Patterns of Survival, Damage, and Growth for Western White Pine in a 16-Year-Old Spacing Trial in Western Washington

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ABSTRACT: *Information about effects of planted spacing on growth and development of western white pine is scant because white pine blister rust disease has severely limited the survival of trees in young plantations. In the early 1980s, we established a western white pine spacing trial in the southern Cascades of Washington, using seedlings from a seedlot comprised primarily of open-pollinated seed from trees screened and certified as resistant to white pine blister rust. Initial square spacings ranged from 2 to 6 m; treatment plots were 0.4 ha in size and were replicated three times (six times for the 3 m spacing). Permanent measurement plots were installed at age 8, and the lower portion of all stems was pruned in the 10th growing season to reduce blister rust infections. The plots were remeasured at ages 11 and 16. Sixteen years after planting, survival averaged 80%; most mortality was associated with blister rust, but the rate of new infections and mortality diminished substantially between ages 11 and 16; 71% of the planted trees were free of blister rust at age 16. Trees averaged 8.4 m tall (ranging from 7.6 m in the 2 m spacing to 8.8 m in the 4 and 5 m spacings) and 12.7 cm dbh (10.3 in the 2 m spacing to 14.0 cm in the 5 m spacing). Periodic annual growth from 11 to 16 yr in the three wider spacings averaged 0.7 m in height and 1.0 cm in diameter. Antler rubbing by elk caused substantial damage to stems, but wounds on most trees were overgrown in 2 to 4 yr. Rub damage did not appear directly related to spacing but rather to stem diameter, with damage limited primarily to stems >6 and <15 cm. Early growth rates in this trial were much greater than those attained in older, natural stands (as inferred from site index curves and yield tables) and in progeny tests and other young silvicultural trials planted elsewhere. We believe rust-resistant stock of western white pine merits greater consideration for planting in the Douglas-fir region.*
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Key Words: *Pinus monticola, Cronartium ribicola,* pruning, rust resistance, animal damage

Western white pine *(Pinus monticola)* is one of the largest pines in the world and among the fastest growing conifers in the western United States. The species has widespread distribution as a component of mixed-species stands in forests of the coastal, Cascade, and Sierra Nevada ranges from British Columbia to northern California. It attains its greatest commercial importance in the Rocky Mountains of northern Idaho and adjacent areas of eastern Washington, western Montana, and interior British Columbia where it constitutes a plurality of the stocking in the western white pine cover type (Graham 1990). High volume stands and light-weight, straight-grained, and easily worked wood made the species one of the mainstays in early development of the timber industry in the Inland Empire. Much early research in that region was focused on the species (e.g., Haig 1932). But by the early 1940s it became apparent that blister-rust disease (caused by the fungus *Cronartium ribicola),* would severely limit the survival and development of future stands of western white pine. As a result, most subsequent silvicultural research focused on mixed-species stands and other coniferous species, while forest pathologists and geneticists researched approaches to dealing with the exotic fungal pest. The successful development of rust-resistant seedling stock in genetic improvement programs (Bingham 1983) made western white pine management once again feasible in the Inland Empire and in the coastal and Cascade zones of the Douglas-fir *(Pseudotsuga menziesii)* region.

Most plantations in the Douglas-fir region (i.e., west of the Cascade Range from southern British Columbia to northern California) have been and continue to be planted with Douglas-fir seedlings. This focus is associated with the favorable traits of Douglas-fir

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(rapid growth, suitability for diverse sites, high value wood) and with the nursery and regeneration experience available, which is considerably greater for Douglas-fir than for other conifer species. But as forest management objectives have shifted in response to changes in ecological, economic, and social conditions, there is greater interest in managing tree species previously neglected in westside forestry. Thus, there is a need to develop information that will help forest managers choose among a greater number of species and cultural options. In the early 1980s, spacing trials were established for several conifer species on the Wind River Experimental Forest in the southern Cascades of Washington; one of these trials was with western white pine. At the time, there were no ongoing spacing trials for the species. Few such trials for western white pine had been previously established, and those established had been abandoned because of severe mortality caused by white pine blister rust.

This article reports performance of western white pine during the first 16 yr after planting in the Wind River spacing trial. Patterns of survival and growth as well as incidence of blister rust and animal damage are summarized. Trends in tree growth and stand development are then compared with limited published data on young white pine stands elsewhere.

