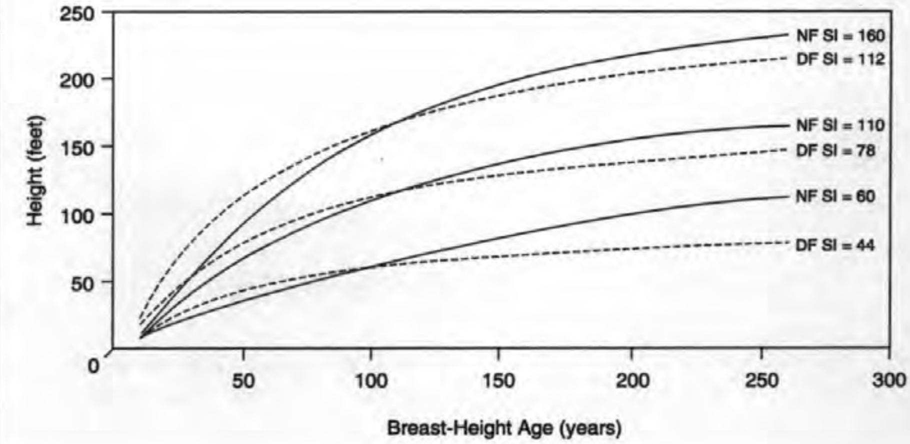

Figure 2. Comparison of site index (SI) curves for noble fir (NF) on a 100-year base (Herman et al. *1978) with those for Douglas-fir (DF) at lower elevations on a 50-year base (King 1966).*

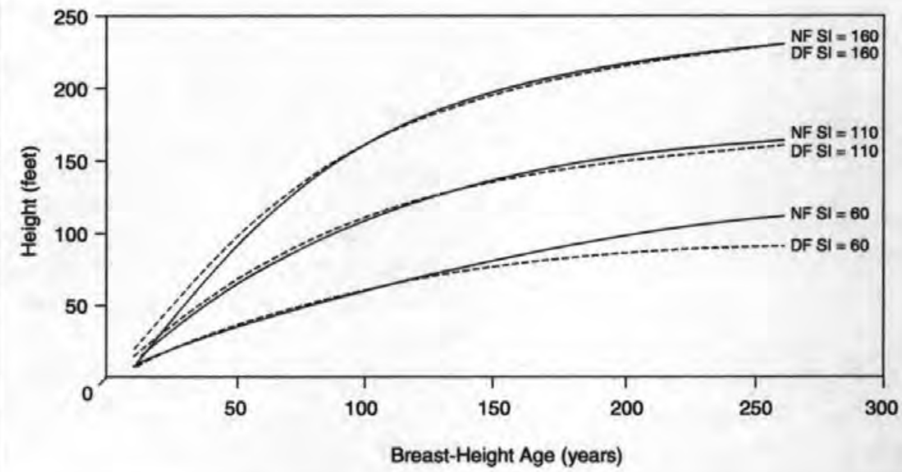

Figure 3. Comparison of site index (SI) curves for noble fir (NF) (Herman et al. *1978) with those for Douglas-fir (DF) at higher elevations (Curtis* et al. *1974).*

fir and noble fir were equivalent in one association, the average site index of noble fir had a 10-ft superiority at 100 years in five of the associations, and it was only 2 ft lower on two others (Hemstrom *et al.* 1982). In another mature stand in northern Oregon, Douglas-fir and noble fir each comprised 20 percent of the individuals in the stand, but noble fir contributed 46 percent of the volume while Douglas-fir contributed 24 percent (Hanzlik 1925). At yet another stand on a site class III area, average diameter at breast height (dbh) of noble fir became larger than that of Douglas-fir at age 120 years (Hanzlik 1925).

On seven sites where site indexes for Douglas-fir and noble fir were both high and nearly equivalent and where stand age was 68 to 160 years, actual volume of noble fir was from 10 to 51 percent greater in board feet/acre than the volume predicted from yield tables for Douglas-fir of the same age. On five of the sites, average dbh for Douglas-fir was greater than that of noble fir, but, because of more trees/acre, basal area for noble fir averaged 31.7 percent more. On one site, in spite of noble fir having 16 percent less basal area than Douglas-fir, noble fir volume was still 32 percent greater because of its superior form (Franklin 1982).

Thinning Studies in Older Stands

No published studies on thinning in older noble fir stands were located in our literature review. Several studies addressing other related species, including Douglas-fir, may be relevant.

