AN ABSTRACT OF THE THESIS OF

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Title: Thinning Response in Alnus rubra and Arbutus
menziesii: Effects of Spacing, Light and Moisture

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In western Oregon, hardwood trees occupy 20% of the timberland but account for less than 1% of the timber harvest. Information about how to manage them effectively is limited.

The objective of this study was to examine: 1) effect of thinning on tree growth, plant moisture stress, and crown cover expansion and 2) the inter-relationships of these three factors.

The study site for red alder was on the western slope of the central Oregon Coast Range. The trees were about 20 years old when thinned in 1986. The red alder experiment was designed as a completely randomized design and each treatment was replicated three times. The average stem densities per ha were 1466(100%), 535(36%), and 412(28%).

The Pacific madrone study site was about 8 km west of

Central Point in southwestern Oregon. Tree ages ranged from 40 to 45 years when thinning was done in 1984. Measurements continued for 5 years. The study was designed as a randomized block design and composed of three blocks. The average stem densities per ha were 2290(100%), 486(21%), and 272(12%).

The data were analyzed for two groups of sample trees, average plot trees and crop trees. The average plot trees were random samples of each plot. The crop trees were dominant trees that would be left to harvest at the end of the rotation.

The effect of thinning on soil moisture availability was evaluated by measuring predawn plant moisture stress (PMS) with a pressure chamber once in a summer.

To determine the effect of thinning on light availability, five fisheye photographs of crown cover were taken per each plot and analyzed using an automated fisheye photograph analysis system.

For tree basal area, red alder crop trees in the heavily thinned plot increased 66% (13.1 cm^2) more than those in the control stand but average plot trees did not grow more. Tree growth of red alder was negatively correlated with stem density, but was not significantly correlated with plant moisture stress. For Pacific madrone, average plot trees in the heavily thinned stand increased 286% more than those in the control stand, while crop trees increased 589% (13.2 cm^2) more. Tree growth of Pacific madrone was significantly correlated not only with stem density but also with plant moisture stress. However, it was not significantly correlated with crown cover. Plant moisture stress might be a reason for marked effects of thinning on Pacific madrone tree growth.

Total height and merchantable height growth were not significantly different among the treatments for both species. For red alder, however, height growth of the heavily thinned plot was significantly less than that of the control plot. Total height and merchantable height growth were not significantly correlated with stem density or plant moisture stress.

There were no significant differences in plant moisture stress among the treatments for red alder. For Pacific madrone, however, plant moisture stresses of the thinned plots were 37-42% lower than those of the control plot in the third and fifth year after thinning.

The increases of stand basal area and volume were not significantly different among the treatments for both species. If the management objective is to increase growth of crop trees without losing stand productivity, it is recommended that the stands should be managed at a low density range (stand density index 300-360 for red alder, 200-290 for Pacific madrone).

Thinning Response in Alnus rubra and Arbutus menziesii : Effects of Spacing, Light and Moisture

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I. INTRODUCTION

Red alder (Alnus rubra Bong.) is the most common hardwood in western Oregon, accounting for over 50% of all hardwood volume (Poppino and Gedney 1984). Pacific madrone (Arbutus menziesii Pursh), native to the Pacific coast, constitutes about 6% of the hardwood growing stock in western Oregon. However, hardwoods are frequently ignored, destroyed, or harvested preceding conversion to conifers. The presence of these hardwood stands is now imposing important management questions in areas where they are to remain such as the need for thinning and the method of thinning.

Red alder is used as pulpwood, furniture stock, and cabinet stock. It can improve soil quality by its rapid litter decomposition and symbiotic nitrogen fixation (Fowells 1965). Currently it is considered as a primary alternative crop on moist coastal sites infected with laminated root rot (Phellinus weirii) (Nelson et al. 1978). Tarrant et al. (1983) compared the present net worth of systems for managing red alder and Douglas-fir, and suggested that red alder grown to sawlog size in 28 years could be profitable. Pacific madrone is widely used as fire wood and produces premium charcoal.

Both red alder and Pacific madrone show some potentials for more effective management. The objective of thinning is to concentrate the potential wood production of the stand on the remaining trees (Smith 1986). The effects of thinning vary depending on species, tree class, site conditions, and thinning intensities. To achieve the objectives of thinning, these factors should be fully considered. However, management information on hardwood species is limited, especially for Pacific madrone. This study was initiated to determine effects of thinning on growth, plant moisture availability and crown cover, and on their inter-relationships.

II. LITERATURE REVIEW

Red alder

Red alder, the largest species of the genus Alnus, is the most important hardwood of the Pacific Northwest. It is distributed along the Pacific coast. Although it grows along streams in northern Idaho, it usually occurs no farther inland than 170 km and no higher than 750 m (Fowells 1965). Red alder stands are usually found in damp, fertile creek bottoms. It grows well on deep, well-drained loams or loamy sand; soil types generally are not a serious limitation. Red alder grows in a humid climate. Its range is limited by temperatures below -15°C. It is a short-lived species, rarely attaining the age of 100 years; trees of this age rarely show more than 80 annual rings. Young alder trees grow very rapidly. Red alder is taller than Douglas-fir and western hemlock for the first 30 to 40 years and produces more stand volume for the first 18 or 20 years (Atterbury 1978). Red alder produces seeds from about age 10, reaching maximum seed production at about age 25. Peak seed production years occur on a 4-year cycle, with moderate crops occurring in the middle of cycle (Kenady 1978).

Red alder can contribute to the fertility of nitrogen-deficient forest soil. Alder foliage has a much higher nitrogen content than does conifer foliage, and the amount of litterfall greatly exceeds that of conifers (Gessel and Turner 1974, Turner et al. 1976). Another major route of nitrogen into the forest soil is by direct excretion from living roots and nodules. In one lab study, 60% of the soil nitrogen added in red alder stands came from nodule excretions or free-living microorganisms (Zavitkovski and Newton 1967). Dense alder stands may fix up to 320 kg nitrogen per ha annually on nitrogen-deficient soils (Newton et al. 1968).

Red alder may be important in reducing soil-borne diseases of conifers. In a study of microbial and chemical characteristics of the soil of mixed and pure stands of red alder and conifers on the northern Oregon coast, bacterial concentrations of the soil were higher under conifer stands than under the mixed alder-conifer stands. Streptomyces in O_f soil layers were more abundant under the mixed stands than under the conifer stands at all seasons (Bollen et al. 1967). Red alder also tends to acidify soils, a product of the N-fixation process. Nitrate nitrogen and acidity were higher under an alder stand than under a Douglas-fir stand (Van Miegroet and Cole 1985).

Red alder can enhance site fertility and growth of interplanted conifers. Miller and Murray (1978) found that red alder increased diameter and height of the dominant Douglas-fir and that maintaining red alder in Douglas-fir stands could increase merchantable yields on nitrogen-deficient sites. Douglas-fir stem growth per unit of leaf area was found to increase by 250% in the presence of red alder (Binkley 1984). On infertile soils, mixed stands greatly increased production in conifers after age 30. On fertile sites, mixed stands did not exceed the production of pure conifer stands. Rather, conifer growth was impaired throughout stand development (Binkley and Greene 1983). Newton et al. (1968) found that success of Douglas-fir depended on a delay of 4-9 years in establishment of red alder and that juvenile rapid growth of red alder might limit the ability of intermixed conifers to attain dominance unless that adjustment period is provided.

Red alder has been used as pulpwood, furniture stock, and cabinet materials. It has uniform color in both heartwood and sapwood although there may be a physiological heartwood. The color of fresh-cut wood changes rapidly over time. When it is first cut, the wood color is nearly white and may turn to pinkish white with some exposure to air and light. As the wood dries, the color becomes ivory or a reddish brown, depending on temperature and moisture conditions. Red alder is a diffuse porous wood. The pores and vessels are small and evenly distributed among the fibers. This gives the wood a uniform grain with a smooth texture; this makes red alder easy to work (Leney et al. 1978).

Pacific madrone

Pacific madrone is a member of the heath family that grows west of the Cascade Range from British Columbia to southern California. It is the dominant species in the mixed-evergreen (Pseudotsuga-Sclerophyll) zone with Douglas-fir and *Lithocarpus densiflorus* (Franklin and Dyrness 1973). The climatic environment in which madrone is found is highly variable. It ranges through superhumid and subhumid, and annual rainfall is as much as 4000 mm or as little as 450 mm. No definite soil association is evident although madrone is most often found on sites in which soil moisture is low during the growing season. The time of seed germination varies from February to April, according to the climate. Its shade tolerance has been described as intermediate (Baker 1949) but it frequently persists in understories of mature Douglas-fir. It responds well to release and also grows well as an understory tree. This species is tolerant of high temperatures and drought (Fowells 1965).

Pacific madrone is a representative of evergreen sclerophylls that retain their photosynthetic tissue through the year and have only moderate photosynthetic rates. Morrow and Mooney (1974) found that it was able to fix carbon even when leaf water potentials dropped as low as -25 bars and that leaf size varied according to the moisture conditions in the spring. Pacific madrone holds its leaves slightly longer than a year, beginning leaf drop early in June of the second year and continuing until late in the summer (Pease 1917). Some factors such as drought, temperature and day length, are related with summer deciduousness. Mooney et al. (1975) stressed mostly the importance of drought to leaf drop, while Nilsen and Muller (1981) reported that photoperiodic control during water stress had the greatest influence.

There has been no study of thinning on Pacific madrone.

Effects of thinning

Thinning focuses the site resources on the remaining trees by regulating the distribution of growing space. The primary objective of thinning is to increase usable tree volume and produce higher quality wood. Sometimes yields can be increased by salvaging merchantable dead trees. It is commonly found in thinning studies of red alder that DBH growth is accelerated by thinning (Lloyd 1955, Warrack 1964). However, Hibbs et al. (1989) reported that thinning decreased height growth by 56%.