Materials and Methods

Site Description

The spacing trial is located in a gentle mid-slope position (elevation 680–720 m) on the west-facing aspect of Trout Creek Hill in the Wind River Experimental Forest, about 20 km north and slightly west of Carson, WA (lat. 45°50'N, long. 122°0'W). The soil (mapped as a medial, amorphic, mesic, Vitric Hapludand similar to the Stabler soil series) is derived from basaltic lava that has weathered rapidly to produce a uniform, moderately deep (1 to 2 m) loam over cobbly or gravelly loam. At the nearby Wind River weather station (about 7 km distant with an elevation 200 m below the study site), the average frost-free growing season is 140 days, and average annual precipitation is 2,550 mm. Nearly 75% of the annual precipitation (1,850 mm) occurs as rain or snow during the November through March period. Mean annual temperature is 9°C; mean temperature during the growing season is 16°C. Vegetation is intermediate between the western hemlock *(Tsuga heterophylla)* and Pacific silver fir *(Abies amabilis)* zones (Franklin and Dyrness 1973). The forest cover type on Trout Creek Hill ranges from predominantly Douglas-fir (Site class III to Site class IV, McArdle et al. 1961) to a western hemlock-Pacific silver fir mix. Western redcedar *(Thuja plicata)* and noble fir *(Abies procera)* are the other overstory tree species. The understory is composed of vine maple *(Acer circinatum),* Pacific yew *(Taxus brevifolia),* and Pacific dogwood *(Cornus nuttallii).* Ground vegetation includes salal *(Gaultheria shallon),* Oregon-grape *(Berberis nervosa),* vanilla-leaf *(Achlys triphylla),* beargrass *(Xerophyllum tenax),* and red huckleberry *(Vaccinium parvifolium).*

Western white pine was a significant species throughout the area; it averaged 9,100 bd ft (Scribner, 16 ft logs) per acre (metric equivalent not available) and represented about 10% of the merchantable timber volume in the original old-growth forest prior to 1950 (DeBell and Franklin 1987). By the 1980s, however, bleached-out snags of western white pines killed by blister rust and mountain pine beetles *(Dendroctonus ponderosae)* and a few seedlings and saplings infected with blister rust were all that remained of the species. The study site was, and the surrounding stands are, dominated by old-growth Douglas-fir, western hemlock, and Pacific silver fir, much of which is defective with high incidence of broken tops, dwarf mistletoe, root rots, and other diseases. Natural regeneration of coniferous tree species in the area includes Douglas-fir, western hemlock, Pacific silver fir, western redcedar, and western white pine; the latter, however, usually succumbs to blister rust prior to growing beyond the small sapling stage.

Study Installation and Design

The western white pine spacing trial was installed on the lower half of a 32 ha clearcut that was harvested in 1979. Residual slash was machine piled and burned, and much of the area was also scarified to remove a dense cover of salal and vine maple that had developed as a result of openings and sparse canopies created by *Phellinus weirii* root rot. The plots were laid out and seedling positions marked with small wire pin flags a year before the area was planted. To minimize shading and other edge effects, all plots were established at least 35 m from mature timber on the south side of the unit and 25 m from other boundaries.

Western white pine seedlings were grown as bareroot stock (2-0) at the USFS Wind River Nursery. The seedlot consisted of wind-pollinated seed collected from 13 trees growing in a seed production area near Mount Adams, some 65 km from the study site. Twelve trees had been screened at the USFS Dorena Tree Improvement Center and determined to be rust-resistant, but one bushel came from a tree that had been selected for phenotypic resistance but had not been screened. Thus, the seedlot—though not certified as "improved"—was assumed to have a moderate amount of resistance. Planting was done in the spring of 1982 using a power auger. Nominal spacing was very close to prescribed spacing except where large stumps or logs prevented planting at the designated planting spot. Dead trees were replaced with similar western white pine seedlings every spring for 3 yr following the initial planting, but relatively few required replacement. Thereafter, a nearby naturally seeded or volunteer tree, usually Douglas-fir, was selected for retention and measurement so as to maintain competition levels approximating those initially established for testing. Volunteer trees in excess of those selected as replacement trees were cut between ages 11 and 16.

Blister rust infections were observed on a few trees in summer 1990, and in summer 1991 all trees were pruned to remove no more than one-third of the live crown or to a height of 2 m, whichever was lower. In addition, any reachable branch with a canker was also cut. Procedures were similar to those described by Russell (1989) and Hunt (1991). Volunteer trees selected as replacements for planted trees that had

died were pruned in like manner. Subsequent pruning was done to the same specifications when trees were measured in 1992 and 1997. Weed control and removal of other volunteer trees was done periodically to reduce competition from noncrop vegetation.

The study was a complete randomized design with five square spacings—2, 3, 4, 5, and 6 m. Each spacing was replicated three times, except there were six plots for the 3 m spacing of western white pine. The spacings were selected to include the range of spacings that might be used in future management regimes. In addition, three replicates each of pure Douglas-fir plots and plots of 50:50 mixtures of Douglas-fir and western white pine were established at 3 by 3 m spacings in conjunction with the spacing trial. Data from these supplementary plots are mentioned briefly in the results and discussion section. All treatments were installed in square 0.40 ha plots. Temporary sample plots (5 rows per plot in 2 to 5 m spacings and 4 rows per plot in the 6 m spacing) were measured at age 3. Permanent measurement plots were established at age 8; these plots differed in size depending on spacing, from two measurement subplots of 0.04 ha in each 2 m treatment plot, to 0.160 ha for the 4 and 5 m spacings, to 0.176 ha in the 3 and 6 m spacings. The number of trees measured in each permanent plot was 200 trees for the 2 m spacing (100 in each of two 100-tree subplots), 196 for the 3 m spacing, 100 for the 4 m spacing, 64 for the 5 m spacing, and 49 for the 6 m spacing. All measurement plots were buffered by at least three rows of the same tree species and spacing; except for the 2 m plots, the permanent measurement plots were as large as they could be, given the three-row buffer restriction. All trees within the permanent sample plots were tagged with identification numbers.