Other True Firs

Perhaps the most relevant existing information comes from a thinning study installed in a 100-year-old true fir stand in northern California (Oliver 1988). A stand dominated by California red fir, a close relative of noble fir, was thinned from a control basal area of 367 ft^2/acre to several densities including 260, 230, 200, 170, and 140 ft^2/acre of residual basal area (Table 1). The response to thinning was significant within the first 10 years; a negative, nearly linear relationship was found between residual basal area and periodic annual increment (PAI) in dbh (Table 2, Figure 4). The most heavily thinned plot had an average dbh growth of 0.32 in./year while control plots averaged 0.12 in./year. Figure 4 suggests that dbh increment could be even greater at a lower basal area. The annual basal area increase was approximately 4.6 ft^2/acre for all plots. Mean height growth ranged from 1.1 ft/year in the most heavily thinned plots down to 0.3 ft/year in unthinned plots. Total net volume growth was greatest in the unthinned plots (321 ft^3/acre/year) and least in the most heavily thinned plots (196 ft^3/acre/year); however, the differences in net volume growth were insignificant for plots whose residual basal area was 200 ft^2/acre and above.

Table 1. Stand characteristics before and after thinning a California red fir and California white fir sawtimber stand in northeastern California [Source: Oliver (1988); reproduction courtesy of USDA Forest Service.]

Targeted basal area (ft^2/acre)	Before thinning: Trees (Avg. No./acre)	Before thinning: Avg. dbh (in.)	Before thinning: Avg. basal area (ft^2/acre)	After thinning: Trees (Avg. No./acre)	After thinning: Avg. dbh (in.)	After thinning: Avg. height (ft)	After thinning: Live crown (%)	After thinning: Avg. basal area (ft^2/acre)	Volume: Total[1] (ft^3/acre)	Volume: Merch.[2] (bd ft/acre)
140	616	10.3	350	48	23.3	102	56	142	5,256	28,914
	498	11.8	368	44	23.9	104	57	137	5,376	28,100
170	612	9.8	320	118	16.3	81	57	170	5,300	27,476
	380	13.0	335	66	21.7	100	52	170	6,186	33,106
200	398	12.4	326	142	16.3	85	50	205	6,765	30,826
	306	15.2	355	72	22.7	102	52	202	8,408	40,553
230	518	11.4	364	114	19.5	87	46	236	8,180	45,098
	570	10.3	325	120	18.7	88	53	230	7,813	40,472
260	412	15.2	498	122	19.7	92	38	259	9,924	49,770
	478	12.5	406	160	17.4	84	46	263	8,870	45,054
Unthinned	452	12.1	367	452	12.1	60	38	367	10,520	45,838
	344	13.9	363	344	13.9	60	34	363	10,246	58,984

[1]Total stem volume from stump to tip inside bark.

[2]Board feet (Scribner) for trees 10 in. and larger to a 6-in. top inside bark.

Table 2. Annual increments for 10 years after thinning a California red fir and white fir sawtimber stand in northeastern California [Source: Oliver (1988); reproduction courtesy of USDA Forest Service.]

Targeted basal area (ft^2/acre)	Annual increment						
	Dbh[1] (in.)	Height[1] (ft)	Basal area (ft^2/acre) Gross	Basal area (ft^2/acre) Net	Total volume[2] (ft^3/acre) Gross	Total volume[2] (ft^3/acre) Net	Merchantable net volume[3] (bd ft/acre)
140	0.31	1.1	4.1	4.1	202	202	1,452
	0.32	1.1	3.9	3.9	189	189	1,404
170	0.23	0.8	5.1	4.2	213	183	1,102
	0.30	0.7	5.0	5.0	243	243	1,454
200	0.24	0.8	6.4	6.3	273	270	1,594
	0.28	0.7	4.8	2.7	243	164	1,084
230	0.20	0.8	5.0	4.7	293	285	1,654
	0.22	0.9	5.7	5.5	277	272	1,776
260	0.18	0.6	4.9	4.4	331	316	1,480
	0.20	0.7	6.1	5.0	337	318	1,606
Unthinned	0.12	0.3	6.9	3.7	344	264	1,424
	0.12	0.3	6.7	5.7	399	378	1,874

[1]Trees living through period.

[2]PAI in ft^3 from stump to tip inside bark.

[3]PAI in board feet (Scribner) for trees 10 in. dbh and larger to a 6-in. top inside bark.

