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Initial Shock and Long-Term Stand Development Following Thinning in a Douglas-fir Plantation

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ABSTRACT. Responses following the application of six precommercial thinning treatments to a 27-year-old Douglas-fir plantation (2.4-m spacing, height at age 100 = 24 m) have been monitored for 25 years. Spacing after thinning ranged from 3.4 m to 8.1 m. Immediately following thinning, trees exhibited thinning shock; that is, substantial height growth reductions. The severity and duration of the shock effect were partially related to the severity of thinning. From 15 to 25 years following thinning, however, height growth was positively related to growing space with the best height growth at the wider spacings. Diameter growth increased following thinning, with the range in diameter growth rates between spacings increasing over time. Basal area and volume growth per hectare were reduced by treatment, but the differences among spacings are decreasing. FOREST SCI. 29:33–46.

ADDITIONAL KEY WORDS. *Pseudotsuga menziesii*, precommercial thinning, respacing, thinning shock, height growth, diameter growth.

THINNING is a common and effective method for regulating individual tree and stand development. There are situations, however, where both initial and long-term responses to thinning give unexpected results. For example, initial responses to thinning are not always positive. Negative responses include reductions in height or diameter growth, chlorotic foliage, and damage or mortality associated with increased exposure (e.g., sunscald). These negative responses, individually or collectively, are sometimes referred to as "thinning shock." In addition to the physiological shock responses, thinning can also result in increased physical damage or mortality due to wind, snow, or ice.

A generally unexpected, positive long-term response to thinning is increased height growth. Although it has long been recognized that extremes of stand density can influence tree height growth, it is generally assumed that within the range of densities encountered in managed stands, density will have no effect on height growth (cf. Hagglund 1981). This is a key assumption underlying the use of site index as a measure of site quality. If height growth differences can result from variations in stand densities, it may be necessary to reevaluate yield predictions and the associated decisions by land managers on appropriate management regimes.

There is increasing evidence that at least for some poor-site Douglas-fir stands, both initial stocking levels and thinning can markedly affect height as well as diameter growth. Short-term decreases in height growth following thinning (Miller and Reukema 1977, Crown and others 1977) and long-term increases in height

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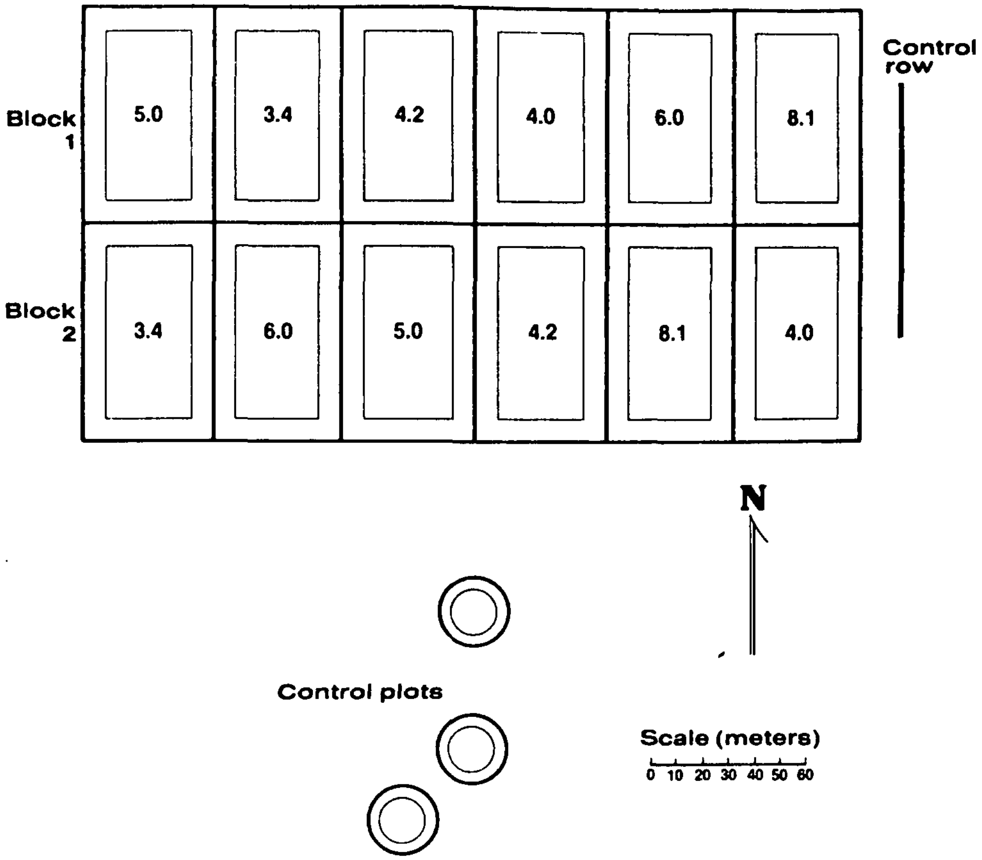

FIGURE 1. Relative locations of study plots, control row, and control plots. Numbers inside study plots refer to approximate spacing in meters after the thinning.

growth associated with plantation spacing (Reukema 1979) have been documented in recent years. This paper summarizes the 25-year growth of a Douglas-fir plantation precommercially thinned to six stocking levels. Both initial thinning shock and long-term increased height and diameter growth with increased growing space were observed.

STUDY DESIGN

The study was designed to determine how stands at various stocking levels develop to commercial size. The plan was to evaluate the potential of both poorly stocked stands and of stands close to optimum stocking for a wide range of target diameters. The six stocking levels selected were 875, 625, 500, 375, 250, and 125 trees per hectare. A randomized block design was used, with six 0.2-ha measurement plots in each of two contiguous blocks; each plot was surrounded by an 8-m buffer strip (Fig. 1). Treatment assignment within each block was random.

