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EFFECTS OF PLANTATION AND JUVENILE SPACING ON TREE AND STAND DEVELOPMENT

J. Harry G. Smith and Donald L. Reukema

The aim of this paper is to summarize current knowledge of effects of initial spacing and respacing of plantations and natural stands on early growth—until the time of first commercial entry—for coastal Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), concentrating on conclusions that can be drawn from the literature and the authors' own studies.

General results of initially close spacings, with or without subsequent thinning, are well known (Evert 1971, 1973, 1984, Hamilton and Christie 1974, Sjolte-Jorgensen 1967), and interest in spacing is increasing. The high costs of stand establishment, limited markets for small trees, ability of technologists to make good use of fast-grown wood, inability to grow clear Douglas-fir except by pruning, and the premiums for large logs and trees have strengthened the view that wider spacings are economically preferable (Smith 1958, 1980, Smith and Kennedy 1983).

To manage stands so that landowner's goals are achieved efficiently, forest managers must set target tree sizes for the products likely to be desired in the future. These tree sizes can be translated into desired numbers of trees per acre (or per ha), and thus into spacing. Fortunately, there can be flexibility in a manager's efforts to control stand development by numbers of trees, basal area, or average dbh. Targets established should allow efficient use of the resources available.

LIMITATIONS OF SPACING TRIALS

Some Existing Trials

The oldest plantation spacing trial of Douglas-fir was established in 1925 on a relatively poor site at Wind River in southwest Washington. Stands were planted at various spacings, from 4 to 12 feet (1.2 to 3.7 m), and were allowed to grow without subsequent treatment (Reukema 1979). All who have visited the Wind River trial have been struck by the dramatic increase in tree size with wide spacings and at edges of the stands. Other spacing trials in the United States include one established in 1961 near Port Gamble, Washington (by Pope and Talbot), where trees were planted at spacings of 6 to 12 feet (1.8 to 3.7 m). Newly established trials include spacings as wide as 20 feet (6 m), but it will be many years before results are known.

The oldest trials in British Columbia were established in 1957 on a very good site at the University of Columbia Research Forest near Haney; plantation spacings ranged from 3 to 15 feet (0.9 to 4.6 m) (Smith 1983, Walters and Smith 1973). Younger trials include spacings up to 16.5 feet (5 m), ratios of distances within rows to distances between rows (rectangularities) up to 1:4, and mixtures of species. Beginning in 1962, the B.C. Ministry of Forests established three trials that include coastal Douglas-fir (K. J. Mitchell, pers. comm.); the widest spacing was 15 feet (4.6 m). These plantations have been maintained and examined, but data have not yet been published.

In France, a spacing trial was established in 1955 on a very good site with seed from Yelm, Washington; plantation spacings of 1.5 to 3.0 m (4.9 to 9.8 feet) have been maintained both without thinning and in association with three intensities of thinning (Mitchell et al. 1983). French foresters have followed results of these trials with interest (Oswald and Parde 1984), and numbers of trees now being planted have been greatly reduced.

No trials in the United Kingdom include wide spacings of Douglas-fir without thinning (Hamilton and Christie 1974). In New Zealand, all old stands of Douglas-fir have been thinned and, with the exception of early agro-forestry trials, there are no data on spacings wider than 8 feet (2.4 m) (Spurr 1961, 1963).

In Germany, trials begun in 1958 and 1961 on good sites include spacings of 1.5 to 5 m (4.9 to 16.4 feet) (Kenk 1981). A younger set of trials includes a range in densities of 500 to 4,000 trees/ha (200 to 1,600/acre), with distance between rows of 2 to 7 m (6.6 to 23.0 feet) (Kenk and Weise 1983). Analyses of thinned stands established in rows 3 by 1 m to 5 by 1 m (9.8 by 3.3 to 16.4 by 3.3 feet) and measured at ages 43 to 73 years confirm the importance of initial spacing (van Tuyll and Kramer 1981).

The major advantage of existing trials of initial spacing is their known history. Most long-established spacing trials include spacings much denser than now considered of practical importance, but none includes the wide spacings necessary to grow trees to final harvest size with no intermediate thinning. The opportunities for meeting objectives that range from maximizing biomass to optimizing growth of large trees of high quality can be appreciated better by considering results from a full range of stand densities. Data suggest that growth of trees in size and value can be increased by using spacings beyond the widest that are now commonly applied.