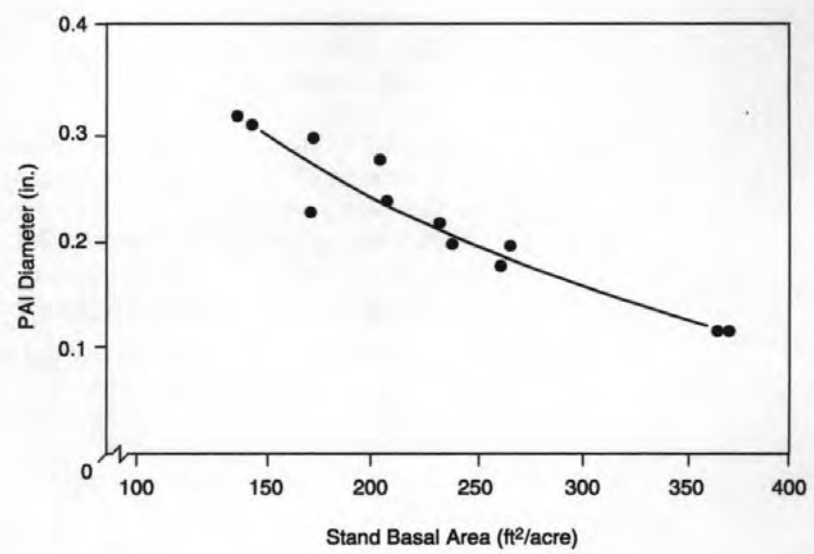

Figure 4. Periodic annual diameter increment in relation to stand basal area after thinning for a young sawtimber stand of true firs in northeastern California. [Source: Oliver (1988); reproduction courtesy of USDA Forest Service.]

Results of the study by Oliver (1988) indicated that stand density had little influence on height growth of crop trees. Thinning heavily from below—leaving only about 50 percent of the original basal area—resulted in little loss in net production but substantially increased diameter increment on residual crop trees. Oliver was cautious about such severe thinning unless healthy, full-crowned trees can be selected for reserves; he expressed concern about possible storm damage in windy sites. For diameter increments of 0.32 in./year, the most widely spaced trees had radial growth of about 6 rings/in., a rate that meets most standards for high-value logs. Oliver also reported on some unpublished studies with white fir in northern California, where stands 60 and 75 years old were thinned to 40, 55, and 70 percent of normal basal area as shown in Schumacher's (1926) yield tables. After 5 years of growth, no significant loss in net volume production was observed for any of the stand density treatments.

Regimes for stand density management of white and grand fir have been studied extensively. While we could locate no specific studies that addressed thinning regimes in older stands, Cochran and Oliver (1988) have demonstrated that stands of these species can produce large amounts of wood if heavily thinned from below. For example, they found that white and grand fir stands managed at 75 percent of normal density produced 93 percent of the gross periodic annual cubic volume of fully stocked stands and that those managed at 50 percent of normal produced 80 percent of the full stocking increment. One difference between these species and noble or red fir may be the ability of the former to maintain more leaf area while growing under shaded conditions. The presence of a larger crown may be an advantage in promoting increased diameter growth after thinning in older stands; however, both grand and white fir are noted for a period of thinning shock as they produce new needles better adapted to a more exposed environment.

In 1973, a thinning study was installed by Weyerhaeuser Company in south-central Oregon in a 50-year-old dense, natural white fir stand (Heninger 1982). A key here is that this was a very dense sapling-size stand. Although this effort did involve thinning in an older stand, results may not be of direct relevance to the older, primarily pole-size or larger noble fir stands of primary interest here. A possible exception, however, is the short-term rate of growth response. After 5 years, plots thinned from nearly 2,700 stems/acre down to 1,000 or 475 or 160 stems/acre responded with the following diameter and basal area growth: 0.05 in./year and 5.43 ft^2/acre/year for controls; 0.1 in./year and 4.56 ft^2/acre/year for the lightest thinning; 0.14 in./year and 4.35 ft^2/acre/year for the medium-density thinning; and 0.18 in./year and 3.61 ft^2/acre/year for the heaviest thinning. Fertilization at the time of thinning substantially boosted both diameter and volume response in the first 5 years over thinning alone.

In northern Idaho, well-stocked vigorous stands of grand fir were studied over a range of sites, ages, and stand densities that included thinning to 15 x 15 ft (Olson and Hatch (1982). Volume growth over the first 2 years was slightly less than that which a model would predict if no thinning were done on those sites. The reduction was, presumably, a result of thinning shock. Volume growth measured in the fourth, sixth, and eighth years after treatment was 14, 22, and 26 ft^3/acre/year greater than that predicted for untreated stands. When 200 lb/acre of nitrogen were applied at the time of thinning, volume growth peaked in the third or fourth year and then remained stable, averaging 56 ft^3/acre/year from the third through the eighth year. The authors did not discuss any age-related response; thus, it is difficult to determine if any older stands were thinned in this study.