The original study was designed to evaluate the effects of spacing, not of thinning per se; it did not plan to compare the thinned plots with the unthinned plantation. It quickly became clear that the thinning did have some adverse effects and 20 trees in a row in the unthinned stand east of the measurement plots were designated to serve as a control for monitoring height growth. To provide a better indication of the growth trends in the unthinned plantation, data from three 0.02-ha plots, established in 1964 to serve as controls in a fertilization study, are included in some of the figures and tables. These unthinned control plots were located just south of the study area in the same plantation. Average tree height (in 1964) in the control plots was approximately equal to that in the control row; thus these plots are on a roughly comparable site.

THE STUDY AREA

The study area is on the Wind River Experimental Forest near Carson, Washington. Topography is relatively uniform with a northerly aspect; elevation averages about 600 m. The area is classified as site V (height at 100 years = 24 m). The soil is a well-drained loam with rapid permeability. Soils in the vicinity are generally considered to be nitrogen deficient; nearby studies involving nitrogen fertilization and alder interplanting have shown marked response. The study area was burned in the extensive 1902 Yacolt Burn and was reburned by another wildfire in 1927.

Weather information is available from the Wind River Ranger Station, which is about 200 m lower in elevation than the study area. Mean annual temperature, at the weather station, is 9°C. Total annual precipitation averages 2,570 mm; however, only 250 mm falls during the frost-free growing season which averages 130 days. The majority of precipitation occurs as rain or snow during the dormant season. The area has a moderate weather-damage hazard due to occasional heavy, wet snows; this wet-snow hazard is common at mid elevations along the west side of the Cascades.

The study area is part of a large plantation that was planted in spring 1929 with 1+1 Douglas-fir seedlings, raised in the Wind River Nursery from an unknown seed source. The seedlings were planted at 2.4 by 2.4 m spacing, or approximately 1,680 per hectare. In 1953, the plantation had about 1,600 trees per ha, averaging 8.8 m in height and 10 cm in diameter.[1] Generally, limbs on the lower third of the stem were dead and diameter increment had slowed slightly in recent years. Based on average tree height, site productivity varied within the study area. The two plots in the northwest corner of the area had higher than average heights; the four plots in the southwest portion had lower than average heights.

TREATMENT

The thinning was conducted to leave the best trees within an acceptable range of spacing for each stocking level. The residual number of trees per plot varied somewhat from the target levels (Table 1). The plots in Block 1 were thinned in the fall of 1953. The plots in Block 2, however, were not thinned until the following spring and summer; all work was completed by the end of July 1954. Felled trees were left on the site.

MEASUREMENTS, COMPUTATIONS, AND ANALYSES

All trees on the measurement plots and in the control row were numbered and tagged. After the growing seasons in 1954, 1959, 1964, 1969, 1974, and 1979, all trees were measured for diameter at breast height (dbh) and their condition was noted. Heights were determined on a subsample in each plot. In 1954 and 1959, 12 to 18 trees per plot (all 20 trees in the control row) were measured for height. Beginning in 1964, 20 trees per plot were measured. The trees measured for height

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[1] Average diameter in this report is the diameter at breast height (1.4 m) of the tree of mean basal area (i.e., quadratic mean diameter).

TABLE 1. Plot characteristics by treatment after thinning, fall 1954.[1]

Spacing[2]	Number	Diameter[3]	Height	Basal area	Cubic volume
m	sph[4]	cm	m	m^2/ha	m^3/ha
3.4	840	12.4	11.3	10.2	50.6
	894	9.7	7.6	6.4	21.6
4.0	627	11.2	9.1	6.1	23.8
	637	11.4	9.4	6.5	27.6
4.2	548	11.4	9.4	5.6	22.6
	563	10.2	7.9	4.6	16.6
5.0	405	13.7	10.7	6.1	28.8
	410	10.2	7.9	3.3	11.2
6.0	252	11.9	8.8	2.8	11.7
	297	10.4	8.3	2.5	9.5
8.1	138	12.7	10.0	1.8	7.3
	168	11.9	10.0	1.9	8.0
Average (all plots)	—	11.4	9.1	—	—

[1] The first line for each spacing is the plot in Block 1, the second line is the plot in Block 2.
[2] Approximate average square spacing of residual trees.
[3] Quadratic mean diameter at breast height.
[4] Stems per hectare.

in each plot spanned the observed range in diameters and were selected so that two-thirds of the tree diameters were greater than the average diameter of the plot. If a tree which had been designated for height measurement subsequently had a broken or dead top, that tree was dropped from the height sample and another tree was substituted for it from then on. In addition, annual leader length for the growing seasons 1953–59 was measured on five trees per plot (10 in the control row).

Five-year height growth was computed for each designated tree that was present at both ends of a measurement period. The plots differed in their average height in 1954; we assumed these differences represented differences in site quality, and adjusted the height growth values to reduce this source of variation. Adjusted height growth per plot was determined for each measurement period by averaging the individual tree values and then expressing growth as a percentage of the 1954 plot height. We were unable to adjust each tree value individually (as we did for diameter growth) because we did not have a 1954 height for all the trees eventually measured for height. Differences in height growth between the thinning treatments were tested using analysis of variance. Tukey's test was used to separate means when treatment effects were statistically significant ($p = 0.10$).

Diameter growth was analyzed for both the total stand and for the 100 largest stems per hectare (sph) using covariance analysis; the covariate was 1954 individual-tree diameter. Diameter growth was adjusted to reduce the variation in the data caused by variations in site quality. Analysis of variance using adjusted means was followed by Scheffe's test to separate means when the treatments were statistically significant ($p = 0.10$).