Problems in Establishing Spacings by Planting

Many factors cause establishment of plantations to be less than perfect: the presence of spots that cannot be planted, seedling mortality, advance regeneration and subsequent natural regeneration, and invasion by brush and hardwoods. These conditions all tend to occur in clumps.

In most research trials cited, seedlings that died the first year (or later) were replaced, volunteer tree seedlings were cut, and brush was at least partly controlled. These procedures were deemed necessary to ensure that the intended spacing was maintained during stand establishment. These procedures have limited the researcher's opportunities to learn the impact of omitting such practices under operational conditions, but it is impractical to duplicate any specific set of operational conditions.

Even with replacement of seedlings that die the first year (fill-planting) in spacing trials, substantial early mortality that is unrelated to spacing may occur. Survival at age 17 at Wind River was 92 to 95%; survival at age 10 at Haney was 86 to 95%. Subsequent trials at Haney without fill-planting lost up to 30% or more—mostly in large patches.

Gains from Juvenile Spacing

When spacing is established by thinning excess trees from existing stands, of either natural or plantation origin, residual spacing is usually less uniform than plantation spacing. Subsequent mortality and invasion by tree or brush regeneration, however, are minimal. More important, a manager can select trees that occupy the best microsites and have the best phenotypic and, perhaps, genetic potential. Gains can be quite large and important, but to achieve them requires careful selection of trees worth leaving.

Stands receiving juvenile spacing vary greatly, especially in stand structure and age at the time of spacing. Plantations receiving spacing control have often been precommerically thinned because of extensive fill-in by natural regeneration. Respacing in plantations that have not had much natural fill-in is another matter and may offer even greater opportunities for selecting leave trees that will maximize yields.

Considering all factors that influence stand development, Reukema (1975) suggests that stands should be respaced when leave trees are 10 to 15 feet (3 to 5 m) tall and 10 to 15 years old. Wiley and Murray (1974) make a similar recommendation. At this stage, trees are tall enough to escape animal damage and old enough to exhibit potential for superior growth and quality. The desired spacing should be established early to maximize the gain. As stands become older, and crowns become shorter with increased competition, responses to respacing can be substantially reduced.

TREE AND STAND DEVELOPMENT

Two common assumptions about tree and stand development are that (1) height is unaffected by spacing and (2) other stand attributes are largely a function of spacing and attained height. In many yield tables, attained dbh, mortality, and yield are modeled as functions of spacing and height (e.g., Mitchell and Cameron 1985); each of these is then related to site index and age through the assumed rate of height growth. If these assumptions were strictly true, effects of spacing, and other treatments, on stand development would be easy to model.

Variation in these relationships may be substantial, however, from one area to another, and perhaps from one stand to another. The authors have observed effects of spacing on tree dimensions and yields that differ from the common assumptions about tree and stand development. They attribute the differences between their observations and results reported in other regions to others' reliance on a few dense (closely spaced) plots and on thinned stands. The observations that follow suggest a range of "expectations" about stand development.

Height Growth

At close initial spacings, height growth can be greatly reduced; and at wide spacings, both mean height and top heights can be increased substantially as a result of enhanced crown development (Curtis and Reukema 1970). The authors expect that height growth in relation to age (and thus site index) can be improved by controlling stand density, especially on poor sites.

Two striking examples of beneficial effects of wider spacings on height growth are the Wind River plantation spacing trial started in 1925 (Reukema 1979) (Figure 1) and the Planting Creek respacing in a 27-year-old stand in 1954 (Harrington and Reukema 1983). Unfortunately, both plantations are on fairly poor sites and both were established with off-site seed sources; the authors do not believe that the effect of using off-site seed is likely to vary with spacing, but it is a possibility. Other studies, such as the Haney spacing trial (Figure 1), show much lesser effects of spacing on height growth, and some