Douglas-Fir

Several thinning studies have been initiated in older Douglas-fir stands. These studies may be relevant because some of the stands on the Warm Springs Indian Reservation have significant components of Douglas-fir and because the results may also help corroborate information from the true fir studies. Seven stands in the Oregon and Washington Cascades were thinned at ages between 68 and 110 (Williamson and Price 1971). Strategies ranged from low to crown thinnings, with densities reduced to as little as 50 percent of normal basal area. All of these plots have been abandoned for many years, but, if reconstructed, they represent a potential opportunity to obtain nearly 40 to 60 years of data on post-thinning behavior. Unfortunately, Williamson and Price (1971) focus on traditional growth-response variables and do not include such information as change in diameter over time.

These authors report that the relative increase in basal area after thinning was affected not by thinning intensity or residual basal area but rather by differences in the age of the stands when they were thinned (the older stand had less basal area increase). As stand age increased, growth declined. Thinnings from below primarily benefitted trees in lower crown classes, while crown thinnings primarily benefitted larger trees. Losses to windthrow and bark beetles were substantially reduced in thinned stands. The authors conclude that foresters can vary growing stock from 60 to 90 percent of normal and still obtain near-maximum utilization of sites by residual trees. They recommend that initial thinnings in older stands be concentrated on codominant and dominant trees whose removal will relieve clumpy conditions and provide release to better codominants and dominants.

Williamson (1982) reported on a remeasurement of a stand 19 years after it was thinned at 110 years old. He found that gross volume growth in the thinned plots over time was only slightly below that of the controls. Mortality, however, was much greater in the unthinned plots, i.e., more than 5 times greater than in the heavily thinned plots. This factor amounted to 86 percent of gross growth in the control plots and to only 20 to 30 percent of that in the thinned plots. In the control plots, mortality resulted in large unstocked openings as opposed to scattered trees. Net growth therefore was much less than normal in the control plots, but it was 119 and 136 percent of normal in the lightly and heavily thinned stands, respectively.

In the stand remeasured by Williamson (1982), 25 percent of what would be considered normal stocking for that site index was removed in the lightly thinned plot and 50 percent in the heavily thinned plot. The thinnings removed trees in all crown classes, but efforts were made to retain the most vigorous dominants and codominants. To take into account differences among the plots in stocking and site index, Williamson (1982) considered the dependent variable to be the ratio of gross volume growth on the plot during the previous 19 years to that which should have occurred on a fully stocked stand having the same site index. When adjusted for the differences in original stocking levels and site index, the thinned plots had the same increase in gross volume as the controls over the 19-year period.

In each of the studied plots, some trees were sectioned by stem-analysis techniques. This analysis revealed that the ratio of volume growth during the previous 19 years to the volume growth for the 19 years prior to thinning was 30 percent greater in the heavily thinned plots than in the controls, while it was

8 percent greater in the lightly thinned plots than in the controls. At both thinning levels, all crown classes showed greater response than did the controls. Growth response in all crown classes was greatest in the heavily thinned plots where the ratios were about 1 for the dominants, codominants, and intermediates and 1.23 for the suppressed trees (i.e., the heavy thinning benefitted all crown classes, but it benefitted the suppressed trees more than the others).

Thus, thinning in these stands salvaged trees that would have died in the future and also stimulated a meaningful growth response in the residual trees. Further investigation of the original stand records is necessary to clarify the change in individual tree diameters as a function of growing space after 19 years.

Unpublished Administrative Studies

We have yet to locate any unpublished studies focusing on managed stands of noble fir in this older age class. All of the existing research plots in managed stands in Oregon and Washington have been established in younger stands. In the past, a few older stands dominated by noble fir have been managed by thinning on the Willamette, Mt. Hood, and Gifford Pinchot National Forests; however, recent harvests, personnel changes, and poor documentation have made these stands difficult to find. Nevertheless, opportunities apparently exist for these stands to be studied by retrospective techniques as they are relocated.

A substantial number of permanent plots exist in older unmanaged stands (J. Franklin, University of Washington, personal communication). While such plots constitute a valuable source of ecological information about noble fir over time, they are of little relevance to this report.

Pruning Studies

In recent years, pruning has received increased attention throughout the world because of the recognition that second-growth, fast-grown plantations will not provide much clear, knot-free wood. No published studies of pruning in older noble fir stands were located. Most of the focus has been on radiata pine and Douglas-fir, and the prevailing strategy is to prune green branches at young ages to minimize the knotty core to about 4 in. in diameter. Pruning the butt log in older noble fir stands would be unconventional in that it would remove primarily dead limbs that had not self-pruned. A rule of thumb is that 2 in. of radial diameter growth is required before (1) the branch stub is completely healed over and (2) grain distortion in the wood is eliminated such that high-grade veneer is being produced (e.g., see Cahill *et al.* 1986). Depending on the cost of pruning, the time available until final harvest, and log grades and wood values, such practices may or may not be appropriate.