The tarif system (Turnbull and others 1970) was used to determine a local volume equation for each measurement period. Volume growth per plot was determined by summing the volume increment of each tree which survived the growth period. All volume computations were made on the basis of total stem cubic volume.

STAND DEVELOPMENT

Overview.—The immediate effects of the thinning treatments were detrimental. Opening up the stand resulted in chlorotic foliage, sunscald, and snow and ice damage in the form of broken tops and branches and leaning trees; one of the plots at the widest spacing had particularly heavy damage. In addition, height growth was reduced by thinning as previously reported by Staebler (1956). The amount of height growth reduction during the first 10 years was roughly proportional to the severity of thinning.

Long-term effects of increased growing space have, however, been beneficial. Following the initial shock, height growth did recover in the thinned plots. In fact, height growth is currently greatest at the widest spacings. Diameter growth increased in response to thinning—the wider the spacing, the greater the rate of growth. Even at the widest spacings, tree form is good and branch size is quite satisfactory.

Height and diameter growth have slowed in recent years in the closer spacings, and the range in growth rates among spacings has increased over time. Basal area and cubic volume *per tree* are greatest at the widest spacings. Due to the many fewer trees per plot at the wide spacings, however, basal area and cubic volume *per hectare* are greatest at the closest spacings.

Height Growth.—Height growth decreased immediately following thinning. The 1954 leader lengths of all measured trees in Block 1 (thinned fall 1953) averaged only 50 percent of the previous year's length. Trees in Block 2 (thinned summer 1954) had 1954 leader lengths that averaged 23 percent less than in 1953. The reductions in height growth were even greater in subsequent years than in the 1st year. The least height growth occurred in 1957 and 1958 when the height growth of the thinned trees averaged 70 percent less than the 1953 growth. In contrast, during those two years, the trees in the control row grew 19 percent and 12 percent *more* than in 1953.

The 5-year height growth patterns by thinning treatment are presented in Figure 2. Height growth on thinned plots averaged half of that in the control row during the first 5 years (1.0 m versus 2.3 m) (Fig. 2a); it was significantly less at the 5.0- and 6.1-m spacings than at the three narrower spacings.

During the second 5-year period, height growth on the thinned plots averaged about 16 percent less than height growth in the control row with the exception of the widest spacing (Fig. 2b). Height growth at the 8.1-m remained sharply depressed during this measurement period, and was significantly less than that at other spacings.

In the third 5-year period (Fig. 2c), the 8.1-m spacing again had the poorest height growth, but it was not significantly less than any except the 6.0-m spacing. Average height growth in the thinned plots was similar to that measured in the control row. Thus, 10 years after thinning, the shock effect was no longer a factor influencing height growth.

During the fourth and fifth 5-year periods, height growth was roughly proportional to growing space with the *greatest* height growth at the wider spacings (Fig. 2d, 2e). During the 4th measurement period, height growth at the 3.4-m and 4.0-m spacings was significantly less than that at the 6.0-m spacing. In the last measurement period, the 3.4-, 4.0-, and 4.2-m spacings all had significantly less height growth than the 6.0-m spacing; the height growth at the 3.4-m spacing was also significantly less than the growth at the 8.1-m spacing. All of the treatments had better 10-year height growth than the control row; 10-year height growth in the control row was very close to the expected height growth of 2.4 m for a stand of its age and site index (McArdle and others 1961). The widest spacings had 10-year height growth increments of 4 to 5 m.