The effect of thinning may vary by tree crown classes or species. Erdmann et al. (1985) reported that heavy crown release of 54-year-old red maple (Acer rubrum) increased average DBH growth 70% for dominants, 96% for codominants, and 108% for intermediates over the unreleased control. In a study of Douglas-fir, however, Reukema (1961) and Staebler (1956a) reported that dominant trees responded more quickly to release than codominant or intermediates and were benefited most by release.

The effect of thinning on growth depends on the methods used. Forty-nine-year-old western hemlock stands were thinned by crown thinning and by low thinning (Staebler 1957). The stand volume increment of the crown-thinned stands was about two times that of the unthinned stands but there was only a slight difference between the low-thinned and unthinned stands.

Thinning has the effect of increasing tree vigor and thereby reducing occurrence of insects. Mitchell et al. (1983) showed that thinning lodgepole pine improved vigor of remaining trees and reduced beetle attack. However, decay is sometimes associated with wounds resulting from thinning (Hunt and Krueger 1962).

Stands may not respond or respond negatively to thinning (usually referred to as thinning shock). Seidel (1980) reported that thinning from above reduced net volume growth because of mortality caused by windthrow and exposure to light. Staebler (1956b) found that height growth in the thinned stands fell off sharply whereas that in the unthinned stand increased. However, volume growth was not considered in determining thinning shock.

The effects of thinning on growth largely result from increases in resources such as soil moisture, soil nutrients, and light. Donner and Running (1986) reported that in Pinus contorta stands in Montana, leaf water potential was significantly higher (0.17-0.35 MPa) in thinned stands than in unthinned stands and also suggested that 21% greater seasonal photosynthate production could occur as a result of this higher water potential. Aussenac and Granier (1988), Helvey (1975) and Sucoff and Hong (1974) also found that thinning increased the soil water reserve and decreased moisture stress. In a study of Douglas-fir, Brix and Mitchell (1986) also showed that thinning increased soil water potential by as much as 1 MPa regardless of fertilization during the dry summer periods and that fertilization effect on soil water potential was slight in spite of large increases in leaf area (50% increase after 7 years). Zahner (1958) and Roberts et al. (1982) stressed that understory vegetation competed strongly for soil moisture.

The increased rate of crown expansion into openings created by release may be a major factor for improvement in stem growth. Shirley (1932) reported that optimum light intensity varied by species. According to Logan (1959), height growth of white pine increased rapidly with light up to 55% of full light and branch length increased up to full light. However, needles were usually longest in the lowest light studied. In a study of a 50-year-old Douglas-fir stand, however, Reukema (1964) reported that release tended to reduce rather than increase crown expansion including branch elongation. Moreover, height growth slightly decreased following release.

The information of thinning on hardwood species is limited, especially for Pacific madrone. At present it is not clear how Pacific madrone will respond to thinning.

III. EFFECTS OF THINNING ON RED ALDER

Methods

Site characteristics

The red alder study site was located on the western slope of the central Oregon Coast Range in Lincoln County. The area has a maritime climate. Summers are warm and dry but frequent fog and low clouds ensure minimal moisture stress. Winters are cool and wet. July mean maximum temperature is about 22.5-24.5 ^{o}C and January mean minimum temperature is 2.5 ^{o}C (Franklin and Dyrness 1973). Average annual rainfall ranges from 1700 mm to 2000 mm. Elevation of the site ranged from 150 m to 240 m. Aspect was generally northeast to northwest and slopes ranged from 0 to 60% with an average of 30%. The soils were moderately deep gravelly loam. Parent material was residuum and colluvium of weathered sandstone and other sedimentary rock. The site index for red alder was 90 (Worthington et al. 1960). The unit was a 20-year-old stand of hardwoods and conifers that regenerated following logging. There was a lot of Douglas-fir in pockets and some western hemlock and sitka spruce, but red alder was the dominant species. Douglas-fir originated from planting in 1965 when the land was under the management of the Bureau of Land Management. The experimental plots were selected from the sites occupied primarily by red alder. The understory cover ranged from 64% to 96% with an average of 82%. Major understory species and cover percents were salmonberry (Rubus spectabilis) 30%, thimbleberry (Rubus parviflorus) 10%, salal (Gaultheria shallon) 10%, and swordfern (Polystichum munitum) 20%. Minor species were vine maple (Acer circinatum), elderberry (Sambucus callicarpa), red huckleberry (Vaccinium parvifolium) and hazel (Corylus cornuta) (Cloughesy personal communication).

Treatment

The thinning was done in spring, 1986. This study was designed as a completely randomized design and each treatment was replicated three times. The unit of treatment was 0.2 ha. In the center of each treatment plot, a 400 m^2 circular measurement plot was installed. Trees within the measurement plot were numbered and then DBH was marked and measured.

There were three treatments; control, light thinning, and heavy thinning. Treatment levels were decided on the basis of number of trees per ha. The leave trees were selected on the basis of form and quality to produce a uniform spacing. The average density of each treatment was 1466, 535, and 412 trees per ha in the control, lightly thinned, and heavily thinned plot, respectively (Table 1).

Data collection

Plots were measured from spring, 1986 to fall, 1989. Data were analyzed for two groups of sample trees, average plot trees and crop trees. Average plot trees were subsamples of all trees on the plot and 10 average plot trees were chosen systematically. Thus, the average plot tree analysis represented an analysis of the whole plot. Crop trees were dominant trees that would be left to harvest at the end of the rotation. They were the trees of which growth response was of greatest interest. A sample of about 10 crop trees was chosen systematically from among dominant trees on each plot and every other tree was used for measurement. For growth analysis, DBH, total height, and merchantable height were measured in March, 1986, before the start of the growing season. DBH was remeasured annually in November after that. The data measured in March, 1986, were presented as 1985. Basal area (BA), stand basal area (SBA), volume, stand volume, stand density index (SDI) (Reineke 1933), and relative density (RD) were calculated using the following equations:

$$BA=3.14*DBH^2/4$$

$$SBA=BA*TPHA$$

$\log(\text{volume})=-8.8272 + 2.4999*\log(DBH)$ (Snell and Little 1983)

$$\text{Stand volume}=\text{volume}*TPHA$$

$SDI=TPHA(QMD/25)^{1.6}$ (Long 1985)

$RD=100*SDI/1125$ (Hibbs and Carlton 1989)

where QMD: quadratic mean diameter

TPHA: trees per hectare.

Merchantable height was defined as height to a minimum merchantable diameter or the bottom of the live crown whichever was less. Total height and merchantable height were measured with a clinometer and measuring pole using the following equation (Curtis and Bruce 1968):

$$\text{Height} = P\,\frac{(\text{slope } AB - \text{slope } AD)}{(\text{slope } AC - \text{slope } AD)}$$

where P: pole length

A: observer's position

B: tip of tree to be measured

C: tip of measuring pole

D: base of both tree and pole

Increased moisture availability after thinning has been considered important for tree growth. It was evaluated by measuring predawn plant moisture stress (PMS) with a pressure chamber (Scholander et al. 1964, Waring and Cleary 1967). Five trees per plot were randomly selected for PMS measurement. PMS was measured once in July, 1986 and September, 1988. These dates were chosen as near the end of a several week period without rain. This was the time when the differences among the treatments were expected to be greatest.

Light availability is an important resource affected by thinning and crown expansion may be related to increased light availability. To determine their relationship, five points (center and four directions) were set up to measure crown expansion with the fisheye photograph with view angle of 180°. The camera was mounted on a sturdy tripod 1 m above the ground, leveled and then oriented true north. Pictures were taken in September, 1986 and 1988 during early morning or late afternoon when radiation was mostly diffuse. Sky area (% of area which is not occupied by crown) was read using an automated fisheye photographic analysis system (Chan et al. 1986) and crown covers (% of area which is occupied by crown) were calculated.

Data analysis

Effects of thinning on tree growth and resource availability were compared by analysis of variance (completely randomized design) and least square means without and with a covariate (initial size) and the interaction between treatment and years was analyzed by repeated measures analysis of variance using SAS general linear model (SAS 1987a). The relationships of plant growth response with density and resource measures were determined by correlation analysis using SAS correlation procedure (SAS 1987b). The significance level was set at $p=0.05$.

Results

The stem densities of the thinned plots were 28-36% of that of the control plot, while SDI were 43-51% in the thinned year (Table 1). However, there were no significant differences in size of individual trees among treatments.

There was a significant difference in number of dead trees between the thinned plots and the control plot (Table 2a, b).

Average plot trees

1. Basal area and volume

In the first year after thinning, there were significant differences in the accumulated increments (increments accumulated after thinning) of tree basal area and tree volume between the thinned plots and the control plot but not thereafter (Figure 1, 2). Periodic annual increment (PAI: average annual increase during the period) of tree basal area ranged from 15.34 to 27.18 cm^2 and that of tree volume from 0.015 to 0.031 m^3. However, PAI's of tree basal area and tree volume were not significantly different among treatments ($p=0.18$, $p=0.16$, respectively), nor were significant interactions between treatment and year found (Table 5). When the initial size (tree basal and tree volume measured immediately after thinning) was included as a covariate, PAI's of tree basal area and tree volume were significantly related to its initial size, respectively, but not significantly different among treatments. The increments of tree basal area and tree volume significantly decreased as stem density increased but were not significantly related to SDI, stand basal area or PMS (Table 3).

2. Total height and merchantable height

Total height and merchantable height increased annually 0.13-0.55 m and 0.04-0.25 m, respectively, but the growth rates were not significantly different among treatments (Table 5). When the initial height (height measured immediately after thinning) was included as a covariate, Total height PAI's of the thinned plots were significantly less than that of the control plot, but merchantable height PAI's were not significantly different among treatments. The increases of total height and merchantable height were not significantly correlated with stem density, but the increase of merchantable height was correlated with SDI and stand basal area (Table 3).