Data Collection and Analysis

The temporary sample plots were measured for height at age 3. Data on survival, tree condition, and tree height were collected in the permanent measurement plots at plantation ages 8, 11, and 16 yr. Breast-height diameter (1.3 m above ground) was measured, and stem damage and blister rust infection (presence/absence) were assessed at ages 11 and 16 yr. A wildlife biologist attributed most stem damage to antler rubbing by Roosevelt elk based on the appearance, height, and timing of damage as well as evidence from scat of heavy use of the area by elk *(Cervus elaphus).* Means for survival, stem damage by rubbing, rust infection, height of all trees and the largest 100 trees/ha, diameter (quadratic mean) for all trees and the largest 100 trees/ha, and basal area were calculated for each plot. Stem volumes were estimated from height and diameter measurements (using the western white pine equation in Wykoff et al. 1982), with volume expressed in m^3 outside bark for the total stem. Basal area and volume summaries were expanded to a per ha basis. Results at age 16 yr were examined by analysis-of-variance procedures; means were judged to be significantly different when $P \leq 0.05$. Trends in mortality and blister rust incidence and stem damage (antler rub) over time and among spacings were also evaluated, and data were plotted on maps of the trial to assess existence of spatial patterns. In addition, stem damage was examined graphically in relation to diameter distribution, and its effect on growth was evaluated by regressing diameter growth over an index of its extent or severity (percentage of tree's circumference rubbed X vertical length of rub).

Results and Discussion

Survival

Survival of western white pine during the first few years was excellent; relatively few seedlings were replaced. At age 8, 95% of the planting spots in the trial were occupied by living western white pine seedlings; mean survival ranged from 93% in the 2 m spacing to 98% in the 6 m spacing (Table 1). Survival began to decrease thereafter, primarily as a result of blister rust infection. At age 11, survival averaged 86% with little difference among spacings. At age 16, it averaged 80%, and although mean survival among the various spacings ranged from 77 to 84%, such differences were not statistically significant ($P = 0.66$).

Replacement Trees

Positions occupied by dead or missing trees were replanted during the first 3 yr with similar western white pine seedlings; thereafter the positions were "refilled" whenever possible with trees selected from among adjacent naturally regenerated ingrowth trees. Douglas-fir accounted for the vast majority (92%) of replacement trees in the plots, followed by western hemlock (5%) and western white pine (3%). In general, the size of the replacement trees was smaller (~35% shorter) than the average planted western white pine tree on the permanent plot, particularly in the closer spacings. Since greater competition and size differentiation would be expected in the closer plantings at age 16 (i.e., some trees would be smaller than others even if no mortality had occurred) and there were additional trees during much of the spacing trial's life to date, we doubt that mortality to date has substantially affected mean growth performance of western white pine trees in the various spacing treatments.

Blister Rust Infection and Mortality

Symptoms of blister rust infection were first observed in the spacing trial at age 9, and all trees were pruned during the next growing season. Because the first tally of infections did not occur until after pruning, the amount of infection documented in the 11 yr measurement was probably lower than it would have been if the stand had not been pruned or if the tally had been made prior to pruning (i.e., most cankers occur on

Table 1. Survival of western white pine at age 8, 11, and 16 at different spacings on Wind River Experimental Forest, Washington. Differences in survival among spacings were not significant ($P \leq 0.05$).

Spacing (m)	Survival at age 8	11	16
	(%)		
2	93	86	79
3	95	87	82
4	94	85	77
5	97	86	80
6	98	87	84

Table 2. Trends in blister rust infection (BR) and mortality by spacing and age in western white pine spacing trial at Trout Creek Hill.

Tree status at each measurement	Spacing (m) 2	3	4	5	6	Mean (all trees)
	(trees/ha)					
Live at age 8	2,495	1,101	621	394	274	977
	(% based on number of live tree s at age 8)					
Dead at age 11	14	13	16	14	12	14
Living at age 11						
BR noted age 11	8	7	7	16	10	8
No BR noted age 11	78	80	77	70	78	78
Dead at age 16						
BR noted age 11	4	3	5	3	6	4
No BR noted age 11	4	3	3	5	3	3
Living at age 16						
BR noted age 11	4	4	4	11	6	5
New BR noted age 16	4	3	2	3	5	3
No BR noted age 16	70	74	70	64	67	71
Total dead all years plus those with BR age 16	30	26	30	36	33	29

branches within 2 m of the ground and thus would have been removed with pruning).

Trends in blister rust infection and mortality are documented by measurement age and spacing in Table 2. The number of live trees at age 8 is used as the base (i.e., 100%) because the permanent sample plots were established and first measured at that age. Although foliage and branches of some trees were probably infected at the time, no trees had yet displayed symptoms (such as flagging) that were noticed and recorded by measurement crews.