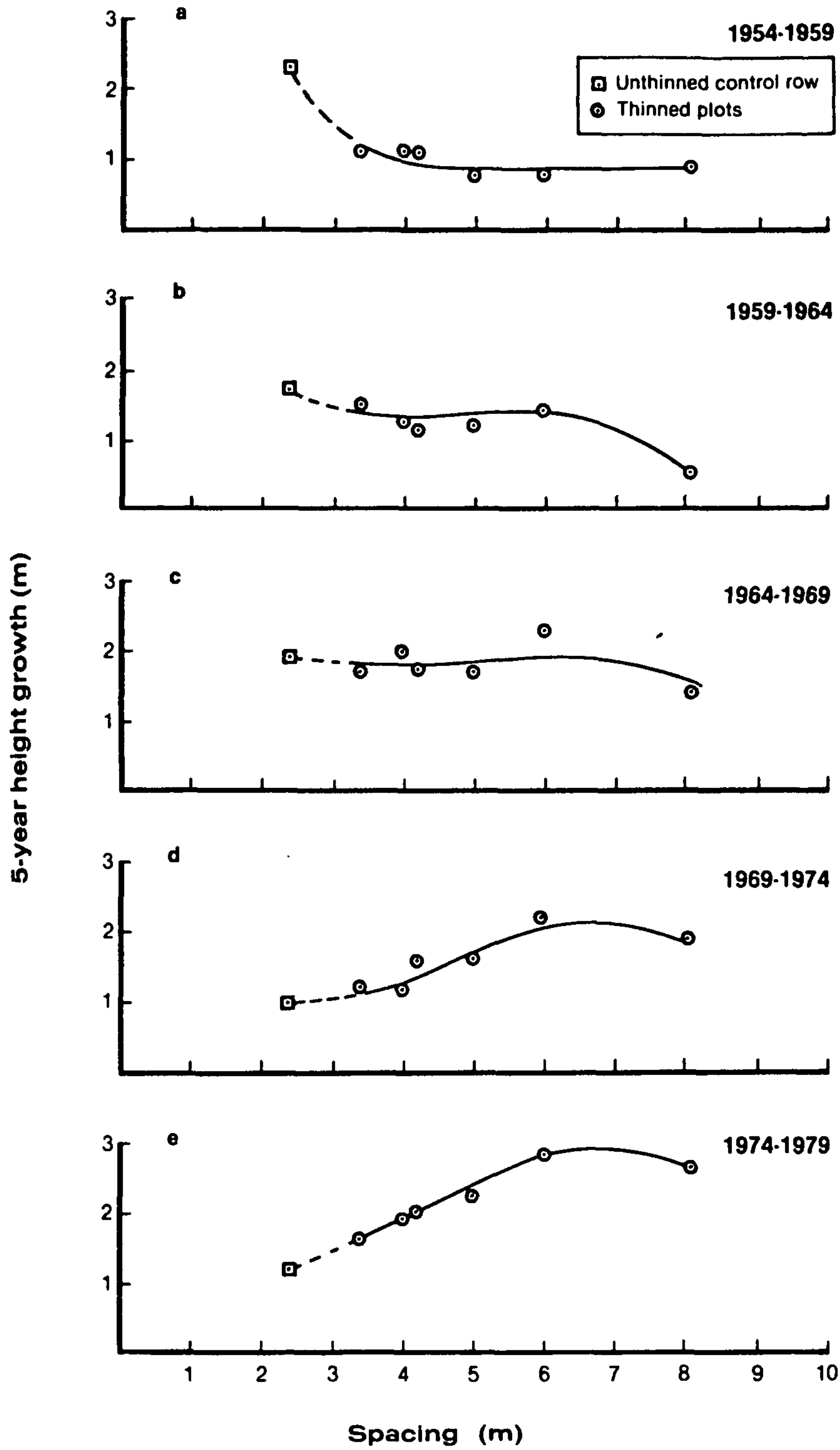

FIGURE 2. 5-year height growth by spacing, (a) 1954–59, (b) 1959–64, (c) 1964–69, (d) 1969–74, (e) 1974–79.

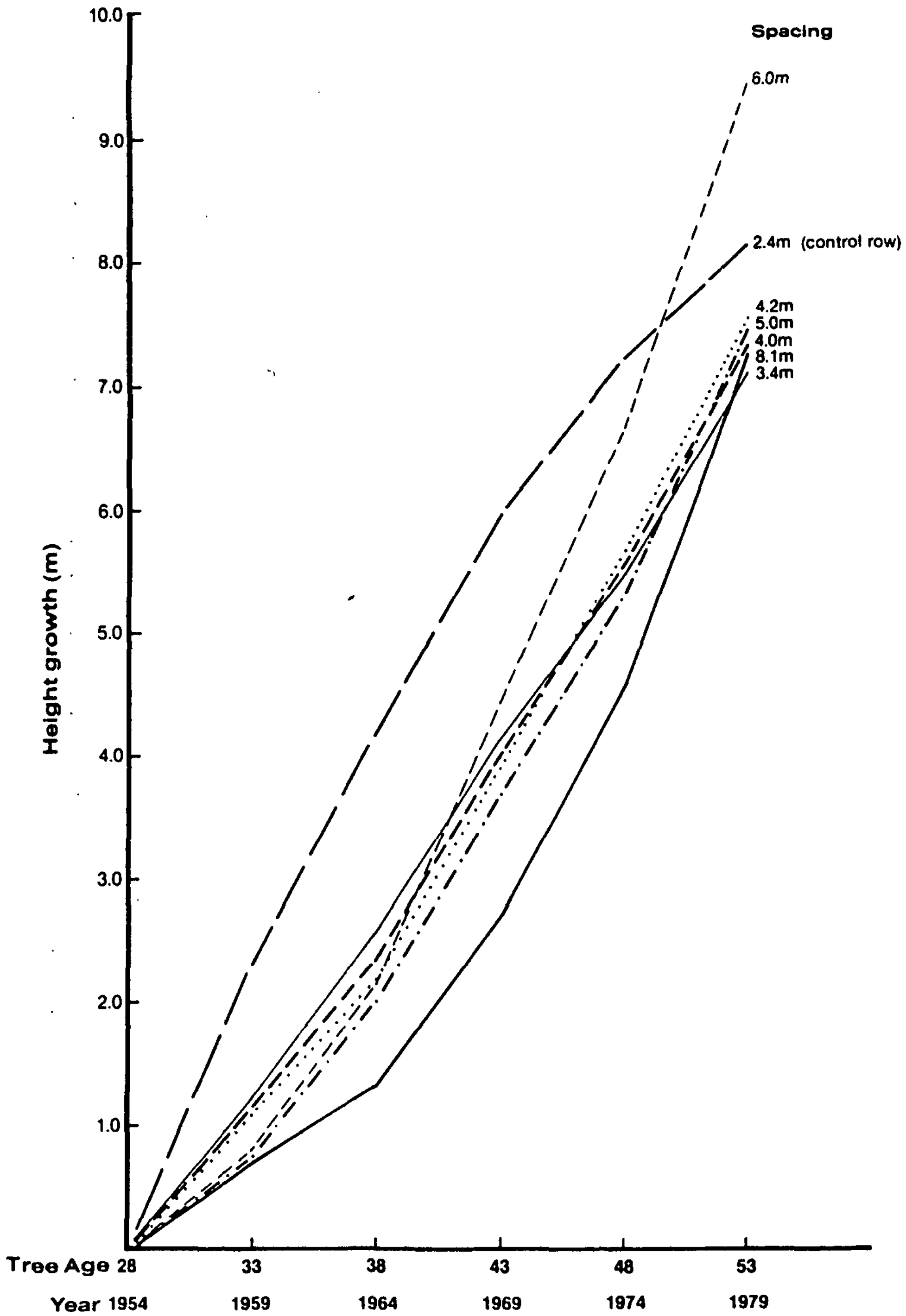

FIGURE 3. Average tree height by spacing and measurement period (heights adjusted to a common 1954 height).