3. Stand growth

There were no significant differences in the accumulated increments (Figure 3, 4) and PAI's of stand basal area and stand volume among treatments (Table 5). However, the relative growth rates (growth/initial size) of the thinned plots were considerably higher than that of the control plot (p=0.09, for stand basal area, p=0.10 for stand volume). The relative growth rates of stand basal area were 3.66%, 6.36%, and 6.50% in the control, lightly thinned, and heavily thinned plot, while those of stand volume were 5.15%, 7.80%, and 8.18%. The increases of stand basal area and stand volume were positively correlated with stand basal area but not correlated with stem density, or PMS (Table 3).

4. Plant moisture stress (PMS)

In the first and third year following thinning, there were no significant differences in PMS among treatments (Table 1).

5. Crown expansion

Crown covers were not significantly different among treatments in the thinned and the second year after the thinning (Table 1). However, the crown cover of the control stand expanded annually 180% more than that of the lightly thinned stand. Crown expansion rates were positively correlated with crown cover and all three density measures (Table 3) but not significantly correlated with PMS.

Crop trees

1. Tree basal area and tree volume

Until two years after thinning, there were no significant differences in the accumulated increases of tree basal area and tree volume among treatments (Figure 5, 6). However, the differences in the accumulated growth between the heavily thinned and the control plot became significant from the third year after thinning. There were significant interactions between treatment and year, and PAI's of tree basal area and tree volume of the heavily thinned plot were 66% and 77% more than those of the control plot (Table 5). The differences between the lightly thinned and the control plot were not significant ($p=0.08$ for tree basal area, $p=0.13$ for tree volume). When the initial tree basal area or tree volume was included as a covariate, the difference between the lightly thinned and the control plot became significant. The increases of tree basal area and tree volume were negatively correlated with stem density (Table 4).

2. Total height and merchantable height

PAI's of total height and merchantable height were not significantly different among treatments nor the interactions between treatment and year were significant (Table 5). When the initial total height was included as a covariate, total height PAI of crop trees on the heavily thinned plot was significantly less than that of the control plot. The increase of total height was not significantly correlated with stem density or PMS but the increase of merchantable height was closely correlated with all three measures of density (Table 4).

Discussion

It was evident that crop trees were more benefited than average plot trees by the thinning. For average plot trees, there were no significant differences in the accumulated increases of tree basal area and tree volume among treatments from the second year through the fourth growing season (Figure 1, 2). For crop trees, differences in the increases of tree basal area and tree volume became significant from the third year after thinning (Figure 5, 6). For tree basal area, PAI of average plot trees on the heavily thinned plot was not larger than that on the control plot ($p=0.08$), while that of crop trees was. In a study of Douglas-fir, Oliver and Murray (1983) found that large trees grew more than small trees. To evaluate the real effect of thinning, the initial size should be considered as a covariate. When the initial tree basal area was included as a covariate, there were still no significant differences among treatments for average plot trees but there were for crop trees. This result was consistent with the findings of Reukema (1961) and Staebler (1956a).

Considering the above result, density management regimes may vary depending on specific objectives. For example, if sawlogs are the objective, stand density should be maintained at a low SDI to maximize individual tree growth until some harvest.

The effect of thinning on crop trees seemed to be immediate, though no significant differences were found until the third year after the thinning. It is because the growth rates of crop trees in the heavily thinned stand were almost constant over years after the thinning (that is, crop trees in the heavily thinned stand grew at about the same rate after the thinning).

Total height and merchantable height growth were not significantly different among treatments regardless of whether average plot trees or crop trees were examined (Table 5). These two height measures were not correlated with stem densities or PMS. When the initial height or merchantable height (measured in the thinned year) was included as a covariate, however, total height PAI's of the heavily thinned plot were significantly less than those of the control plot, while merchantable height PAI's were not. Smith (1986) noted that the effect of thinning on total height was generally independent of stand density and regulated by the totality of growth-supporting factors of the site. However, it may depend on species. For example, a reduction in total height growth is commonly found in thinning studies of red alder (Warrack 1964, Hibbs et al. 1989).

The increases of stand basal area and stand volume were almost independent of stem density. The increases of stand basal area and stand volume were not significantly different among the treatments (Figure 3, 4) and not significantly correlated with stem density (Table 3). However, the relative stand basal area growth rate (basal area growth/initial basal area) of the heavily thinned plot was 78% higher than that of the control plot, while the mortality rate was significantly lower. Consequently, differences in initial densities were largely compensated for by differences in growth rates and mortality. The above results were consistent with the management guide of Hibbs and Carlton (1989). They recommended 50-60% of the maximum density as upper limit and 25-35% of the maximum SDI as lower limit for the maximum stand productivity. The thinned plots in this study fell at the lower end of this recommended density range.

The effects of thinning largely depend upon increased resource availability such as soil moisture, light, and nutrients resulting from release. However, soil moisture availability might not be an important factor restricting red alder tree growth on a wet site. The increases of tree basal area and tree volume were only slightly correlated with PMS.

There were no significant differences in PMS among treatments, although there appeared to be an emerging trend that might be significant in the future. Soil moisture availability is usually most affected in the first few years after thinning and then the effect gradually decreases (Aussenac and Granier 1988, Helvey

1975). So it was hard to expect that there would be any effect on PMS in the future.

There might be some serious errors in analyzing the crown cover of red alder. For example, in the thinned year, the crown cover of the control plot could not be the same as those of the thinned plots, yet results indicate that it was (Table 6). The sources of error include 1) error of the fisheye photograph system itself 2) different time of taking picture 3) error in reading. Consequently, it was not meaningful to use and discuss the crown data of red alder further.

Table 1. Tree and stand characteristics of red alder immediately after thinning in the spring of 1986 and after 3 years of growth (1986-1989).

	'85*			'89		
	Control stand	Lightly thinned stand	Heavily thinned stand	Control stand	Lightly thinned stand	Heavily thinned stand
Density (trees/ha)	1466a	535b	412b	1318a	527b	404b
Stand density index	702a	360b	304b	777a	439b	373b
Relative density(%)	62a	32b	27b	69a	39b	33b
Stand basal area(m^2/ha)	28.8a	16.0b	13.9b	33.7a	20.7b	18.1b
Stand volume(m^3/ha)	224.6a	136.0ab	122.4b	280.0a	187.4a	170.0a
Basal area(cm^2)						
Plot tree	199.3a	303.1a	340.6a	260.6a	397.4a	449.3a
Crop tree	326.5a	367.2a	418.7a	405.5a	482.5a	549.9a

* The data presented as '85 were measured in the spring of 1986. Values within a row for a given year followed by the same letter are not significantly different (p=0.05). Sample size=9.

(Table 1. Continued)

	'85			'89		
	Control stand	Lightly thinned stand	Heavily thinned stand	Control stand	Lightly thinned stand	Heavily thinned stand
Volume(m^3)						
Plot tree	0.16a	0.26a	0.30a	0.22a	0.36a	0.42a
Crop tree	0.28a	0.32a	0.38a	0.37a	0.45a	0.54a
Height(m)						
Plot tree	19.0a	18.5a	17.9a	21.2a	19.0b	18.8b
Crop tree	21.0a	19.1a	18.9a	22.8a	20.3b	19.6b
Merchantable height(m)						
Plot tree	9.3a	9.1a	9.1a	10.3a	9.6a	9.3a
Crop tree	8.7a	9.0a	8.9a	10.9a	10.0a	9.2a
Plant moisture stress (MPa)	0.24a	0.26a	0.24a	0.40a	0.35a	0.31a
Crown cover(%)	50.2a	54.1a	52.2a	66.5a	56.0a	62.0a

Plant moisture stress and crown cover were measured in 1986 and 1988.

Table 2a. Analysis of variance of annual mortality of average red alder plot trees during 1986 and 1989.

Source	df	Mean square	F value	Pr > F
Treatment	2	1225.4	20.6	0.002
Error	6	59.4		
Total	8			

Table 2b. Comparison of annual mortality of average red alder plot trees by treatment (least square mean was used).

Treatment	Annual mortality (trees/ha)	Pr>|T| i/j	H_0:treatment(i)=treatment(j) 1	2
1	37	1	.	
2	2	2	0.001	.
3	2	3	0.001	1.0

Table 3. Correlation among densities, crown cover, and growth responses of average red alder plot trees.

	Annual crown expansion	Annual tree basal area increment	Annual stand basal area increment	Annual tree volume increment	Annual stand volume increment	Annual height increment	Annual merchantable height increment
Density trees/ha	0.66 (0.05)	-0.73 (0.03)	.	-0.73 (0.02)	.	0.59 (0.09)	.
SDI	0.69 (0.04)	.	.	.	.	.	0.80 (0.01)
SBA	0.66 (0.05)	.	0.66 (0.05)	.	0.68 (0.04)	.	0.84 (0.01)
Crown cover	0.79 (0.01)	.	.	.	.	.	.

where SDI: stand density index

SBA: stand basal area (m^2/ha)

The number in ( ) is a probability > $|R|$ under H_o: R=0. Only correlations with $p \leq 0.10$ are presented. The data used in crown cover were those analyzed at view angle 180°. Sample size: 9.

Table 4. Correlation between densities and growth responses of red alder crop trees.

	Annual tree basal area increment	Annual tree volume increment	Annual height increment	Annual merchantable height increment
Density trees/ha	-0.79 (0.01)	-0.74 (0.02)	.	0.64 (0.07)
SDI	.	.	.	0.63 (0.07)
SBA	.	.	.	0.59 (0.09)

where SDI: stand density index
SBA: stand basal area(m^2/ha)
The number in ( ) is a probability > $|R|$ under H_o: R=0.
Only correlations with $p \leq 0.15$ are presented.
Sample size: 9.