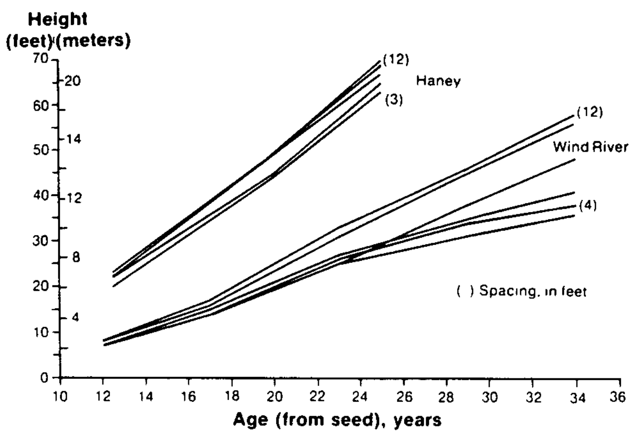

Figure 1. Attained height of average trees, by age and spacing, in Douglas-fir spacing trials at Wind River and Haney.

show little or no apparent effect on top height. In the French trial, reduction in top height appears to be developing at the closest spacing (Mitchell et al. 1983). One set of trials in Germany suggests a decrease in both average height and top height with increased spacing (Kenk 1981).

The immediate effect of precommercial thinning or respacing may be to retard height growth for a time (i.e., thinning shock). This effect may be quite severe initially, especially with late precommercial thinning on poor sites, but it is generally not long lasting. In some instances height growth is subsequently improved by the increased growing space.

In the Planting Creek trial, stands were respaced 25 years after the stands were planted, from 8 foot (2.4 m) spacing to spacings ranging from about 11 to 26 feet (3.4 to 8 m). This late respacing caused a severe reduction in height growth (Staebler 1956). After a recovery period of about 10 years, however, height growth improved and now increases as spacing increases (Harrington and Reukema 1983).

In thinning and fertilizing trials at Shawnigan Lake, B.C., stands were thinned at age 24 to levels of about 360 and 780 trees/acre (890 and 1,925/ha). Height growth was reduced on thinned plots for the first two years following thinning, more so on the more heavily thinned treatment. Since then, through the ninth year, height growth has been better on thinned than on unthinned plots (Barclay et al. 1982).

The levels-of-growing-stock (LOGS) trials, begun in the 1960s, involved late precommercial thinning or juvenile spacing. Most stands were thinned to 350 to 400 trees/acre—about an 11 foot (3.3 m) spacing—when trees were 15 to 25 years old and about 25 to 40 feet (7.5 to 12.0 m) tall (Williamson and Staebler 1971). Only on one poor site was there any reduction in height growth, and the reduction was minor and of short duration.

Diameter as a Function of Height

With early spacing control, the wider the spacing the larger the average diameter of trees for a given site and age. Diameter growth increases with increased spacing up to the spacing at which trees grow without competition, which may be much wider than usually thought. The relation of diameter to height at a given spacing can vary substantially from one stand to another.

For example, at an average height of about 60 feet (18 m), trees had substantially larger average diameters at wide spacings in the Haney trials than in the Wind River trials (Figure 2). This 60 foot (18 m) height was attained prior to age 25 at Haney but not until after age 35 at the wider spacings at Wind River. Results in the French trial are similar to those at Haney. Relationships for the German trials are known for only a single age, but some inconsistencies appear relative to the French and Haney trials. Perhaps the data from Wind River and Haney illustrate approximate extremes that might be expected; for a given number of trees per acre (ha) at a height of 60 feet (18 m), stand volumes were about 15% greater at Haney than at Wind River.

Variation in dbh at a given height does not appear related to site index, but an effect of site may be hidden by other causes of variation. These other causes can only be hypothesized:

1. Crown structure of a tree of a given height must vary with age of the tree when that height is attained: an older tree has either more whorls of branches or a shorter crown or both. This variation in crown structure could affect diameter growth and height growth unequally. Also, trees with different crown structures might not have the same stem form.

2. Climatic differences may also have an effect on relative growth of height and diameter. For Douglas-fir, the growing season for diameter is potentially much longer than that for height, and the difference in both length of season and weather

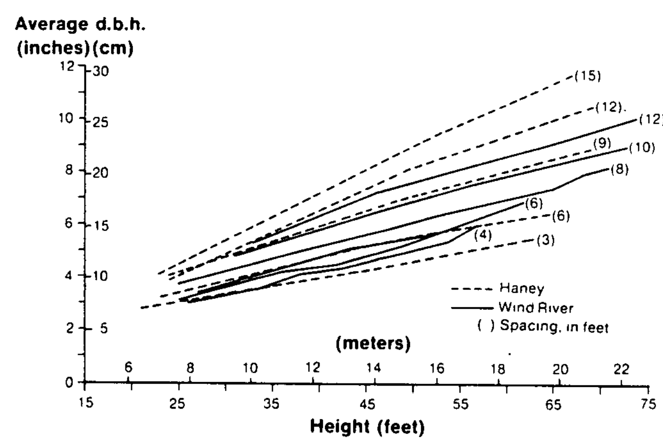

Figure 2. Average dbh at attained average heights, by spacing, in Douglas-fir spacing trials at Wind River and Haney.

patterns over the season varies from one location to another. In a stand where the extended growing season for diameter is relatively more favorable, trees of a given attained height may be larger in diameter.