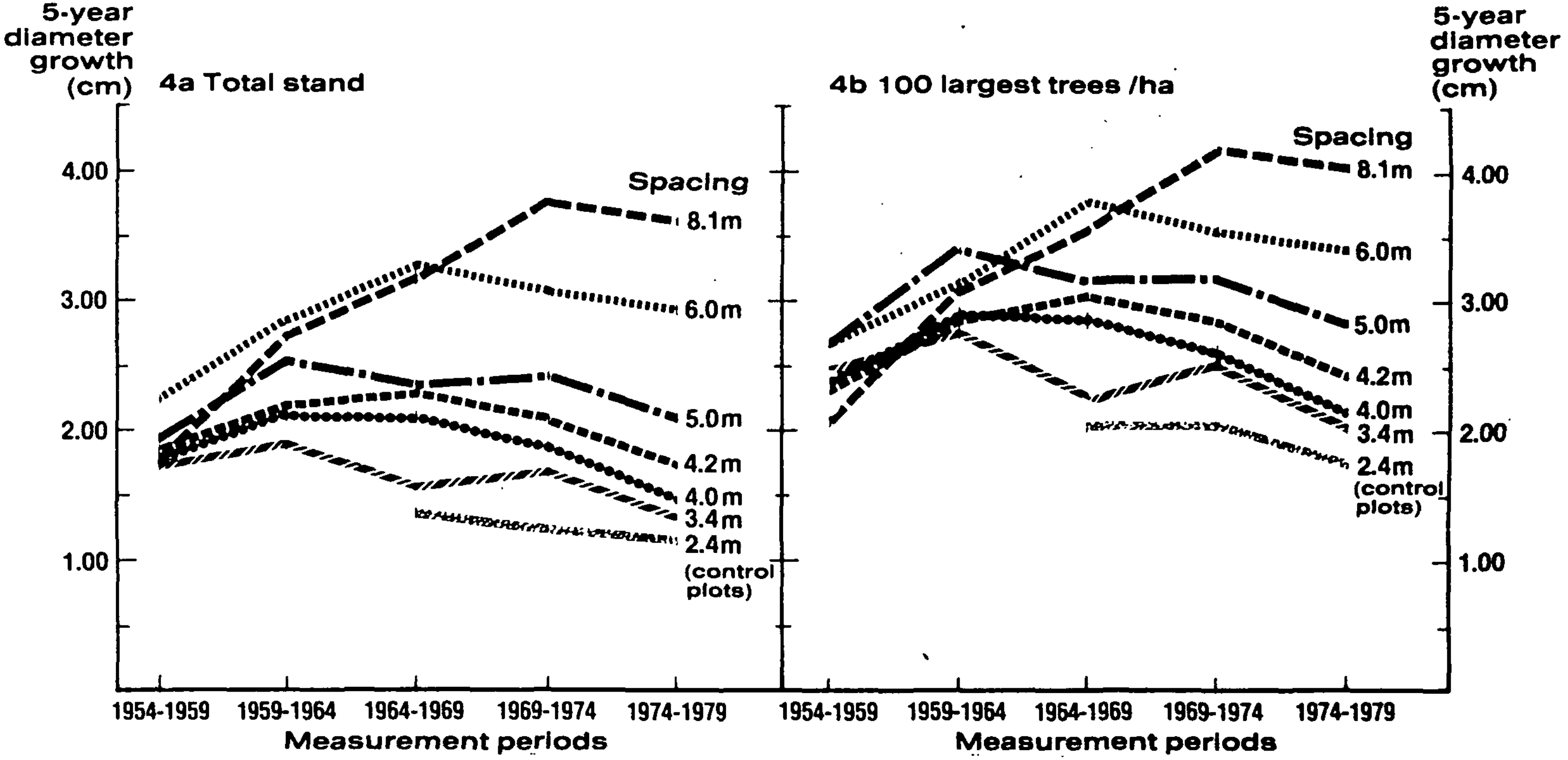

FIGURE 4. Five-year diameter growth of surviving trees by spacing and measurement period (diameter growth adjusted by covariance) (a) for the total stand and (b) for the 100 largest trees per hectare.

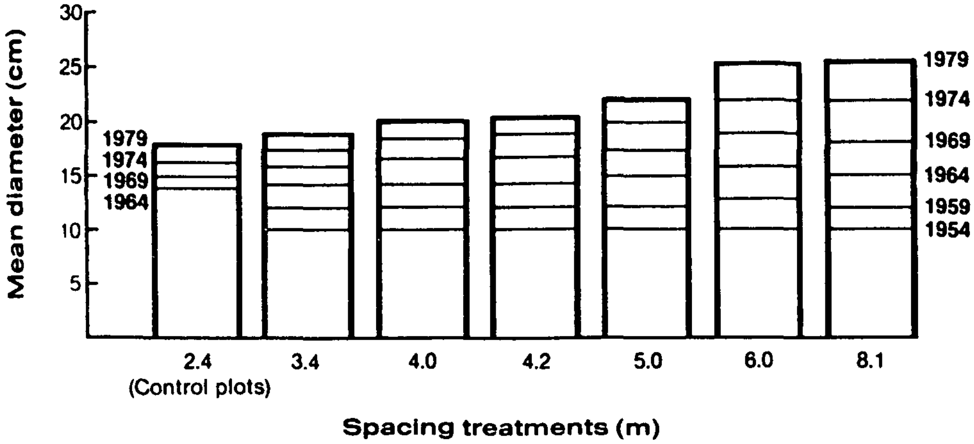

FIGURE 5. Mean diameter of trees surviving the 25-year period by spacing and measurement period (diameters adjusted by covariance).