Table 5. Periodic annual increments (PAI) of red alder over 4 years (1986-1989).

	Control stand	Lightly thinned stand	Heavily thinned stand
Tree basal area growth(cm^2)			
Plot tree	15.34±5.06a	23.56±3.08a	27.18±3.56a
*Crop tree	19.73±1.36a	28.83±3.45ab	32.79±3.65b
Tree volume growth(m^3)			
Plot tree	0.015±0.006a	0.026±0.004a	0.031±0.005a
*Crop tree	0.022±0.002a	0.033±0.005ab	0.039±0.006b
Stand basal area growth (m^2/ha)	1.22±0.41a	1.16±0.07a	1.04±0.22a
Stand volume growth(m^3/ha)	13.84±4.50a	12.85±1.26a	11.92±2.64a
Height growth(m)			
Plot tree	0.55±0.08a	0.13±0.24a	0.23±0.07a
Crop tree	0.45±0.09a	0.31±0.34a	0.18±0.05a
Merchantable height growth(m)			
Plot tree	0.25±0.11a	0.12±0.02a	0.04±0.54a
Crop tree	0.53±0.20a	0.26±0.11a	0.07±0.12a
Annual crown expansion(%)	8.1±1.9a	2.9±0.6b	4.9±1.2ab

* The interaction between treatment and year was significant in this variable.

Crown covers were measured in 1986 and 1988.

The value following the sign (±) is a standard error and the same letter means there is no significant difference at significant level 0.05. Sample size: 9.

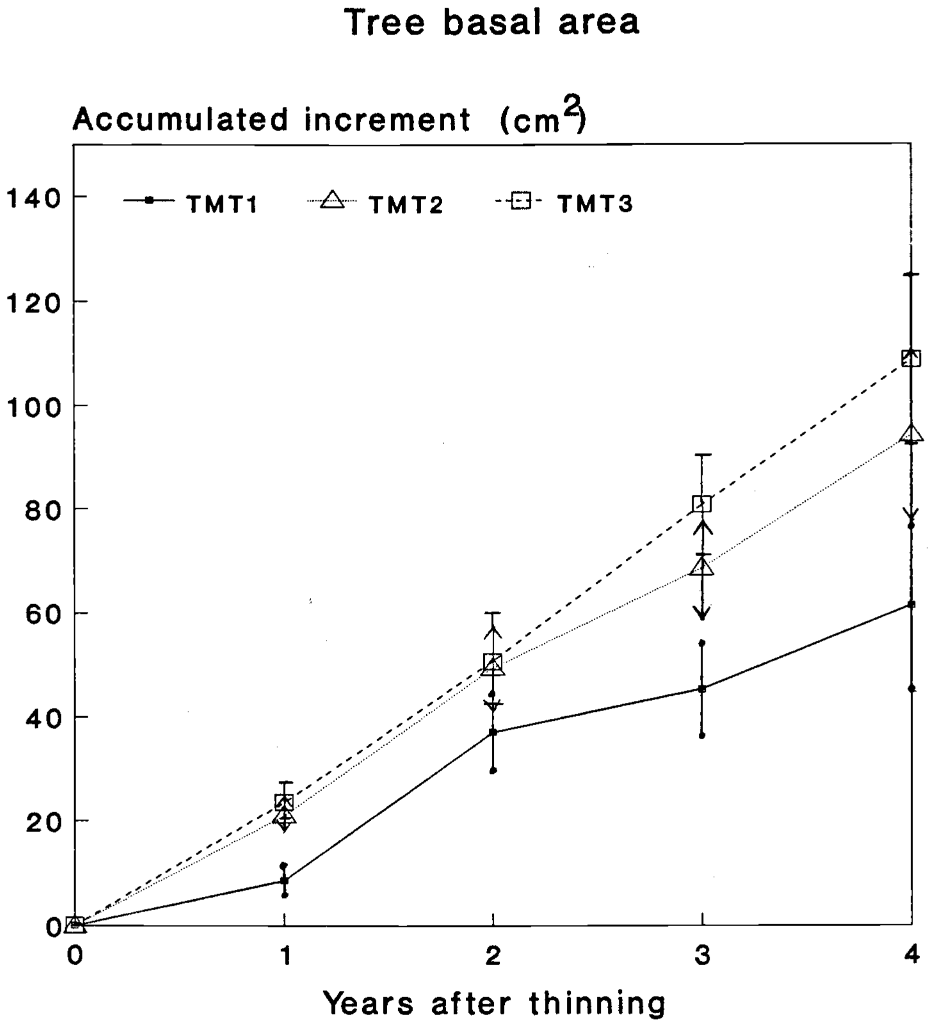

Figure 1. Tree basal area increment of average red alder plot trees accumulated over years after thinning. where TMT1(control stand): SDI 702 (relative density=62%), TMT2(lightly thinned stand): SDI 360 (relative density=32%) and TMT3(heavily thinned stand): SDI 304 (relative density=27%). Standard error is shown as a vertical bar.

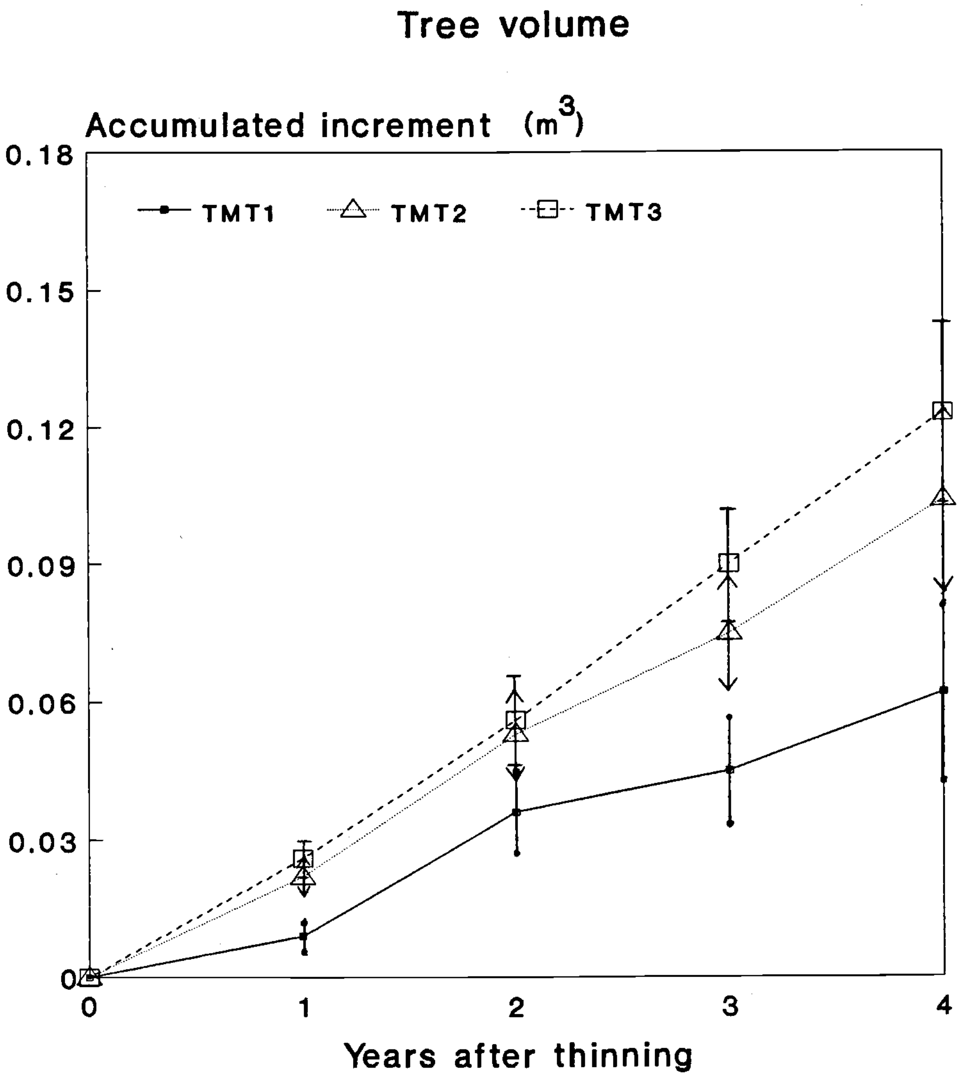

Figure 2. Tree volume increment of average red alder plot trees accumulated over years after thinning. where TMT1(control stand): SDI 702 (relative density=62%), TMT2(lightly thinned stand): SDI 360 (relative density=32%) and TMT3(heavily thinned stand): SDI 304 (relative density=27%). Standard error is shown as a vertical bar.