3. Genetic differences sometimes account for such variations. Trees from different provenances planted at a given site can have similar heights but different diameters.

4. The relationship between spacing, height, and diameter may also be influenced by any direct effect of spacing on height growth.

Reduced Benefits from Delayed Spacing

Benefits from delayed spacing will be less than when spacing is controlled earlier, but they may still be substantial. For example, in the Planting Creek respacing trial, average dbh at age 53 was 45% larger at the 26 foot (8 m) than at the 11 foot (3.4 m) spacing (Harrington and Reukema 1983).

Omule (1984) reported on 28 years of observations of a spacing and thinning study near Lake Cowichan, B.C., where prolonged early suppression reduced the ability of a stand to respond to subsequent respacing. He reported that "except for extremes of density, stand merchantable volume of all trees and of crop trees are not affected by stand density."

Despite the late precommercial thinning in the LOGS trials, on the other hand, stands on the better sites responded quite well; diameter growth response of crop trees was immediate. At the Hoskins installation, diameter growth of crop trees during the interval of 50 feet (15 m) of height growth was about twice as great in thinned stands as in unthinned stands (Tappeiner et al. 1982).

Extension to Wider Spacing

The LOGS trials (Arnott and Beddows 1981, Tappeiner et al. 1982, Williamson and Curtis 1984) provide some idea of what could be expected with wider spacing, as frequent thinnings have maintained even the densest stands in a relatively open condition. During the fourth treatment period, average stand densities in the three most-advanced trials ranged from about 60 to 280 trees/acre (150 to 690/ha), corresponding to spacings of about 12.5 to 26.5 feet (4 to 8 m). In the wider spacings, stands will be essentially open-grown for a long period. Even at these wide spacings, the rate of diameter growth of crop trees increased with yet wider spacing. As a result, cubic volume growth per acre (ha) at about 20 and 26 foot (6 and 8 m) spacings was 81% and 60%, respectively, of that at 15 foot (4.5 m) spacing. If trees had been spaced this wide initially, relative gains in tree growth would have been even greater.

Similarly, during the most recent growth period in the Planting Creek respacing trial, stands at 20 and 26 foot (6 and 8 m) spacings grew 90% and 63%, respectively, as much as stands at 15 foot (4.5 m) spacing.

Open-grown, naturally established trees near the Wind River plantation spacing trial, and about the same age, are beginning to accumulate substantial basal area per acre (ha), despite their spacing of around 30 feet (9.1 m). It is apparent that on such sites, natural Douglas-fir can benefit from very wide initial growing space; average dbh of these open-grown trees is about twice that of the trees planted at 12 foot spacing.

These examples illustrate that rates of individual-tree growth continue to increase with spacing up to very wide spacings. Wider spacings can be expected to produce less total yield per acre (ha) than 12 and 15 foot (3.5 to 4.5 m) spacings, but their net value may be as great or greater, especially where it is not feasible to thin commercially. Stem quality will probably set the upper limits on practical spacings.

STAND CHARACTERISTICS AT THE TARGET FOR FIRST COMMERCIAL ENTRY

The target for first commercial entry is the stand density (level of competition) to which one believes a stand should be grown before a thinning is needed to forestall mortality and maintain tree vigor. Early spacing control is directed to influence stand characteristics at this stage of stand development. This target may be expressed in terms of number of trees per acre (per ha) and stand average diameter (Dg); the fewer the trees, the larger their size when the target is reached. The target relationship suggested by Reukema (1975) is illustrated in Figure 3.