Neither observed blister rust infections nor mortality were significantly related to spacing, and there was no apparent competition-related mortality through age 16. Between the 8 and the 11 yr measurements, 14% of the trees died (presumably associated primarily with blister rust); another 8% of trees were recorded as living but infected with the disease. Five years later, at age 16, about 40% of the trees recorded as infected at age 11 (i.e., 3% of total trees at age 8) were dead. Between ages 11 and 16, another 4% died with no apparent sign of blister rust, and an additional 3% became infected with blister rust. Thus, the rate at which trees were developing obvious symptoms of infection or dying from blister rust appeared to be substantially reduced (from 22% in the 3 yr period from age 8 to age 11 to only 7% in the next 5 yr period). This reduction can probably be attributed to pruning at age 10 and to the likelihood that the most susceptible trees had been infected earlier. The total proportion of living and dead trees in the plantation that was *recorded* as having blister rust infection since it was first tallied at plantation age 11 averaged 11%. If we *assume,* however, that all trees that died between age 8 and 16 were *infected,* then 29% of the trees present at age 8 were either killed by or infected with rust during the next 8 yr (by plantation age 16).

Because a spacing trial must represent and maintain different stand densities, we were disappointed to find a substantial amount of blister rust infection at Trout Creek Hill. We knew that blister rust infection sources would be present due to the observed mortality from blister rust in the area but hoped that planting with stock screened for rust resistance would keep the infection level low enough to be tolerated. That particular area of Trout Creek Hill was selected for the western white pine spacing trial rather than for similar trials with Douglas-fir or western hemlock because trees in the study area showed evidence of serious root rot damage *(Phellinus weirii),* and thus we judged the site too risky for major plantings of the more susceptible conifers. Recently, former root rot areas were reported to have higher infection rates of blister rust than nearby nondiseased areas (Hunt 2000); this difference may be associated with greater deposition of *Ribes* seed by bears foraging among downed logs and root rot fallen timber. Thus, although another site might have had a lower initial infection rate for blister rust, given our reluctance to plant species highly susceptible to *Phellinus weirii,* we feel that western white pine was still a good choice for this site.

Prognoses given by geneticists and pathologists 20 yr ago were that about 35% of the seedlings from rust-resistant seedlots would be susceptible to the disease (Bingham 1983, Fins et al. 2001). These earlier expectations are consistent with the level of infection and mortality to date and also with the apparent slowing of infection rate. Genetic research and tree improvement efforts on western white pine during the past two decades have focused on developing additional, diverse mechanisms for blister-rust resistance while maintaining survival rates at similar levels, thereby providing insurance against mutation of rust genes (Bingham 1983, Yanchuk et al. 1994). Thus, present reforestation efforts can anticipate losses similar to those we have encountered to date.

Earlier and continued pruning to greater heights might result in considerably lower losses, however. Pruning was not begun in our trial until age 9, and branch removal was limited to the lower 2 m of stems. Had pruning been initiated earlier (perhaps as early as age 3) and continued until trees could be pruned to a height of 3.0 m as currently recommended (Hunt 1998) or even higher, the level of blister rust infection may have been even lower.

We suggest that pruning be initiated earlier (at age 3 to 5 or when trees are 0.6–2.0 m tall) and be continued until at least one 5 m log is branch free. In addition to decreasing

blister rust infection, such pruning would result in clear lumber and veneer in young-growth stands of this commercially useful species and extend the "stand-initiation" phase (Oliver and Larson 1996) during which light conditions support an abundance of understory vegetation and, presumably, associated plant and animal species. Forest managers may want to increase planting density to compensate for anticipated losses due to blister rust, especially in situations where natural fill-in is not expected to be abundant. For similar reasons, juvenile thinning or cleaning might be delayed until most blister rust infection and mortality have occurred.

Animal Damage to Stems

Many western white pine saplings in the Trout Creek Hill plantings suffered stem damage from antler rubbing by elk, and western white pine appeared to be the species of choice for such activity. Douglas-fir saplings in adjacent pure plots and in mixed plots containing white pine and Douglas-fir had negligible damage (<1% of trees). Overall, 8% of trees in sample plots of the western white pine spacing trial had rub damage at the time of the 11 yr measurement. Damage did not appear related to location of the trees with regard to uncut timber nor were there any trends apparent in relation to other aspects of spatial position. The frequency of damage was not equally distributed among spacings, however. At age 11, only 3% of trees in the 2 m spacing were damaged; damage increased to 8% in the 3 and 4 m spacings, and to 11 and 18% in the 5 and 6 m spacings, respectively. This apparently strong relationship to spacing was correlated closely to tree size: only 12% of rubbed trees were ≤6.0 cm dbh, 52% were between 6.1 and 9.0 cm dbh, and 36% of rubbed trees were 9.1 cm dbh or larger. The percentage of rubbed trees in the 9.1 to 12.0 cm and the 12.1 to 15.0 cm dbh classes was greater than the proportion of all trees in these dbh classes (Figure 1 a). It therefore seems probable that the disproportionate amount of rub damage in wide spacings at the 11 yr measurement occurred because the wider spacings had larger trees on average and, thus, a larger percentage of trees in the size classes preferentially rubbed by elk. The measurement at age 16 yr revealed fresh damage to trees damaged previously and to trees that had no previous damage, amounting to 7% of all trees. Most (74%) of the fresh damage was on trees with no prior damage. There was no longer a strong trend of increased damage with increased spacing. In fact, 90% of the new damage occurred on trees in the two *closest* spacings. Only 3% of all trees at age 16 were ≤6.0 cm; thus, the vast majority of trees in all spacings had reached sizes that seemed to be preferentially rubbed, and in wider spacings many of the trees had perhaps grown beyond the size preferred for rubbing (i.e., of 132 trees with rub damage at age 16, only 4 were >15 cm diameter, and 34% of trees in the two widest spacings had surpassed that diameter. The percentage of rubbed trees in the dbh classes >15 cm is disproportionately low in relation to the percentage of all trees in these larger size classes; Figure lb). Analyses of the relation of 4 yr diameter growth to 11 yr dbh and severity of rub damage indicated that the damage had no