We might speculate about the potential to produce clear wood in light of the previously noted thinning studies. Using the diameter growth rates for red fir thinned to various basal areas, we can roughly estimate the time required before branch stubs are healed over. Thinning to 140 ft^2 of basal area produced diameter growth rates in the next 10 years of about 0.32 in./year (i.e., about 6 rings/in. of radial growth) as opposed to about 0.12 in./year (i.e., about 17 rings/in. of radial growth) in the unthinned control. The red fir trees averaged about 12 in. dbh at 100 years when thinned. The thinned plots would require about 13 years to grow 4 in. in diameter and begin producing clear wood at about 16 in. dbh. In contrast, the unthinned plots would take about 34 years. If density management could maintain the diameter growth rates noted above, a 4-in. rind of clear wood might be produced in an additional 25 years, at a dbh of 24 in. It appears that, without thinning, a similar clear rind would take nearly 80 years to produce.

We do not know if these assumptions are realistic for older noble fir stands on the WSIR, but we may gain some initial insight by reviewing continuous forest inventory (CFI) plots and looking at diameter increment as a function of stand density. The key is the diameter growth rate. Better information would be generated over the long term by establishing a set of thinning (density) and fertilization trials on the WSIR.

Fertilization Studies

Limited research has been conducted on fertilization of older noble fir stands. Powers (1992), however, has conducted several experiments with fertilization of true fir stands in California, including at least one red fir stand 75 years old. In general, he concludes that subalpine sites are nutrient-limited, specifically for nitrogen and possibly for phosphorous. Improved growth of up to 80 percent has been observed in some stands with fertilization (Powers 1981).

In Powers' studies, fertilization response was related to tree size. Trees up to about 10 in. responded strongly to fertilization. Somewhat poorer response was observed for trees with larger average diameters. Results showed that response to fertilizer was greater with 200 than with 400 lb/acre, apparently because the greater amount of fertilizer damaged the fine root mass near the soil surface in these high-elevation forests. The interaction between thinning and fertilization appears complex in true fir because, when large, these trees cycle large amounts of nutrients internally; therefore, efficient use of fertilizer requires that crowns have adequate room for expansion so that the added nutrients can be added to the internal nutrient pool.

For true fir in California, Powers (1992) stated that an "ideal" low-risk, economical opportunity for fertilization would be to select a stand with an 8- to 10-in. dbh, thin it to 150 ft^2/acre of basal area, and apply no more than 270 lb/acre of nitrogen along with an equal amount of phosphorous. Although this generalization would appear to fit some stands on the WSIR, nutrient status of local soils should be determined first and economic assumptions used by Powers should be reevaluated in light of local, current conditions.

Disease Studies

Of all the true fir species in the Pacific Northwest, noble fir is supposedly one of the least affected by diseases, especially root and stem decays. Noble fir is listed as "moderately damaged" by the major root pathogens: *Armillaria ostoyae, Phellinus weirii,* and *Heterobasidion annosum* (Hadfield *et al.* 1986). "Moderately damaged" species can be infected when grown in close association with "highly damaged" species. They usually undergo more butt decay than mortality when infected. Indeed, they are seldom seriously damaged if they are not growing in association with the "highly damaged" species.

Most of these observations are from unentered or lightly harvested stands; susceptibility of noble fir to root disease in intensively managed stands is largely unknown. In a study in southern Washington, precommercial thinning of mixed noble fir and Douglas-fir stands did not increase mortality of crop trees (including noble fir) infected by *A. ostoyae* after 10 years (G.M. Filip and D.J. Goheen, in preparation). Other minor root pathogens reported on noble fir include *Phaeolus schweinitzii, Inonotus tomentosus, Perenniporia subacida,* and possibly *Amylostereum chailletii* (Hepting 1971). The USDI Bureau of Indian Affairs (BIA) is collaborating with the Forest Pest Management units of the USDA Forest Service in Portland and Bend to re-examine and monitor the CFI plots on the WSIR for root disease incidence and severity (E. Goheen, personal communication, USDA Forest Service, Portland, OR).

Noble fir is susceptible to several species of stem decay fungi including Indian paint fungus (*Echinodontium tinctorium*), *Phellinus pini, P. robustus, Oxyporus nobilissimus,* and *Fomitopsis pinicola* (Hepting 1971; Filip and Schmitt 1990). Although *H. annosum* is a serious cause of stem decay in second- growth grand fir and white fir (Aho *et al.* 1987), such decay has not been reported in noble fir. No cull studies have been reported for noble fir (probably because it is relatively decay-resistant), and neither has it been tested in the stem decay models developed for advanced grand and white fir regeneration (Filip *et al.* 1983).