Total height growth by treatment over the 25-year period was essentially the same at all except the 6.0-m spacing, which was significantly better (Fig. 3). The improved growth in recent years has been sufficient to overcome the losses due to thinning shock. Recent trends indicate that all of the thinned stands will produce taller trees than the unthinned stand, and that this height will increase with spacing, up to a spacing of at least 6 m. The difference in height in the future will depend on how long the wide spacings maintain their superior height growth.

Diameter Growth.—Diameter growth of trees in all treatments increased in response to thinning, and the wider the spacing the greater the growth (Fig. 4a). The relatively poor diameter growth at the 8.1-m spacing in the first measurement period can probably be considered another symptom of thinning shock. We cannot tell if this shock effect on diameter growth was limited to the widest spacing; however, any negative impacts on diameter growth were probably most severe and longest lasting at the widest spacing.

Overall, the closer spacings had relatively small increases in diameter growth which lasted for a few years, while the wider spacings had greater increases in diameter growth which lasted longer. Diameter growth of trees surviving the 25-year period averaged more than 80 percent greater at the 8.1-m spacing than at the 3.4-m spacing (0.60 versus 0.33 cm per year). During the most recent measurement period, growth was almost three times as much at the 8.1-m as at the 3.4-m spacing (0.72 versus 0.26 cm per year). In this last measurement period, there were significant differences in growth between all of the spacings, with the one exception that the two narrowest spacings did not significantly differ from each other. The added increments in diameter growth rates at the widest spacings were greater than anticipated. Rather than observing a diminishing effect of additional growing space on diameter growth as we would have predicted, the reverse appears to be true. Because the range in diameter growth rates among spacings has continued to widen over time, the differences in average diameter between spacings should continue to widen in the future (Fig. 5).

Diameter growth of the 100 largest trees per hectare generally followed the same trends as diameter growth of the total stand (Fig. 4b). Although the range is less, even for these largest trees in the stand, the wider the spacing, the greater the diameter growth. Averaged over the 25-year period, the 100 largest trees per hectare grew about 40 percent faster at the 8.1-m spacing than at the 3.4-m spacing

TABLE 2. Number and diameter of stems lost to mortality by spacing and measurement period.

Spacing (m)	Mortality by period									
	1954–59		1959–64		1964–69		1969–74		1974–79	
	sph[1]	Dg(cm)[2]	sph	Dg(cm)	sph	Dg(cm)	sph	Dg(cm)	sph	Dg(cm)
2.4[3]	–	–	–	–	198	10.9	165	14.0	49	9.4
3.4	0	–	5	13.7	10	15.7	30	12.7	35	13.6
4.0	2	8.1	5	12.2	7	11.7	15	18.3	10	15.2
4.2	0	–	2	7.6	5	14.5	0	–	5	16.8
5.0	5	12.7	12	16.3	7	14.2	5	23.9	0	–
6.0	7	11.7	7	14.5	2	15.0	5	21.3	0	–
8.1	12	11.2	7	12.4	2	14.7	5	20.1	0	–

[1] Stems per hectare.

[2] Quadratic mean diameter at breast height.

[3] Unthinned control plots.

(0.67 versus 0.48 cm per year). During the most recent period, they grew twice as fast at the 8.1-m as at the 3.4-m spacing (0.81 versus 0.40 cm per year). In the last measurement period, diameter growth of the 100 largest trees per hectare differed significantly among the 3 widest spacings and between the three wider spacings and the three narrower ones. Thus, even the largest trees per hectare are still growing significantly better at the widest spacings.

Diameter growth within the spacings was quite variable. At the widest spacing, where theoretically all trees have been free to grow, 25-year diameter growth of surviving trees ranged from 7.4 to 26.2 cm. The range at the 3.4-m spacing was from 1.5 to 15.0 cm. Even among the current 100 largest trees per hectare, 25-year diameter growth ranged from 11.7 to 26.2 cm at the widest spacing and from 8.1 to 15.0 cm at the closest spacing. Diameter growth within a spacing tended to be proportional to tree diameter at the time of thinning; however, there was considerable variation in the rate of increase and commonly the largest (or smallest) trees per plot in 1979 were not the largest (or smallest) trees per plot in 1954.

Mortality and Damage.—Mortality has generally been minor. In the 25 years following thinning, 85 trees (7.3 percent) died in the 12 study plots; this would be equivalent to about 35 trees per hectare. Mortality has been erratically distributed (Table 2); it has not been closely related to spacing, with two apparent exceptions—the initial mortality at the widest spacing and the recent mortality at the closest spacings. Generally, mortality has been associated with snow breakage, sunscald, root rot (*Phellinus weirii*), or insect damage. Most of the mortality in the 10 years following thinning can probably be attributed to the thinning.

Damage, predominately in the form of broken or dead tops following wet snows, was quite closely linked with mortality. Plots having the greatest mortality usually also had the greatest top damage, and severely damaged trees at one measurement were often dead at a subsequent measurement. Trees with minor top damage or sunscald did recover, however.