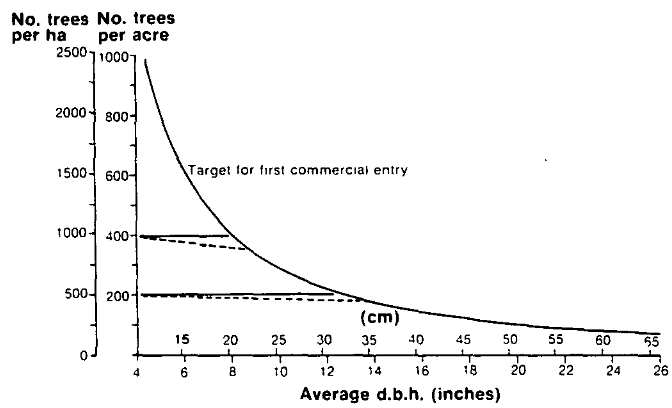

Figure 3. Target for first commercial entry expressed in terms of number of trees per acre (ha) and stand average diameter (Dg) (adapted from Reukema 1975). Horizontal lines show development of stands, without mortality, to two possible target densities: 400 trees per acre at a Dg of 8.0 inches (988/ha at 20.4 cm) and 200 trees per acre at a Dg of 12.7 inches (494/ha at 32.3 cm). Dashed lines show comparable development if 10% of the trees die.

Closely spaced stands may reach the target at very young ages, and small Dg, whereas widely spaced stands will not reach the target until much older ages. The time required is greater on progressively poorer sites. The Wind River plantations reached target densities (Figure 3) at ages of about 20 years with a 4 foot (1.2 m) spacing to 41 years with 12 foot (3.7 m) spacing; thus, stands at all spacings are now far past the appropriate targets. At Haney, all stands except the 15 foot (4.6 m) spacing have, likewise, already passed the targets; the 3 foot (0.9 m) spacing reached it at about age 9.

Effects of Mortality and Damage

Ideally, there would be no mortality between the time a stand is spaced and the time its trees reach target size for the first commercial entry (either for thinning or final harvest). But the ideal rarely happens. Generally, some mortality occurs as a result of factors such as root rot and irregular rates of development in different portions of the stand. Other trees may live but not reach the designated minimum merchantable size.

Less than perfect stand development—with mortality and damage, inferior growth on a substantial number of trees, and perhaps superior growth of groups of trees—may require modifying the preplanned target for average dbh (Dg) and number of trees. The Dg target might be increased to correspond with the actual number of surviving trees, if losses were distributed uniformly. Or the basal area target might be decreased to correspond to actual number and the original Dg target, if losses are patchy. Also, if trees are widely spaced, substantial fill-in by natural regeneration may alter the final target density and stand characteristics.

Diameter Distribution

The justification for establishing appropriate spacing at an early age is the anticipated increase in piece size and merchantable yield. The effect of spacing on diameter growth of crop trees and on the distribution of individual tree diameters may be even more important than its effect on the average dbh of the entire stand.

The relative distribution of diameters among trees within a stand has been found to be very consistent among spacings at a given location, among locations, and over time. Thus, it is possible to predict the diameter distribution expected at the time the target density is reached. At that time, the average diameter of a fixed number of largest trees per acre (ha) is, likewise, closely related to spacing. It is expected that 80 to 90% of the trees that survived the establishment phase will be no smaller than 75% of the average diameter, and that the largest tree will be about 150% of the average.

Some researchers have hypothesized that opportunities for natural selection of superior phenotypes and microsites would ensure that the best trees (e.g., the 100 largest per acre, or 250 largest per hectare) grown at close spacing would maintain their superiority over counterparts grown at wider spacings (Mitchell and Cameron 1985). Both the Wind River and Haney spacing trials, however, provide convincing evidence that advantages of wide spacing are increasing over time. Trees that showed early superiority at close spacings are not being favored by self-thinning among their neighbors to the extent needed to overcome competition; trees released by snow press of their neighbors cannot grow fast enough to make up for their early poor crown development compared with trees spaced wide initially.

Stem Form

Stem taper is important to both (1) tree quality and (2) resistance of tree stems to breakage by wind or snow. Tall, slender trees, if sufficiently large, generally contain both higher quality wood and a greater percentage of recoverable wood than do short, stocky trees. Tall, slender trees, however, are also more likely to be broken by wind and snow. Europeans sometimes suggest that the ratio of height to dbh (H:D ratio), where height and diameter are expressed in the same units, should be kept to less than about 80. The H:D ratios when stands reached targets appropriate to their spacing ranged from 102 to 86 at Wind River and from 111 to 76 at Haney, declining with increased spacing. Height and dbh of the average tree in the stand were used; ratios would be somewhat lower for the dominant and codominant component only.