On the Willamette National Forest in west-central Oregon, old-growth noble fir has been shown to be highly susceptible to infection by the hemlock dwarf mistletoe (*Arceuthobium tsugense*) (Filip *et al.* 1979). Damage is significantly greater in noble fir than in Pacific silver fir and is greatest in larger-diameter trees (Filip *et al.* 1979). Mistletoe-infected branches are subsequently infected by at least three species of canker fungi: *Cytospora abietis, Cryptosporium pinicola,* and *Cylindrocarpon cylindroides.* These fungi cause branch mortality and further tree weakening. As infected branches die, trees are attacked by bark beetles. The susceptibility of young stands of noble fir to mistletoe and canker fungi and the additional effects of forest practices (thinning, pruning, branch tipping) are unknown. Such practices could provide infection courts for these otherwise weak parasites.

Several foliage and stem disease fungi have been reported on noble fir (Hepting 1971). These include gray mold (*Botrytis cinera*), snow mold (*Herpotrichia nigra*), several needle-cast fungi (*Virgella robustra, Lirula abietis-concoloris, L. punctata, Lophodermium piceae,* and *Lophomerum autumnale*), several foliage rusts (*Pucciniastrum goeppertianum, P. epilobii, Uredinopsis pteridis, U. struthiopteris*), a broomrust (*Melampsorella caryophyllacearum*), and a canker fungus (*Aleurodiscus* *amorphus*). Although these fungi have not been reported to cause serious damage in natural stands of noble fir, they could do so in young, intensively managed stands, especially where foliage quantity and quality are important.

Aho *et al.* 1983b reported that, in stands of true fir, Douglas-fir, and ponderosa pine less than 100 years old on the Lassen National Forest in northern California, conventional thinning resulted in wounds on 22 to 50 percent of the crop trees in five stands after 3 to 25 years. In three stands 8 to 15 percent of the crop trees were either killed or became unsuitable as crop trees. Nearly three-fourths of the wounds were basal—such wounds are more likely to become infected and result in decay than are those higher on the tree. In white fir, Aho *et al.* (1983b) found 231 wounds on 186 trees from 11 stands; all of these wounds (average age 13 years) were infected with decay fungi, which caused a loss of 14 percent of board foot volume. In four stands where techniques to minimize such damage were used, only 5 to 14 percent of the crop trees were wounded.

Filip and Goheen (1984) reported that, in 14 uneven-aged stands dominated by either grand fir or white fir along the Cascade crest (where mortality from rot disease was evident), *Phellinus weirii, Armillaria ostoyae*, and *Heterobasidion annosum* caused 4 to 55 percent tree mortality and losses of 8 to 39 percent in basal area and 7 to 33 percent in volume. Noble fir in these stands was less affected than was either grand fir or white fir. In the area surveyed within the WSIR, mortality was 19 percent, loss in basal area was 17 percent, and loss in volume was 18 percent. Many of these stands had undergone either a sanitation-salvage cut or a partial cut several decades earlier.

Minimizing Stand Damage During Thinning

Stem decay is clearly associated with wounding of trees during thinning. There is evidence that careful planning and layout of the timber sale, along with conscientious sale administration, can significantly reduce wounding. To minimize damage to trees and the site during commercial thinning on relatively flat ground, managers should seriously consider the following recommendations:

1. Use designated skid trails. This procedure reduces the area covered by skid trails and reduces soil compaction and damage to trees (Froehlich 1978; Froehlich *et al.* 1981; Garland 1983). Make sure skid trails are as straight as possible to avoid scarring of trees on the inside of sharp turns.
2. Match the size and type of logging equipment to topography, soil type, and tree size (Aho *et al.* 1983a, 1983b; Filip and Schmitt 1990).
3. Confine equipment to the skid trail and pull winchline to logs. This method lowers the chances of machines wounding the trees (Garland 1983).
4. Fell trees to the lead. This arrangement reduces basal scarring when logs are winched to the machine and increases skidder efficiency (Garland 1983). Position the skidder to allow as straight a pull as possible into the skid trail.
5. Restrict the logging season. Log thin-barked true firs during mid- to late-summer when the bark is tight (Aho *et al.* 1983a, 1983b; Filip and Schmitt 1990). Bark is most loose from budburst to the time the new bud is set.