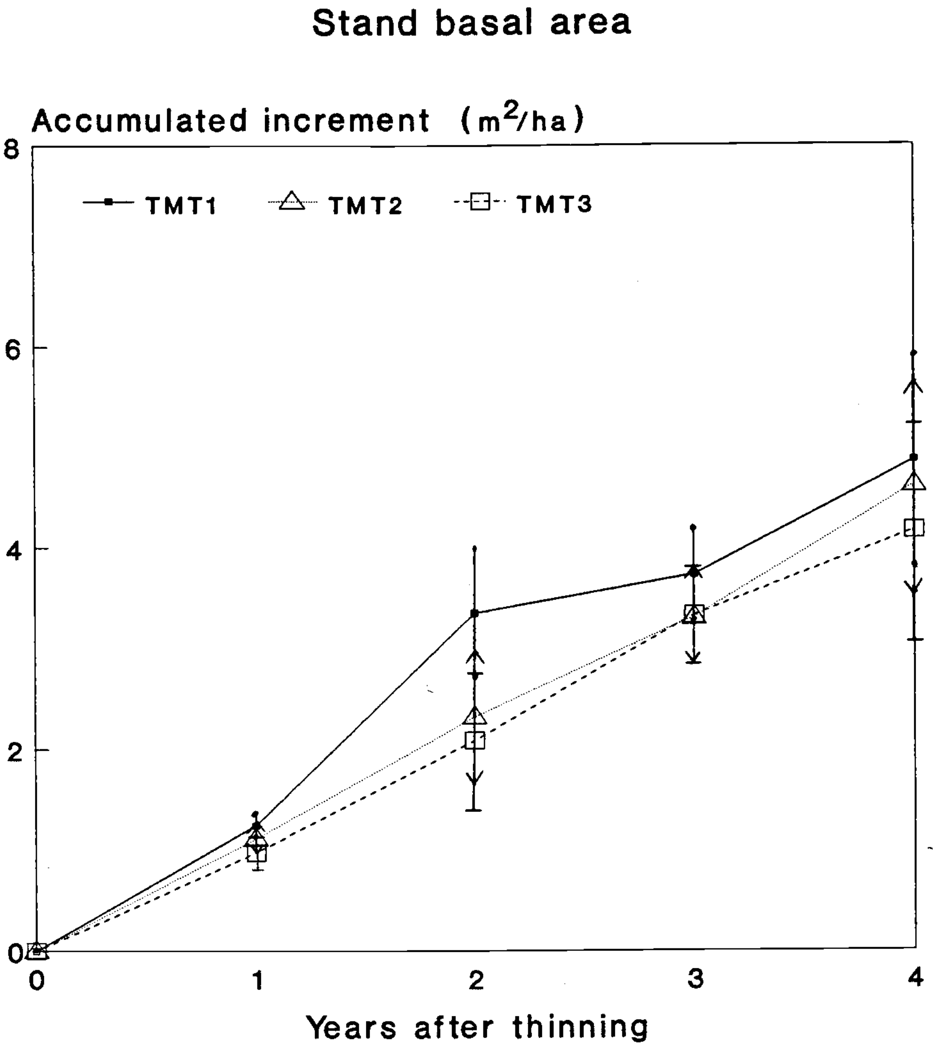

Figure 3. Stand basal area increment of red alder accumulated over years after thinning. where TMT1(control stand): SDI 702 (relative density=62%), TMT2(lightly thinned stand): SDI 360 (relative density=32%) and TMT3(heavily thinned stand): SDI 304 (relative density=27%). Standard error is shown as a vertical bar.

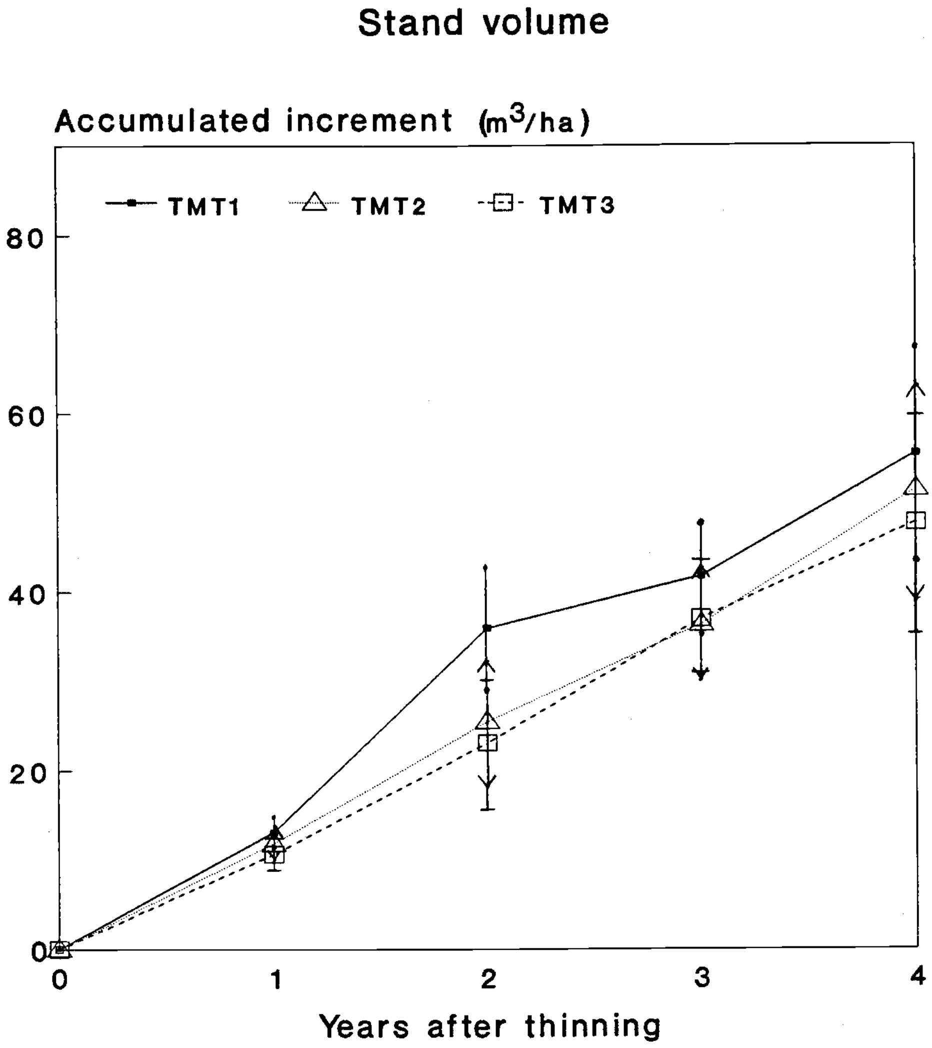

Figure 4. Stand volume increment of red alder accumulated over years after thinning. where TMT1(control stand): SDI 702 (relative density=62%), TMT2(lightly thinned stand): SDI 360 (relative density=32%) and TMT3(heavily thinned stand): SDI 304 (relative density=27%). Standard error is shown as a vertical bar.

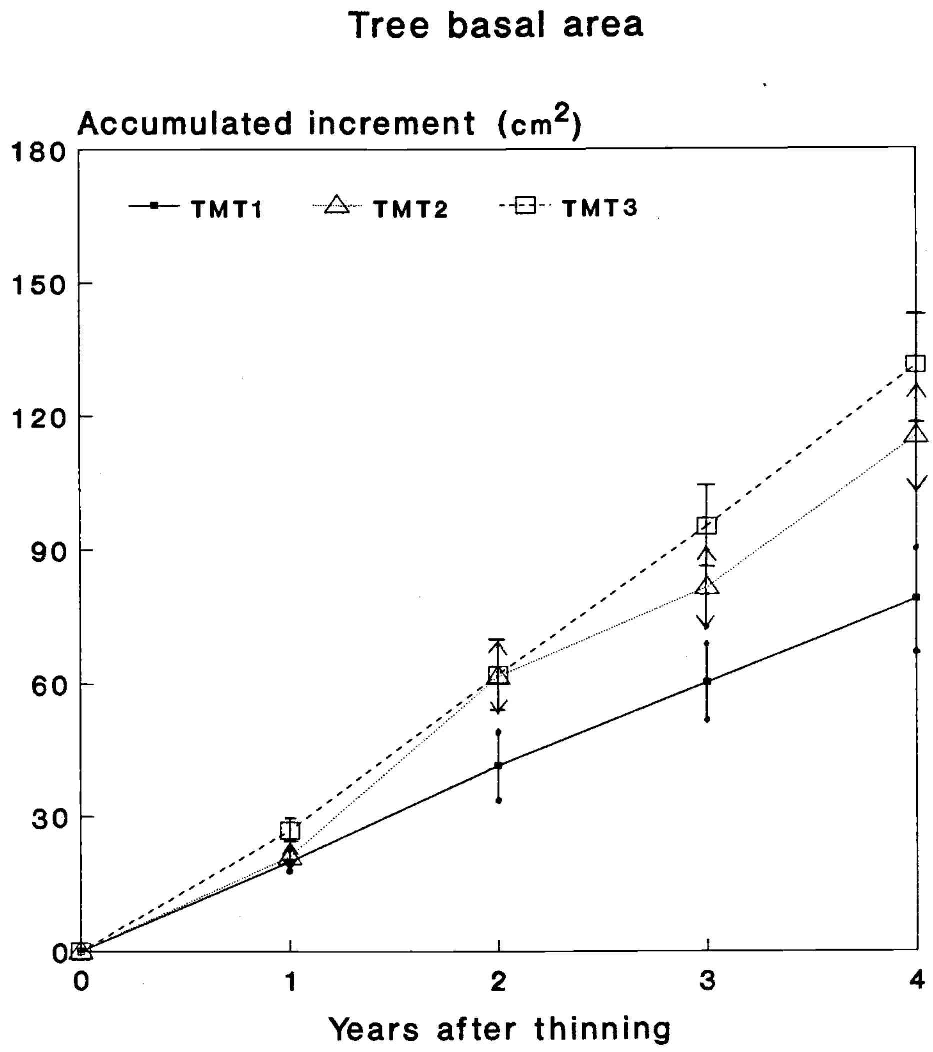

Figure 5. Tree basal area increment of red alder crop trees accumulated over years after thinning. where TMT1(control stand): SDI 702 (relative density=62%), TMT2(lightly thinned stand): SDI 360 (relative density=32%) and TMT3(heavily thinned stand): SDI 304 (relative density=27%). Standard error is shown as a vertical bar.