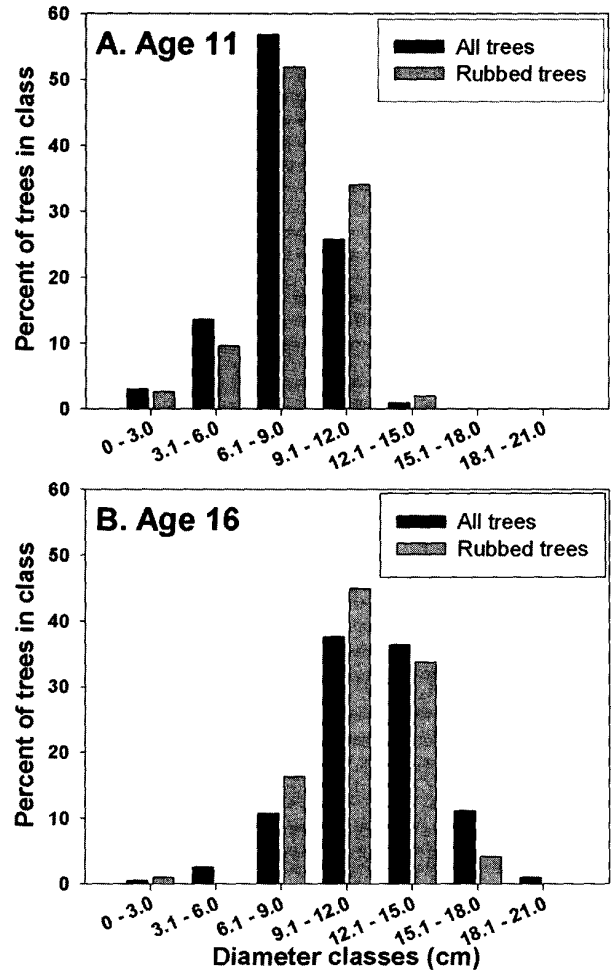

Figure 1. Distribution of trees by diameter class for all trees in the study and for those with stem damage due to antler rubbing by elk: (A) at age 11 and (B) at age 16.

measurable effect on subsequent diameter growth. There are undoubtedly negative effects on quality of some proportion of wood recoverable from the damaged portion of the stem, however.

The amount of damage from elk rubbing was unexpected and may be unusually great because elk use on Trout Creek Hill has increased substantially in response to clearcutting in the late 1970s and early 1980s, which created a few patches of early successional habitat in an area dominated by old-growth timber. Such damage is unlikely to compromise the study because few trees were completely girdled and growth was little affected. Moreover, many of the trees have healed and also have grown beyond the size class most selected for rubbing.

Other Types of Damage

The western white pine trees experienced very little dam-age other than that associated with blister rust infection or antler rubbing as discussed above. There was considerable snow breakage in the general area during the winter following the plantation's 11th growing season. None of the western white pine study trees suffered significant damage; however, some of the Douglas-fir in the associated pure and mixed

Table 3. Mean height for all trees and 100 largest trees/ha of western white pine at age 8, 11, and 16 at different spacings on Wind River Experimental Forest, Washington. Within a column, means followed by the same letter are not significantly different at p ≤ 0.05; means only separated at age 16.

Spacing (m)	All trees, ht at age			100 largest trees, ht at age		
	8	11	16	8	11	16
	(m)					
2	2.9	4.8	7.6 a	4.1	6.0	9.3 a
3	3.0	5.3	8.4 ab	4.9	6.5	10.0 ab
4	3.1	5.4	8.9 b	4.1	6.6	10.3 ab
5	3.1	5.5	8.8 b	4.0	6.6	10.6 b
6	2.9	5.0	8.4 a	3.7	6.2	9.9 a

species plots were damaged. Apparently western white pine, with lighter, less dense crowns, were better able to shed the heavy wet snow common to the area. The incidence of double or multiple stems was 2.2% in the western white pine plantings; among spacings it ranged from 1.0 to 1.5% in the 2, 3, and 4 m spacings, and was 2.7% in the 5 m spacing and 5.3% in the 6 m spacing, but differences among spacings were not statistically significant.

Tree Growth and Stand Development

Tree Height

At time of planting, the western white pine seedlings averaged 20 to 30 cm tall. Early growth of the planted seedlings was relatively slow as characteristic of white pine and most conifer species. Observations recorded at the end of the 3rd growing season indicated that trees averaged 57 cm tall (range 11 to 106 cm). During the next 5 yr, however, growth accelerated substantially (averaging about 50 cm/yr), and mean tree height was 3.0 m at age 8. From ages 8 through 16, height growth was maintained or increased (averaging 60 to 70 cm/yr), and differences in height developed among spacings (Table 3). At age 11 and 16, heights of all trees and of the 100 largest trees/ha increased with spacing up to 5 m (Table 3); trees in the 6 m spacing were slightly shorter than those in the 4 and 5 m spacings and equal to or shorter than trees in the 3 m spacing. Between ages 11 and 16, mean height growth of the 100 largest trees/ha was least in the 2 m spacing (growth of 3.3 m) and increased with spacing up to the 5.0 m spacing (growth of 4.0 m).