6. Mark "leave" trees so that the logging operator will know which trees are to remain. Such marking calls attention to the leave trees and reduces damage (Aho *et al.* 1983a, 1983b; Filip and Schmitt 1990). Trees that have been damaged in past entries should be removed to reduce decay and ensure recovery of the trees' value.
7. Leave "rub" trees along skid trails or in areas where leave trees are likely to be damaged. Remove rub trees on the last entry into the stand (Aho *et al.* 1983a, 1983b; Filip and Schmitt 1990).
8. Log skid trails first. Cut stumps as low as possible so that the vehicle is not jarred sideways into residual trees (Aho *et al.* 1983a, 1983b).
9. Cut trees into logs before skidding. Tree-length skidding increases damage to residual trees (Aho *et al.* 1983a; Filip and Schmitt 1990).
10. To protect true fir stands from *H. annosum* infection, consider treating freshly cut stumps with borax (Graham 1971), or with an equivalent substitute, if adjacent stands show high infection levels.

Several of these guidelines will apply equally well to stands on steeper slopes that require cable-based harvesting equipment.

Insect Studies

The insects most threatening to mortality of noble fir are the bark beetles (*Pseudohylesinus dispar, P. nobilis*, and *P. granulatus*) (Furniss and Carolin 1977). The root collar weevil (*Pissoides dubious*) and the root aphid (*Prociphilus americanus*) also attack noble fir. These insects normally attack trees weakened by other causes such as dwarf mistletoes, root diseases, defoliation, or drought.

Noble fir is not a host of the western spruce budworm (*Choristoneura occidentalis*) or any other major defoliator. Neither is it infested by the balsam woolly adelgid (*Adelges piceae*), but another aphid (*A. nusslini*) has been recorded on ornamentals in British Columbia and California (Furniss and Carolin 1977).

Seed and cone insects can be a problem in noble fir. In one study, 36 percent of the noble fir seeds inspected were affected by insects (Scurlock 1978). The fir seed chalcid (*Megastigmus pinus*) was found in 21 percent of the seeds, fir cone maggots (*Earomyia barbara* and *E. longistylata*) in 12 percent, and a cone moth (*Eucosma siskiyouana*) in 6 percent. *Dioryctria abietivorella* can mine buds, shoots, and trunks as well as cones (Franklin 1990).

Future Research Needs

The preceding synthesis of the literature has highlighted the limited knowledge that exists for managed noble fir stands, particularly the response of more mature stands to various cultural treatments and intermediate entries, especially in the vicinity of the WSIR. Needs for future research can be separated into three aspects: (1) basic mensurational tools that describe the shape and size of noble fir trees; such knowledge is critical to the accurate description of current stand structure as well as projection of future growth, yield, and potential products; (2) data that quantify the response of noble fir trees and stands to various management activities; and (3) information on other elements of forest ecosystems (such as insects, diseases, windthrow, and fire hazard) that may be affected by management activities and that may influence long-term forest health.

Mensurational Information

Development of a taper equation for noble fir would provide a tool for projecting stem volume and the volume of various lengths of stem segments. This capability would enable potential product yields from silvicultural treatments to be determined. Developing taper equations for the range of stands dominated by noble fir on the WSIR would require that 150 to 200 trees be felled and measured. Equations would be developed to predict diameters along the bole as a function of dbh and total height. Crown ratio might also be used as an indicator of form. A preliminary model based on a minimum number of felled trees (i.e., 75) could be completed in one year.

Because uncertainty exists about the validity of existing growth models, a second short-term study could compare measured growth of trees on CFI plots and projections could be made with the various available models. If the CFI data are compatible with the models, then this approach should serve to test the projection of noble fir; however, managed stands of noble fir in this age class are rare and CFI plots in such stands are perhaps even rarer on the WSIR. Additional data from CFI plots may be available from adjacent ownerships that include these types of stands, but a search will have to be conducted.

Growth Response After Management

The short-term approach to acquiring response data is to find stands that have received various cultural treatments or intermediate harvests in the past and conduct a retrospective study to measure response. This approach requires that such stands are available to sample and that reasonable records exist on the nature and timing of previous treatments. Such stands should have been treated at least 10 years ago and ideally 25 years ago. One stand has been located on the WSIR that will be useful for such a retrospective analysis, and preliminary measurements have been taken. Unfortunately, no other stands in this age group on the WSIR have been thinned more than a few years ago. Opportunities may exist on other ownerships, but they have not been verified by field checks. Although each such stand sampled would constitute a case study, results from 5 to 10 such stands would provide a reasonable perspective on likely response to management. A challenge with such operationally treated stands is that finding control areas against which response can be evaluated is difficult. If resources for locating and sampling stands are available, retrospective analyses could be completed in 2 years.