On a percentage basis, the 8.1-m spacing had the most mortality and damage. Although the number of trees lost to mortality was relatively small, the loss of growing stock at the wider spacings was important. One of the plots at the 8.1-m spacing had a 20 percent reduction in number of stems during the initial 10-year period following thinning. The 8.1-m spacing also had a lot of top damage following thinning, especially on one plot. In 1959, 21 trees had their tops out;

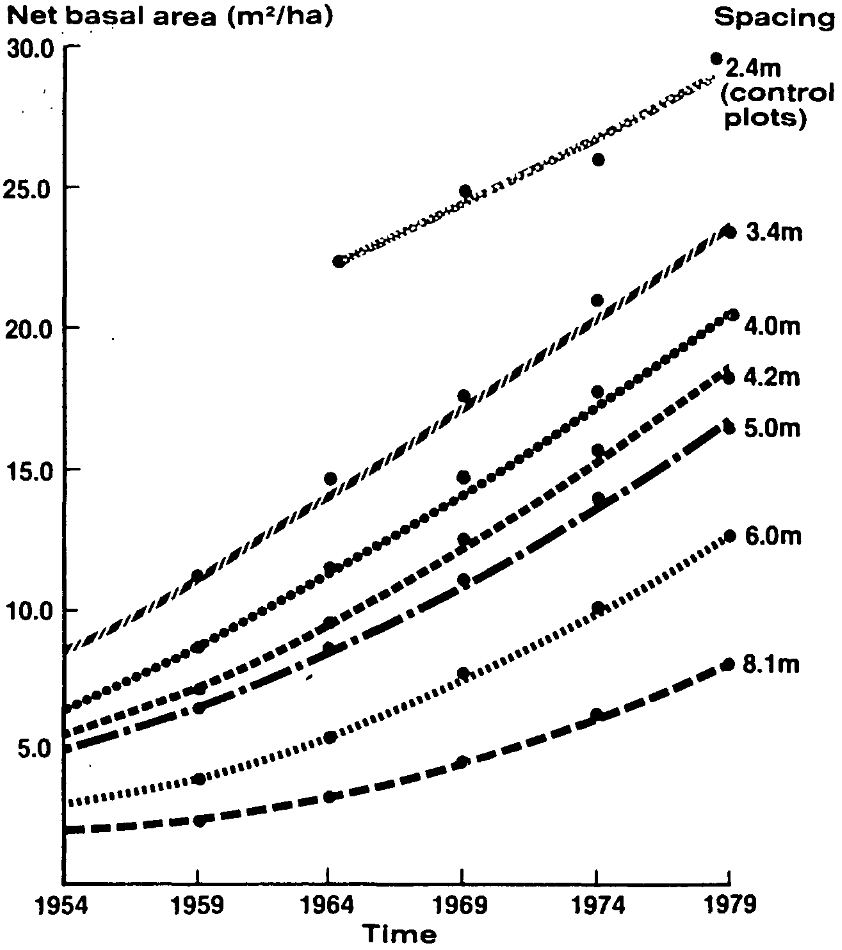

FIGURE 6. Net basal area by spacing and measurement period.

11 were on the 8.1-m plots. In 1964, 38 trees were listed as having damaged tops or poor terminal growth; 20 were on the 8.1-m plots.

In the two most recent 5-year periods, the 3.4-m spacing had the most mortality and the most top breakage. The average diameter of mortality in 1974 and 1979 (at the 3.4-m spacing) was smaller than the average diameter of surviving trees; thus, some of this mortality was most likely competition related. Most of the recent damage at this spacing was also confined to the smaller trees.

Volume and Basal Area Growth.—Basal area growth *per tree* has increased sharply with increased spacing, but the greater growth rates have not been great enough to offset the lesser number of trees. Thus, the initial differences in basal area per hectare between treatments have widened over time (Fig. 6). The rate of gross basal area growth has been improving over time with increased spacing; in addition, the recent mortality at the closer spacings is reducing net growth. In the last 5-year period, the net change in basal area was quite similar (2.7 to 3.0 m^2/ha) at the five closest spacings (i.e., 3.4- to 6.0-m). The 8.1-m spacing has not yet caught up to the others in basal area growth.

Total volume growth per hectare generally followed the same trends as basal area growth. The differences in cubic volume between treatments have widened