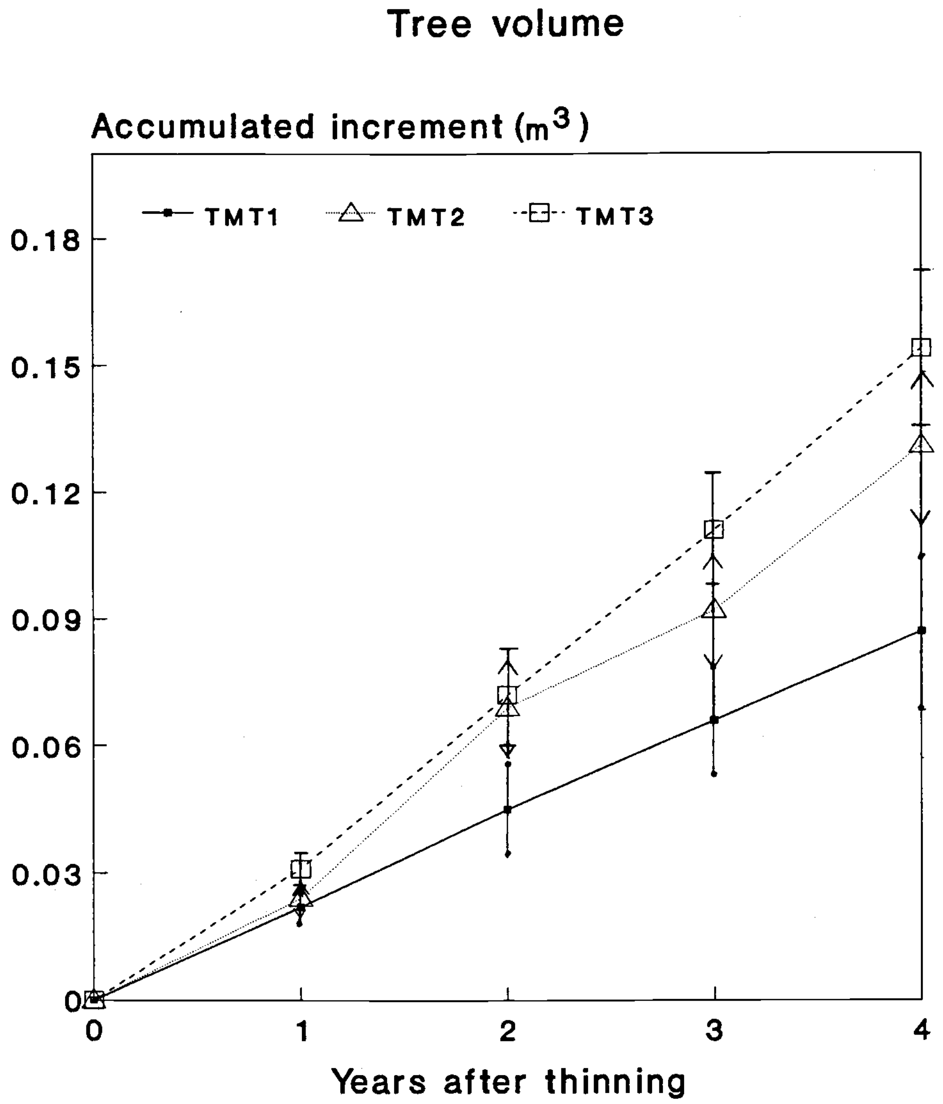

Figure 6. Tree volume increment of red alder crop trees accumulated over years after thinning. where TMT1(control stand): SDI 702 (relative density=62%), TMT2(lightly thinned stand): SDI 360 (relative density=32%) and TMT3(heavily thinned stand): SDI 304 (relative density=27%). Standard error is shown as a vertical bar.

IV. EFFECTS OF THINNING ON PACIFIC MADRONE

Methods

Site characteristics

The Pacific madrone study site was located about 8 km west of Central Point in the foothills immediately above the Rogue River Valley in southwestern Oregon. Elevation of the site was 600 m and the soils were silt loam. Slopes ranged from 0 to 10% and aspect was from south to southeast. Rainfall average is about 500 mm per year and 36 mm during June through August. The mean annual temperature is 11.4 °C, the mean January minimum temperature is -1.2 °C, and the mean July maximum temperature is 31.8 °C (Franklin and Dyrness 1973). Tree ages ranged from 40 to 45 year old, probably resulting from a fire. The stand was composed of 85% Pacific madrone, 10% conifers (Pinus ponderosa, Pseudotsuga menziesii), and 5% oak (Quercus kelloggii). The understory cover ranged from 36% to 87%, with an average of 58%. Major understory species were poison oak (Rhus diversiloba), snow-berry (Symphoricarpos albus), pink honeysuckle (Lonicera hispidula), and Lupinus lepidus. The site class was five for Douglas-fir (Campbell personal communication).

Treatment

The thinning was done in spring, 1984. The experiment was designed as a randomized complete block design. Because of topographic variation on the site, treatment areas were stratified by elevation. This resulted in three blocks. Three treatments were randomly allocated within each block. Treatment levels were based on the number of trees per ha. The leave trees were selected on the basis of form and quality to produce a uniform spacing. The average densities were 2290, 486, and 264 trees per ha in the control, lightly thinned, and heavily thinned plot, respectively (Table 6). Each treatment area was about 0.2 ha. In the center of each treatment area, a 400 m^2 circular measurement plot was installed. Trees within each measurement plot were numbered and DBH was marked and measured.

Data collection

Data were collected for six years, from 1984 to 1989 (In 1989, only PMS was measured). Data were analyzed for two groups of samples, average plot trees and crop trees. DBH was remeasured in the spring (March or April) of 1985 and 1986 before the start of the growing season, and then in the winter (November) from 1986 to 1988. Total height and merchantable height were measured in March 1986 and remeasured in November 1988. Data collected in the spring were presented as the previous year. Basal area was calculated using DBH as previously described in the red alder study but volume was calculated using the following equation: log(volume)=-8.5385 + 2.2969 log(DBH) (Snell and Little 1983). Stand basal area, stand volume, and stand density index (SDI) were obtained as previously described in the red alder study.

Soil moisture availability was monitored by measuring predawn plant moisture stress (PMS) (Scholander et al. 1964, Waring and Cleary 1967). It was measured from five randomly chosen trees in each plot. PMS measurements were taken once in July from 1986 (two years after thinning) to 1989. These dates were chosen to maximize the differences among treatments; later sampling dates would would show lower plant water potential.

To determine the relationship between crown expansion and increased light availability, five points per plot were permanently marked for crown fisheye photographs. Fisheye photographs were taken in June from 1986 to 1988. Sky area percentage was read with an automated fisheye photographic analysis system (Chan et al. 1986) and crown cover was calculated.

Data analysis

Analysis of variance (randomized complete block design) and least square means were used to determine the effects of thinning. The other analysis methods were the same as those for red alder.

Results

The stem densities of the thinned plots were 11.5-21.2% of the control plot in the thinned year, while stand basal area and stand volume of the thinned plots were 23.3-30.6% and 25.6-31.8%, respectively (Table 6). Initial tree basal area and tree volume of the heavily thinned plot were significantly larger (2.0 times, 2.3 times, respectively) than those of the control plot but not significantly different from those of the lightly thinned plot (p=0.07, p=0.07, respectively). Mean annual mortality rates were not significantly different among the treatments (Table 7a, b).

Average plot trees

1. Basal area and volume

In the first year after thinning, the differences in the accumulated increments of tree basal area among the treatments were small (p=0.15). From the second year after thinning through the fifth growing season, the accumulated increment of tree basal area of the heavily thinned plot was significantly larger than that of the control plot, while that of the lightly thinned plot was larger only in the fourth year after thinning (Figure 7). There were significant interactions between treatment and year for tree basal area and volume (Table 10). Tree basal area PAI of the heavily thinned plot was about 3.9 times as large as that of the control plot but that of the lightly thinned plot was not significantly different ($p=0.21$). For tree volume, the accumulated increments of the heavily thinned plot were significantly larger than those of the control plot from the second year after thinning through the fifth growing season but those of the lightly thinned plot were not (Figure 8). The increases of tree basal area and tree volume were negatively correlated with PMS and all density measures (Table 8).

2. Total height and merchantable height

There were no significant differences in total height and merchantable height (Table 6) and growth rates were not different (Table 10). PAI's of total height were 0.12-0.22 m ($p=0.60$), while those of merchantable height were -0.01-0.06 m ($p=0.68$). There were no significant correlations of the increases of total height and merchantable height with years after thinning. The increases of total height and merchantable height were not significantly correlated with PMS or any density measure (Table 8).

3. Stand growth

There were no significant differences in PAI's of stand basal area and stand volume among the treatments

(Figure 9, 10, Table 10). The relative annual increment rates (annual growth/initial size) of stand basal area were 0.41, 1.83, and 3.01% in the control, lightly thinned, and heavily thinned plot, respectively ($p=0.09$), while those of stand volume were 0.68, 2.21, and 3.47% ($p=0.10$). The increases of stand basal area and stand volume were not significantly correlated with PMS or any density measure (Table 8).

4. Plant moisture stress (PMS)

PMS's of the thinned plots were 37-42% less than those of the control plot in the third and fifth year after the thinning (Figure 11). However, PMS of the heavily thinned stand was not significantly less in the fourth year and that of the lightly thinned stand was not in the sixth year. Overall, PMS of the thinned plots was 38% (0.32 MPa) lower than that of the control plot during the third and sixth year after thinning.

5. Crown expansion

Crown covers of the control stand were 34-49% larger than those of the thinned stands in the second year after the thinning (Table 6). However, annual crown expansion rates were not significantly different among the treatments (Table 10). Crown expansion was not significantly correlated with PMS or any density measure (Table 8).

Crop trees

1. Tree basal area and tree volume

The accumulated increments of tree basal area of the heavily thinned plot were significantly larger than those of the control plot from the fourth year since thinning, while those of tree volume were from the fifth (Figure 12, 13). However, there were no significant differences in the accumulated increments of tree basal area and volume between the lightly thinned and the control plot. There were significant interactions between treatment and year for tree basal area and volume (Table 10). PAI of the heavily thinned plot was 6.9 times for tree basal area and 7.7 times for tree volume as large as that of the control plot but that of the lightly thinned stand was not larger (p=0.17, p=0.22, respectively). PMS and stem density were negatively correlated with the increases of tree basal area and volume (Table 9).