This approach may provide helpful information where none other is available, but it is not a substitute for more statistically robust, long-term experiments. Thus, the tradeoff in time and resources committed to retrospective studies that could be directed to rapid establishment of designed experiments must be considered.

Forest Pests

Of highest priority in a short-term study of pests in noble fir would be a sampling of several age classes for incidence of root, butt, and stem decays associated with mechanical wounds—either natural (caused by fire, animals, insects, or abrasions) or induced by humans (caused by equipment or pruning). Tree age and wounding have been shown to be the most important factors affecting amount of decay in white and grand fir (Filip *et al.* 1983). Such a study could be designed to develop a decay equation for noble fir or possibly to modify the existing white/grand fir equation (Filip *et al.* 1990) to accommodate noble fir. This equation could then be used by managers to estimate the current and future amounts of decay in a stand without destructive sampling. Cull rules for individual noble fir trees could be developed. This study could also be designed to estimate incidence of important pathogenic fungi such as *E. tinctorium* and *H. annosum* in living trees. Other studies examining volume and taper equations as well as other tree attributes could be conducted in conjunction with decay studies. These studies could be completed in one field season with results reported within the same year.

A second short-term study should address hazard rating of noble fir sites for pests, especially root diseases. Forest managers need to be able to predict occurrence and severity of root diseases, particularly after stand harvesting and before regeneration. Hazard ratings based on easily collected stand or site characteristics such as plant association, elevation, aspect, slope, topographical position, or stand age would be desirable. Some studies of hazard rating of sites have been conducted with tree species other than noble fir and in other areas besides central Oregon.

The most comprehensive such study was done by McDonald *et al.* (1987) in northern Idaho and northeastern Oregon. They randomly selected plots in forested areas and determined how the occurrence of *Armillaria* root disease across a range of plant associations (subalpine fir, grand fir, ponderosa pine, etc.) was correlated with the presence of human disturbance (thinning, harvesting, road construction, etc.). They found that as site productivity (site index) declined, level of pathogenicity of *Armillaria* root disease increased. Human disturbance increased disease severity on high-productivity sites but decreased severity on low-productivity sites.

A similar study could be conducted in plant associations where noble fir occurs or is expected to be grown (mountain hemlock, western hemlock, Pacific silver fir, and some grand fir associations). The hypothesis to be tested would be that root disease type and severity is correlated with plant association and related site and stand attributes. An adequate number of plots would be pre-selected within each plant association and sampled for severity and type of root disease (*Armillaria*, annosus, laminated, black stain, etc.). Furthermore, areas with high and low levels of human disturbance (management) would be sampled within each selected plant association. Site and stand variables would be recorded for each plot. Correlations would be made by using these variables in regression analyses. Data collection could be completed in two field seasons.

A third short-term study could focus on the incidence of root disease fungi in stumps after thinning or harvesting. This study could be done in conjunction with the monitoring of CFI plots if the latter are adequately distributed within thinned or harvested areas. The root pathogen *H. annosum* has been shown to infect stumps created by precommercially thinning Pacific silver fir in British Columbia (Morrison *et al.* 1986). Crop-tree mortality caused by *H. annosum* was not observed in either noble fir or red fir in precommercially thinned stands in Oregon and Washington, but *Armillaria*-caused mortality was common (G.M. Filip and D.J. Goheen, in preparation). Such a study could be done in one field season. Although this study would determine incidence of root pathogens in thinned or harvested stands, it would not determine the effects of these practices on crop-tree mortality. Such a determination would require an assessment of pretreatment inoculum levels; therefore, a long-term study would be required to test the hypothesis that thinning or harvesting reduces crop-tree mortality caused by root diseases.

A second long-term study might clarify the role of bark beetles in the mortality of noble fir weakened by such agents as dwarf mistletoes and canker fungi. The successional role of bark beetles in noble fir mortality and the ecology and taxonomy of beetle-vectored stain fungi have never been studied. The proposed study would test the choice of leaving pest-infested noble fir during traditional seed tree/shelterwood harvesting or during "new forestry" operations. Equations could be developed to predict the longevity of leave trees on the basis of incidence and severity of pests as well as other tree and stand factors. Selected trees would be non-destructively sampled each year for dwarf mistletoe/canker fungi infections and bark beetle/stain fungi infestations. Such a study would require 3 or 4 years to complete.

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This literature review evaluates existing knowledge about silvicultural treatments to enhance residual tree value, vigor, and growth in 70- to 120-year-old mixed-conifer forests growing within the Pacific Silver Fir zone on the east slope of the Cascade Mountains. The Warm Springs Indian Reservation apparently contains about 30,000 acres of naturally regenerated, largely unmanaged stands in this category.

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