Height growth and site index curves developed by Curtis et al. (1990) for western white pine in the Cascade Range of Washington and Oregon provide a standard for evaluating the height growth of dominant trees in the spacing trial. Dominant trees (i.e., 100 largest trees/ha) in the Trout Creek Hill spacing trial averaged about 10.0 m in total height at a breast-height age of 11 yr (equivalent to 18 yr total age from seed or 16 yr plantation age in our study). The general curves indicate that on the best sites (SI about 30 m at breast-height age 50 yr), dominant trees average about 7.0 m at breast-height age 11; and on medium sites (SI of about 21 m at 50 yr), they are only about 5.4 m tall. Dominant trees on the best sites are not expected to attain heights achieved in the better spacings of our trial until about breast-height age 14. Thus, early height growth of white pine in the spacing trial is substantially greater than that attained by the fastest growing trees in the natural stands sampled for the site index work. It is likely that the number of years to attain breast height is also substantially greater in natural stands than in planted stands, thus making the height growth advantage of the Trout Creek Hill plantings even greater.

Tree Diameter

Diameter was first measured at age 11 when almost all trees had surpassed breast height; it averaged 8.3 cm and increased with growing space from 7.2 cm at the 2 m spacing to 9.0 cm at the 5 m spacing (Table 4). At age 16, mean diameter ranged from 10.3 cm at the 2 m spacing to 14.0 cm at the 5 m spacing and was slightly lower in the 6 m spacing. Mean diameters in the 2 and 3 m spacing differed significantly from each other, and both were significantly smaller than those in the 4, 5, and 6 m spacings. Comparison of mean diameters at age 11 and age 16 (Table 4) indicates that periodic diameter growth was only 0.6 and 0.8 cm/yr in the 2 and 3 m spacings, respectively, whereas growth in the three widest spacings was about 1.0 cm/yr. Similar patterns of size and growth in diameter occurred for the 100 largest trees. The largest trees at age 16 had attained diameters of 18 to 20 cm (Figure 2).

Stand Basal Area and Volume

Both at age 11 and age 16, basal area and cubic volume/ha decreased markedly as spacing increased (Table 5). At age 16, mean basal area ranged from 16.6 m^2/ha at the 2 m spacing to 3.2 m^2/ha at the 6 m spacing. Periodic annual basal area increments for the last 5 yr averaged from 1.6 m^2/ha at the 2 m spacing to only 0.4 m^2/ha at the 6 m spacing. Volume and volume growth followed the same trends with spacing as basal area and basal area growth. Mean volumes ranged from a high of 58.1 m^3/ha at the 2 m spacing to 13.4 m^3/ha at the 6 m spacing; periodic annual volume increments ranged from

Table 4. Quadratic mean diameter at 1.3 m for all trees and 100 largest trees/ha of western white pine at ages 11 and 16 at different spacings on Wind River Experimental Forest, Washington. Within a column, means followed by the same letter are not significantly different at *P* ≤ 0.05; means only separated at age 16.

Spacing (m)	Quadratic mean diameter			
	All trees at age		100 largest trees at age	
	11	16	11	16
	(cm)			
2	7.2	10.3 a	8.6	11.9a
3	8.0	12.1 b	9.5	14.0 b
4	8.8	13.6 c	10.4	15.6 c
5	9.0	14.0 c	10.5	16.1 c
6	8.4	13.3 bc	10.2	15.6 c

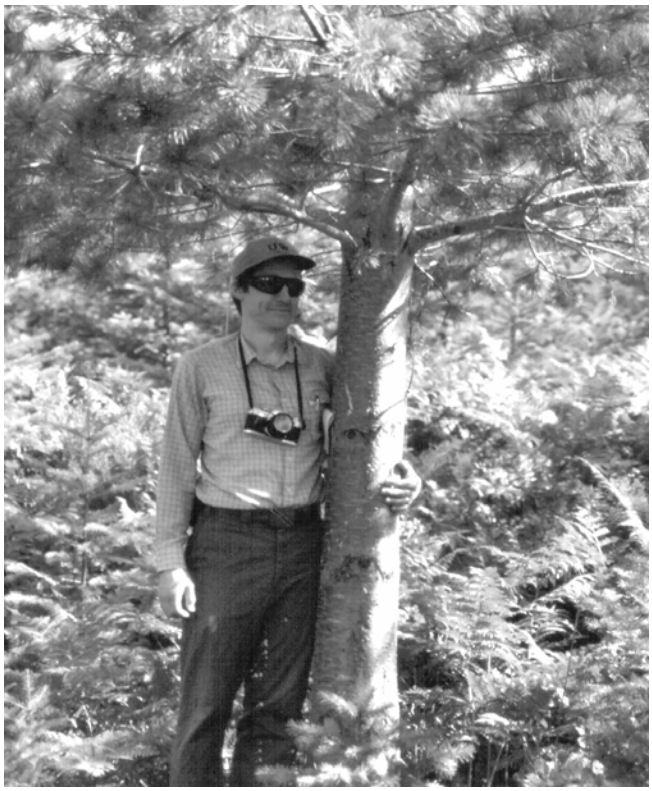

Figure 2. Example of size and form of largest trees at age 16.