2. Total height and merchantable height

There were no significant differences in total height or merchantable height among treatments (Table 6) and PAI's of total height and merchantable height were not significantly different, either (Table 10). The growth of total height and merchantable height were not significantly correlated with PMS or any density measure (Table 9).

Discussion

Crop trees grew more than average plot trees after the thinning treatment. For instance, tree basal area and volume of crop trees on the heavily thinned stand grew 31-33% more than those of average plot trees (Table 10). According to the results of correlation analysis (Table 8, 9), PMS was significantly correlated with tree growth. Crop trees with larger root area might be more benefited by increased water availability than average plot trees were by increased light availability.

The response of Pacific madrone to the thinning treatment appears to have been immediate rather than gradual, though no significant differences among treatments were found in the first several years after the thinning treatment. The growth trends appear linear, indicating an immediate change in growth rate, although more time may be needed before a reliable test of this apparent trend can be done.

For total height and merchantable height, however, growth rates were not significantly different among the treatments regardless of being average plot trees or crop trees (Table 6, 10). Height and merchantable height growth might not be so sensitive to thinning as tree basal area and volume.

In the first and fourth year after thinning, the stand basal area and stand volume of the control plot were less than those in the thinned year. These differences might come from mortality. Density management is described as a compromise between maximization of stand volume production and maximization of individual tree growth (Long 1985). However, for Pacific madrone, maximization of tree growth was attained by thinning without loosing the stand productivity. In a slow-growing Pacific madrone stand, it is recommended that stand density should be managed at a low stand density if the management objective is for both stand and individual tree growth.

There were no PMS data available in the thinned and the next year after thinning. So, it was hard to determine how much PMS was affected by the thinning and if PMS was, then how long the effect would last. Further measurements will be useful to determine the effect of thinning on PMS.

The interpretation of crown cover should be treated with caution because some serious errors were already found in the red alder study. However, a significant difference in crown covers was found between the control and the thinned stands in the first measurement year. So it might be valid to use and discuss the data. Considering the differences in stem density or stand basal area among the treatments, the differences in crown cover were still less than might be expected from the differences in stem density and stand basal area. It might come from overlap of crown covers. For example, only one tree could be shown in a picture when the other trees standing behind in a row were totally overlapped.

Crown covers did not grow proportionally to the increase of light availability resulting from thinning. There was no significant difference in crown growth between the control and the thinned stands (Table 10). In correlation analysis (Table 8, 9), tree growth was not significantly correlated with crown covers. In a dry region, crown growth might not be so important for tree growth as water availability.

Table 6. Tree and stand characteristics of Pacific madrone immediately after thinning in the spring of 1984 and after 4 years of growth (1984-1988).

	'83*			'88		
	Control stand	Lightly thinned stand	Heavily thinned stand	Control stand	Lightly thinned stand	Heavily thinned stand
Stem density (trees/ha)	2290a	486b	264c	2142a	469b	264c
Stand density index	1005a	286b	203b	1010a	307b	230b
Stand basal area(m^2/ha)	40.2a	12.3b	9.4b	41.2a	13.6b	10.9b
Stand volume(m^3/ha)	230.6a	73.4b	59.1b	239.2a	82.4b	70.5b
Basal area(cm^2)						
Plot tree	177.3a	253.5ab	359.0b	192.6a	287.9ab	417.8b
Crop tree	265.9a	341.0a	425.5a	277.2a	388.4a	502.7a

* Data presented as '83 were collected in the Spring of 1984.
Height and merchantable height were measured in the spring of 1986 and in the winter of 1988.
Values within a row for a given year followed by the same letter are not significantly different ($p=0.05$).
Sample size=9.

(Table 6. Continued)

	'83			'88		
	Control stand	Lightly thinned stand	Heavily thinned stand	Control stand	Lightly thinned stand	Heavily thinned stand
Volume(m^3)						
Plot tree	0.10a	0.15ab	0.23b	0.11a	0.18ab	0.27b
Crop tree	0.16a	0.21a	0.27a	0.17a	0.25a	0.33a
Height(m)						
Plot tree	12.8a	13.0a	13.8a	13.1a	13.6a	14.4a
Crop tree	13.9a	14.4a	14.5a	14.0a	14.6a	15.2a
Merchantable height(m)						
Plot tree	6.6a	6.6a	6.8a	6.8a	6.5a	6.9a
Crop tree	8.0a	7.5a	7.3a	7.8a	7.5a	7.4a
Crown covers(%)	61.1a	45.4b	41.0b	67.4a	46.7b	52.2b

Crown covers were measured in 1986 and 1988

Table 7a. Analysis of variance of annual mortality of average Pacific madrone plot trees during 1984 and 1988.

Source	df	Mean square	F value	Pr > F
Treatment	2	792.4	3.38	0.14
Block	2	198.1	0.84	0.49
Error	4	234.7		
Total	8			

Table 7b. Comparison of annual mortality of average Pacific madrone plot trees by treatment (least square mean was used).

Treatment	Annual mortality (trees/ha)	Pr>|T|	H_0:treatment(i)=treatment(j)	
		i/j	1	2
1	30	1	.	
2	3	2	0.10	.
3	0	3	0.08	0.81

Table 8. Correlation among densities, plant moisture stress (PMS), and growth responses of average Pacific madrone plot trees.

	Annual crown expansion	Annual tree basal area increment	Annual stand basal area increment	Annual tree volume increment	Annual stand volume increment	Annual height increment	Annual merchantable height increment
Density trees/ha	.	-0.51 (0.01)	.	-0.54 (0.01)	.	.	.
SDI	.	-0.47 (0.01)	.	-0.49 (0.01)	.	.	.
SBA	.	-0.45 (0.01)	.	-0.46 (0.01)	.	.	.
PMS (-MPa)	.	-0.39 (0.05)	.	-0.41 (0.03)	.	.	0.64 (0.06)

where SDI: stand density index
SBA: stand basal area (m^2/ha)
The number in ( ) is a probability > $|R|$ under H_o:R=0.
Only correlations with $p \leq 0.10$ are given.
Sample size: 9.

Table 9. Correlation among densities, plant moisture stress (PMS) and growth responses of Pacific madrone crop trees.

	Annual tree basal area increment	Annual tree volume increment	Annual height increment	Annual merchantable height increment
Density trees/ha	-0.29 (0.05)	-0.30 (0.05)	.	.
SDI	-0.28 (0.06)	-0.29 (0.05)	.	.
SBA	-0.27 (0.07)	-0.27 (0.07)	.	.
PMS (-MPa)	-0.63 (0.01)	-0.61 (0.01)	.	.

where SDI: stand density index

SBA: stand basal area (m^2/ha)

The number in ( ) is a probability > $|R|$ under H_o: R=0.

Only correlations with $p \leq 0.10$ are given.

Sample size: 9.

Table 10. Periodic annual increments (PAI) of Pacific madrone over 5 years (1984-1988).

	Control stand	Lightly thinned stand	Heavily thinned stand
Tree basal area growth(cm^2)			
*Plot tree	3.05±1.36a	6.89±1.02ab	11.76±2.10b
*Crop tree	2.24±0.48a	9.49±0.38ab	15.43±5.27b
Tree volume growth(m^3)			
*Plot tree	0.002±0.001a	0.005±0.001ab	0.009±0.002b
*Crop tree	0.002±0.000a	0.007±0.000ab	0.012±0.004b
Stand basal area growth (m^2/ha)	0.19±0.27a	0.25±0.08a	0.31±0.05a
Stand volume growth(m^3/ha)	1.71±1.71a	1.80±0.57a	2.28±0.43a
Height growth(m)			
Plot tree	0.12±0.11a	0.22±0.13a	0.19±0.77a
Crop tree	0.04±0.06a	0.08±0.11a	0.23±0.10a
Merchantable height growth(m)			
Plot tree	0.06±0.06a	-0.01±0.01a	0.03±0.05a
Crop tree	-0.04±0.08a	0.00±0.00a	0.04±0.08a
Annual crown expansion(%)	3.1±1.8a	0.7±1.8a	5.6±0.9a

* Interaction between treatment and year is significant in this marked variables.
Crown covers were measured in 1986 and 1988.
The value following the sign (±) is a standard error and the same letter means there is no significant difference at significant level 0.05. Sample size: 9.