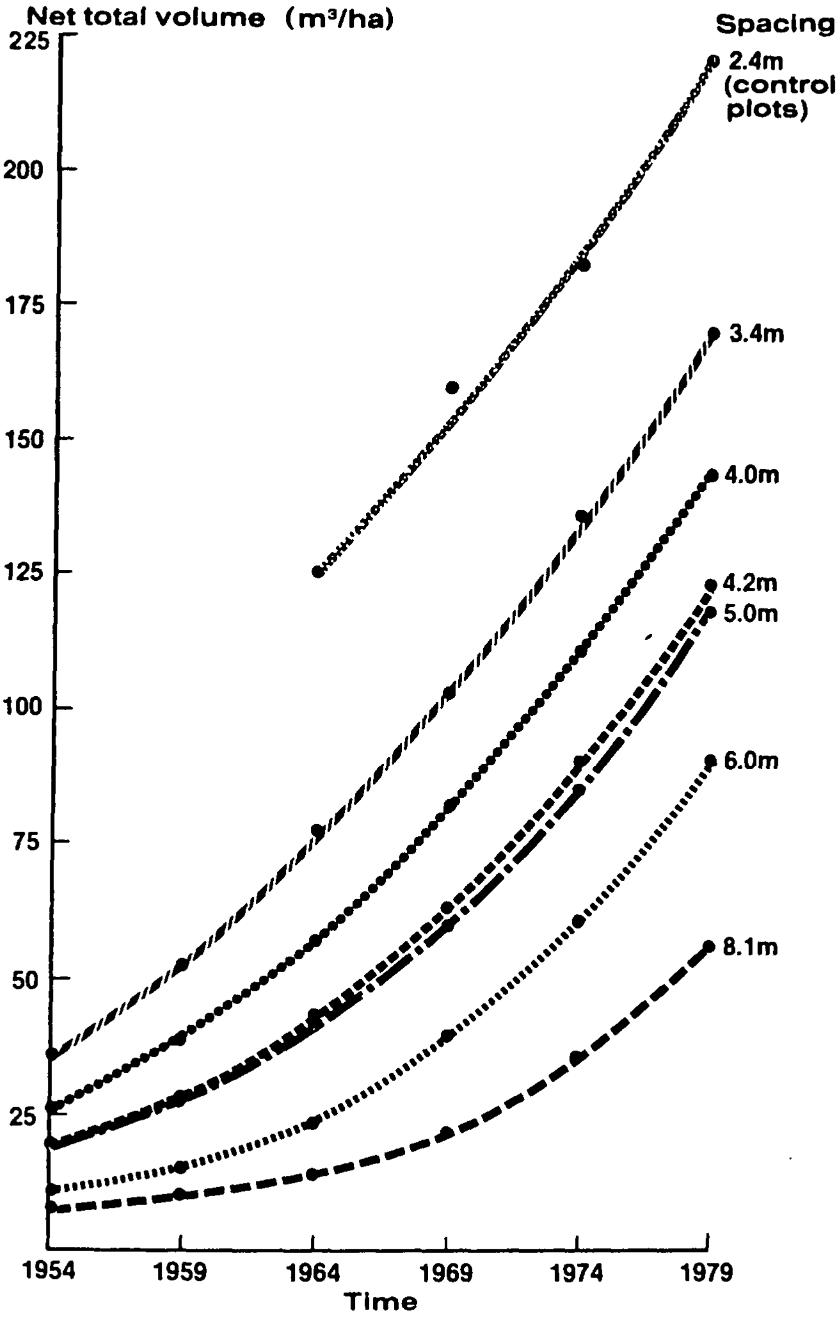

FIGURE 7. Net total cubic volume by spacing and measurement period.

over time (Fig. 7). Among all but the widest spacing (3.4- to 6.0-m), however, the range in volume growth has narrowed. For example, although the 6.0-m spacing has only a third as many trees as the 3.4-m spacing, in the most recent measurement period, its net volume growth was almost 90 percent of that at the closer spacing. Volume growth rates are still increasing over time at all spacings.

DISCUSSION

Precommercial thinning of Douglas-fir can result, at least on some sites, both in immediate decreases and in long-term increases in height and diameter growth. Both thinning shock and increased height growth following thinning have been previously reported; however, this case history is unique in the magnitude of the height growth responses.

Two other studies have also reported thinning shock in Douglas-fir; both were on low quality sites (site V), similar to the site used in this study. The first study (Miller and Reukema 1977) was in a 20-year-old plantation and combined thinning and fertilization of individual trees with nitrogen or nitrogen plus other elements. After 5 years they found that thinning alone had not increased diameter growth and had reduced height growth by about 25 percent. Thinning plus fertilization increased both diameter and height growth. The other study (Crown and others 1977) was in a 24-year-old plantation and included two levels of thinning and two levels of nitrogen fertilization. In their 3-year data, height growth was reduced following thinning with greater reductions in height growth in the heavier thinning treatment. Fertilization reduced thinning shock, and the heaviest fertilizer application had the least height growth reduction. Thus, in Douglas-fir stands which are prone to thinning shock and which are nitrogen deficient, it appears that shock can be reduced or eliminated by fertilization.

The occurrence, duration, and severity of thinning shock are apparently related to thinning intensity, site quality, and tree species, vigor, and age. Thinning shock is not limited to Douglas-fir. Height growth reductions following thinning have also been reported for red pine (Bickerstaff 1946; Berry 1965; Day and Rudolph 1966, 1972), sand pine (Burns and Brendemuehl 1978), Sitka spruce (Jack 1971), balsam fir (Piene 1981), and other species (Braathe 1957). Overall, it appears that both the physiological shock symptoms and the physical damage following thinning are most common when stands are heavily thinned later than the recommended time for precommercial thinning (Reukema 1975). In addition, thinning shock seems to be most common on medium to poor quality sites.

Increasing growing space, either by initial spacing or thinning, can significantly reduce competition for the site's resources and, on some sites, increase height growth. Interestingly enough, two of the studies in which thinning shock was found also showed subsequent increases in height growth. The Douglas-fir plantation reported on by Crown and others (1977), where thinning reduced 3-year height growth, was later reported on by Hall and others (1980). Six years after treatment all the thinned treatments (fertilized and unfertilized) had greater annual height growth increments than the corresponding unthinned plots. The authors concluded that if the present trends in height growth continued, thinning (as well as fertilization) would result in increased total height. Day and Rudolph (1966, 1972) reported on a 25-year-old red pine plantation (height at age 50 = 20 m) thinned by various methods to different residual stocking levels. During the first 3 years following thinning, two of the heaviest thinning treatments had significantly reduced height growth. During the next 4 years, however, height growth on all the thinned plots was better than on the unthinned ones.

On some sites, height growth is apparently depressed by close spacing. In a 53-year-old Douglas-fir spacing trial (located 11 km from our study area), heights at the narrowest spacing (1.2 m) were 37 percent shorter than those at the widest spacing (3.7 m) (Reukema 1979). Braathe (1957), in his review of the European literature, provides additional examples of the effects of initial spacing and thinning on height growth.

Young Douglas-fir stands growing on poor quality sites are capable of taking advantage of additional growing space, and we believe wider than usual spacings are quite promising. On some sites thinning shock may occur, primarily, we think, when stands on poor sites are heavily thinned later than recommended. We believe that the *long-term* result of precommercially thinning such stands will be increased height and diameter growth.

Although confirmation of these results at other locations is needed, we believe it has been shown that height growth of Douglas-fir is not always independent of stand density. The available information may be insufficient for refining current height growth predictions by silviculturists or stand modelers; however, future managed stand predictions should take these effects into account.

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