7.6 m^3/ha at the 2 m spacing to 2.0 m^3/ha at the 6 m spacing.

The only yield tables available for western white pine (Haig 1932) were developed in young-growth stands in Idaho, and "excellent" sites in that region produce dominants that average 21 m at total age 50 yr. Average dominant trees in natural stands on such sites do not attain the mean height of the 100 largest trees/ha in the widest spacings of our 16-yr-old trial until about total age 30; and trees in natural stands are more than 40 yr old before reaching the mean diameter of the three wider spacings. Natural stands are much more dense, however, and will not self-thin to the number of trees of the densest (2 x 2 m) spacing until age 40. Nevertheless, basal area and cubic volume of our densest spacing at plantation age 16 exceeded that of natural stands on the most productive Idaho sites at total age 25. Thus, growth at the tree and stand level in the spacing trial during the first 16 yr after planting has been substantially greater than that expected from measurements obtained in natural stands of western white pine on the best sites in Idaho.

Table 5. Mean basal area and volume of western white pine at age 11 and 16 at different spacings on Wind River Experimental Forest, Washington. Within a column, means followed by the same letter are not significantly different at P ≤ 0.05; means only separated at age 16.

Spacing (m)	Basal area at age 11	Basal area at age 16	Volume at age 11	Volume at age 16
	(m^2/ha)		(m3/ha)	
2	8.5	16.6 a	19.9	58.1 a
3	4.8	10.1 b	12.3	42.0 b
4	3.2	7.2 c	8.1	28.5 c
5	2.2	5.0 d	5.5	20.2 cd
6	1.4	3.2 e	3.6	13.4 d

Because much more work has been done on growth and stocking relationships for eastern white pine than western white pine, we examined our data in relation to stocking guides available for the eastern species (Philbrook et al. 1973, Lancaster and Leak 1978). The tree and stand data from the western white pine spacing study in Trout Creek Hill fall in between the C-line (which represents bottom-line minimum stocking) and B-line (represents minimum stocking for full site occupancy) for the narrow 2 and 3 m spacings. In the wider 4, 5, and 6 m spacings, the data fall below the C-line. Thus, intertree competition is relatively low in all spacings (but especially in the three wider spacings), and the trees have a few years to grow before the site would be considered fully occupied and competition-related mortality would begin, at least according to standards developed for eastern white pine. Such an interpretation is consistent with our previously stated opinion that mortality in the trial through age 16 was associated primarily with blister rust.

In summary, growth of western white pine at the Trout Creek Hill spacing trial was excellent. General trends in tree growth and stand development among spacings were similar to those observed with other northwestern conifer and hardwood species [Douglas-fir, western hemlock, and red alder *(Alnus rubra)]*.

Although there is little specific information on the response of western white pine to planting density, growth in our spacing study can be compared with data on: (1) Douglas-fir planted at the site, and (2) older plantations and progeny and provenance trials of western white pine in British Columbia and Idaho. Informative comparisons can also be made with growth in a western white pine spacing trial in northern Idaho.

Growth, Survival, and Damage of Douglas-Fir at the Trout Creek Hill Unit

Early growth of Douglas-fir planted at the same time on the same site as the western white pine spacing trial also was quite good, though trees made less height growth than western white pine during the first few years. At age 11, Douglas-fir averaged 11% shorter (4.7 vs. 5.3 m) and 20% smaller in diameter (6.3 vs. 7.9 cm) than western white pine planted at the same 3 m spacing. Growth between ages 11 and 16, however, tended to be slightly greater for Douglas-fir than western white pine; its 5 yr height growth averaged 3.5 vs. 3.2 m for western white pine and its diameter growth averaged 4.4 vs. 3.2 cm for western white pine. And at 16 yr, Douglas-fir was only 4% shorter in height (8.2 vs. 8.5 m) and 11% smaller in diameter (10.7 vs. 12.0 cm) than western white pine. Thus, net performance of the two species at the end of the plantations' first two decades is expected to be rather similar. Western white pine and Douglas-fir planted in pure and mixed plots at 3 m spacing had similar amounts of multiple stems (1.3% for western white pine and 0.8% for Douglas-fir). Overall, both species have grown well but have been susceptible to different damaging agents. The

Table 6. Early growth in western white pine plantings at other locations in North America.[1]

Location	Spacing (m)	Total age (yr)	Dbh (cm)	Height (m)	Reference
Northern Idaho	2.1	23	10.7	NA	Boyd and Deitschman (1964)
Montana	1.9	29	11.9	NA	Boyd and Deitschman (1964)
Northern Idaho	NA	14	NA	2.3	Rehfeldt and Steinhoff (1970)
Northern Idaho	NA	16	NA	4.1	Steinhoff (1979)
British Columbia	NA	7-8	NA	0.9	Meagher and Hunt (1998)
Vancouver Island, BC	NA	12	NA	1.8	Bower (1987)
Northern Idaho	2.4	11	NA	0.8	Hoff and Steinhoff (1980)
Northern Idaho	NA	15	NA	7.0	Fins and Rust (1997)
Northern Idaho	2.4	17	9.7	5.5	Rehfeldt et al. (1991)