Lower-bole taper is influenced very little by spacing once crowns lift. At both Wind River and Haney, the ratios of diameter at 9 feet (2.7 m) to dbh have been maintained at about 0.93 to 0.95.

Crown Size

At both Wind River and Haney, crown width apparently reached its maximum at quite an early age. At Haney, maximum width occurred prior to age 20, or to a height of 50 feet (15 m), at all spacings. At close spacings, this crown width greatly exceeded the nominal average spacing between trees as a result of crown overlap. Further increases in crown width are not expected. Likewise, crown length appears to have substantially stabilized at all except, perhaps, the widest spacing; of course, the wider the spacing the longer the crown. Crown lengths at age 25 at 12 and 15 foot (3.7 and 4.6 m) spacings were about 40 and 46 feet (12 and 14 m), respectively. Corresponding ratios were 60 and 66%.

Natural Pruning

Crown lift starts later with wide spacings; but once crown lift begins, it apparently progresses at about the same rate at all spacings. Height to live crown at Haney has been increasing rapidly at all spacings. Even at the 15 foot (4.6 m) spacing, live crown had receded to the top of the first log (20 feet, or 6 m) prior to age 25. Close spacings increase natural pruning, as expressed by heights to dead and live crowns, at great cost in terms of seedlings planted and diminished opportunities for future rapid growth of individual trees. The wider crowns and coarser branching resulting from wide spacing can be managed most efficiently by pruning to ensure that clear wood will be grown (Smith and Kennedy 1983).

EFFECTS OF DELAYING COMMERCIAL THINNING

Mortality and Tendency Toward Stagnation

Competition-related mortality generally is not serious until well after the target density appropriate to the spacing is reached; however, this occurs at a very early age at close spacings. At both Wind River and Haney, snow press of closely spaced trees has been serious. At Wind River, heavy wet snow has decimated portions of the stands planted at 4 and 5 foot (1.2 and 1.5 m) spacings. At Haney, heavy wet snow has destroyed 95% of the pure Douglas-fir plantations established at 1 foot (0.3 m) spacing, and up to 80% of the area covered by trees planted at 3 foot (0.9 m) spacing. The greater variety in tree canopy resulting from species mixtures in other trials at Haney has, to date, enabled survival of most trees planted at 3 and 4.5 foot (0.9 and 1.4 m) spacings.

Aside from the probability of heavy and clumped mortality and breakage, the uniform stands resulting from early spacing control may not self-thin well after they reach target density. Growth is likely to slow down drastically if all trees compete strongly with one another. The Martha Creek stand, at Wind River, that was thinned at age 9 by two methods—"exact spacing" to 8 by 8 feet (2.4 m) and approximate spacing to 8 feet but favoring dominant trees—illustrates the important effect of stand structure and uniformity on self-thinning. Early evidence showed the latter method (conventional precommercial thinning) gave superior results up to about the time the stand reached the target density, at which time it should have received another thinning (Steele 1955). Thereafter, the stand thinned to exact spacing had more variation in tree size and crown class differentiation, and thus self-thinned nicely. The stand thinned to favor dominant trees did not self-thin well, and growth slowed markedly on the larger trees.

CONCLUSION

Interest is strong in the potential gains from wide spacings. In British Columbia, number of trees planted has decreased from 1,000 per acre in the postwar years to about 450 per acre now (2,500 to 1,100/ha) (Kramer and Smith 1985); a similar trend exists in the United States. There is a reluctance to reduce further the number of trees planted because of difficulties of establishment, concerns about mortality, uncertainties about future demands for thinnings, and projections made by simulation models that are based on observations in closely spaced plantations and on plots that have not suffered substantial irregular mortality.

Results to date have demonstrated, conclusively, the great importance of initial spacing in plantations and respacing of plantations and natural stands as a technique by which an owner's objectives can be met efficiently. Strong interest in establishing a desired number of crop trees very early in the life of the stand and the high costs of shaping stands by delayed thinning underscore the need for a new series of trials that includes very wide spacings. Potential gains from optimum spacing and pruning are large.

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