[1] Data given for treatment or provenance with best growth

Douglas-fir was more susceptible to damage from wet snow (leaning trees and top breakage), less likely to be damaged by elk, and resistant to blister rust infection. Mortality of Douglas-fir through 16 yr was about 7%, less than half the rate in the western white pine 3 m plantings (19%). The mortality of the Douglas-fir, however, was greatest in the most recent measurement period (and most attributed to root rot) while the western white pine plantings had their greatest mortality prior to age 8 and the rate has declined over time. Thus, differences between species in survival will probably decline in the future.

Growth in Other Plantations and Trials

Most currently available information on growth of planted western white pine is based on studies in the Inland Empire; the exception being early results from provenance and progeny trials in coastal and interior regions of British Columbia. The growth (primarily height) attained *in the best treatments* of these studies in both geographic areas is summarized in Table 6. Although growth in these other plantings (with comparisons limited to the plantings more than 10 yr old) is also better than growth in natural stands, it is lower than that found in the Trout Creek Hill spacing trial.

Growth in Another Spacing Trial

A spacing trial established with 2-0 bareroot stock on a "good" western white pine site (SI of about 18 m at total age 50) in north central Idaho (Graham 1988) provides the most relevant examination of planting density (Table 7) and comparison with trends in our study. The Idaho trial was established prior to the availability of rust-resistant stock; mortality increased over time, and the trial was eventually abandoned. We assumed, however, that the *relative* patterns of initial growth with spacing would be unaffected by later mortality. Four of the five spacing treatments were very comparable to four of those in the Trout Creek Hill study and spanned the same range (square spacings of ~2 to 6 m).

Table 7. Characteristics of western white pine growing at five spacings at age 18 on the Deception Creek Experimental Forest in north central Idaho (Graham 1988). This study is on a "good" western white pine site.

	Square spacings (m)				
Characteristic	1.5	2.1	3.0	4.3	6.1
Height (m)	4.3	3.7	4.3	4.6	3.7
Dbh (cm)	7.6	5.6	7.6	7.6	6.6
Basal area (m^2)	10.8	4.1	3.9	2.1	0.9
Volume (m^3)	27.8	10.1	11.1	6.2	2.2

General trends were similar in both studies: reduced tree size in the closest spacing (2 m or less), increasing size with increased spacing to 4 or 5 m, followed by a decline in size at the widest (6 m) spacing. There were, however, large contrasts in tree sizes and accumulated stand yields at the two locations. Trees at age 16 (18 yr from seed) in the Trout Creek Hill study were more than twice as tall as trees at age 18 (20 yr from seed) in the Idaho study and nearly twice as large in diameter. Basal areas at Trout Creek Hill were three to four times greater, and cubic volumes were four to nearly six times greater, than those achieved in Idaho.

Conclusions and Implications

Western white pine achieved outstanding growth on a site of a medium to low quality (Site III-IV for Douglas-fir) in the Cascade Range and responded to spacing in a manner similar to other intolerant species in the region. Trends in tree growth and stand development indicate that the 6 m spacing is excessively wide; growth in height and diameter was somewhat poorer than in the 4 and 5 m spacings, and there was a larger proportion of trees with multiple stems. Moreover, patterns of mortality and damage suggest that denser plantings would be more appropriate even if tree performance did not decline at the 6 m spacing. In fact, in consideration of the probability of significant mortality loss to blister rust, we suggest initial spacings of 3 to 4 m, despite the slightly better individual tree growth attained in the 5 m spacing.

A total of nearly 30% of the trees were infected with blister rust or died during the first 16 yr after planting, but the initiation of new infections appears to be ebbing. The relatively low losses and the slowing in development of new infections is probably due to a combination of some level of inherent rust resistance and the pruning of lower branches. Since our plantings were established, breeding has advanced to provide additional resistance mechanisms, and information about various pruning regimes and the benefits of pruning has improved (e.g., Schwandt et al. 1994) as have opportunities to capture financial returns from high-quality, young-growth timber.

We recommend that forest managers consider planting rust-resistant lots of western white pine more widely throughout the Douglas-fir region. Its growth on a mediocre site in this region was comparable to that of Douglas-fir and equal to or better than growth attained by western white pine in other locations (such as northern Idaho) where it has received much greater management attention. Western white pine can grow well under a wide range of site conditions, and is

better adapted than most associated species to drier, sandy soils. It is also well-suited for areas with frost pockets or susceptible to unseasonable frosts as it is one of the most frost-tolerant northwestern tree species (Minore 1979, Graham 1990), and in this study it showed good resistance to snow damage. Although western white pine is not immune to *Phellinus* root rot, it is less susceptible than Douglas-fir and western hemlock (Minore 1979) and thus may offer a less risky alternative to the latter species for areas severely infested with *Phellinus weirii*.

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