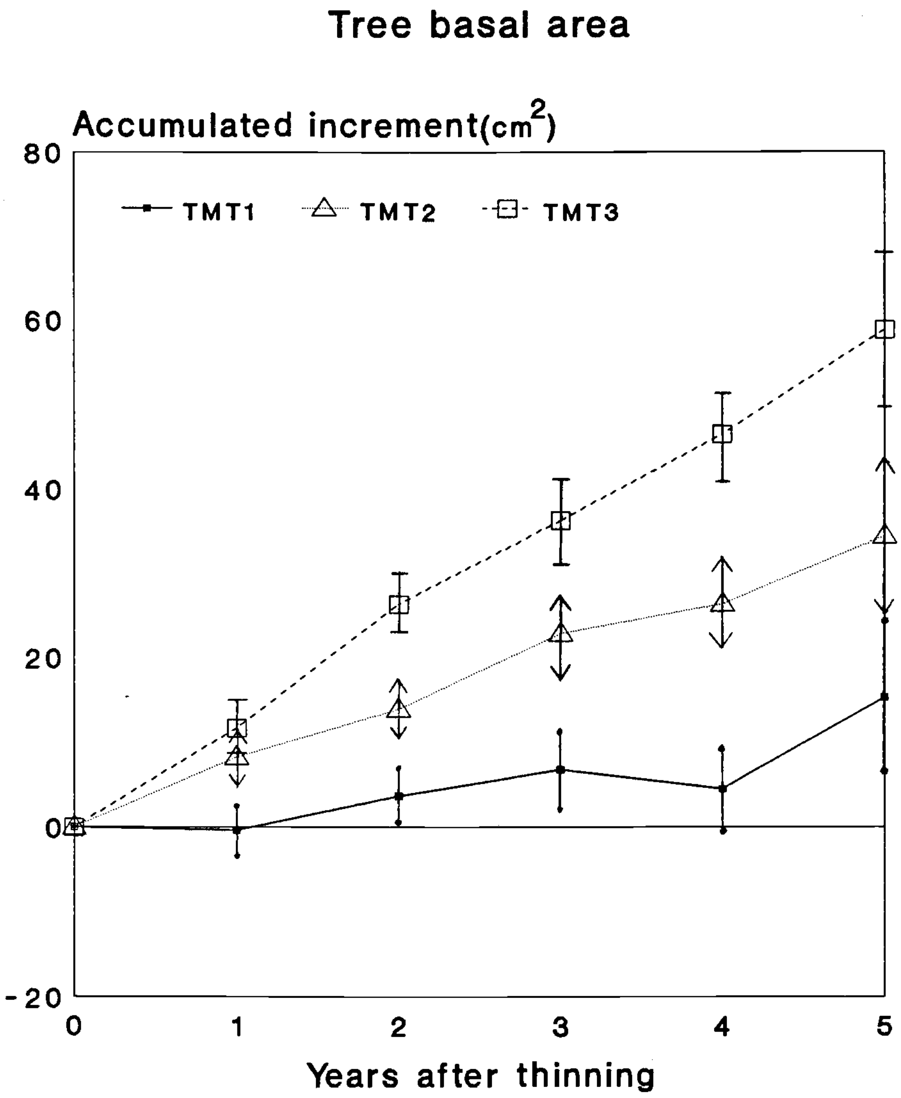

Figure 7. Tree basal area increment of average Pacific madrone plot trees accumulated over years after thinning. where TMT1(control stand): stem density 2290 trees/ha (SDI 1005.0), TMT2(lightly thinned stand):stem density 486 trees/ha (SDI 286.2) and TMT3(heavily thinned stand): stem density 264 trees/ha (SDI 203.2). Standard error is shown as a vertical bar.

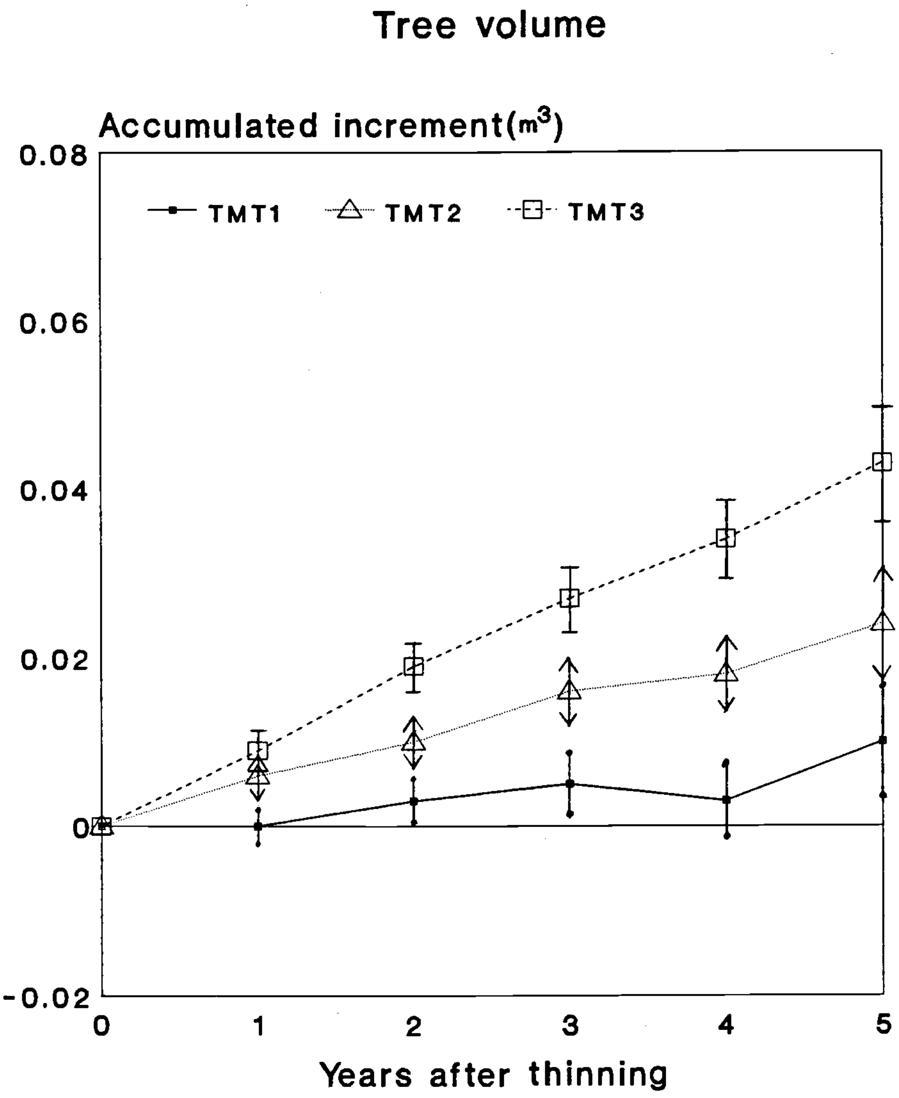

Figure 8. Tree volume increment of average Pacific madrone plot trees accumulated over years after thinning. where TMT1(control stand): stem density 2290 trees/ha (SDI 1005.0), TMT2(lightly thinned stand): stem density 486 trees/ha (SDI 286.2) and TMT3(heavily thinned stand): stem density 264 trees/ha (SDI 203.2). Standard error is shown as a vertical bar.

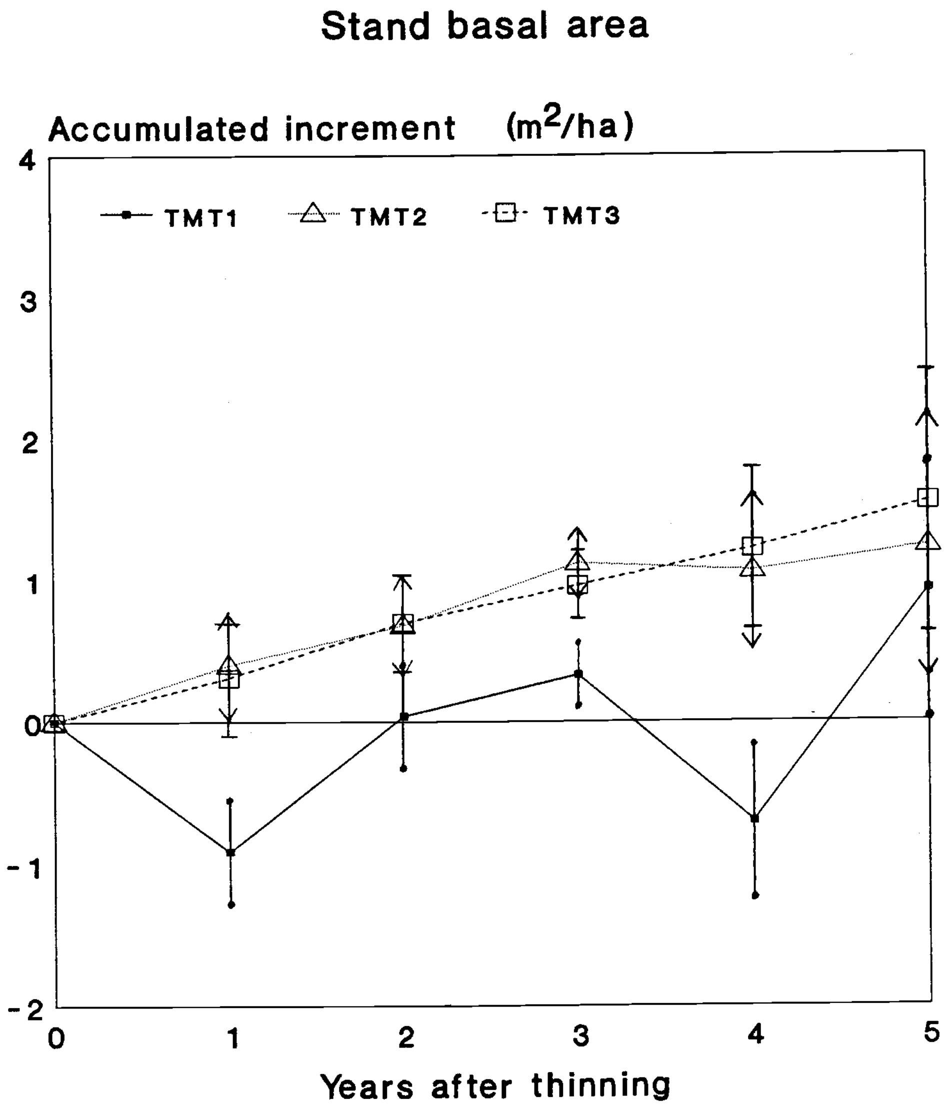

Figure 9. Stand basal area increment of Pacific madrone accumulated over years after thinning. where TMT1(control stand): stem density 2290 trees/ha (SDI 1005.0), TMT2(lightly thinned stand): stem density 486 trees/ha (SDI 286.2) and TMT3(heavily thinned stand): stem density 264 trees/ha (SDI 203.2). Standard error is shown as a vertical bar.

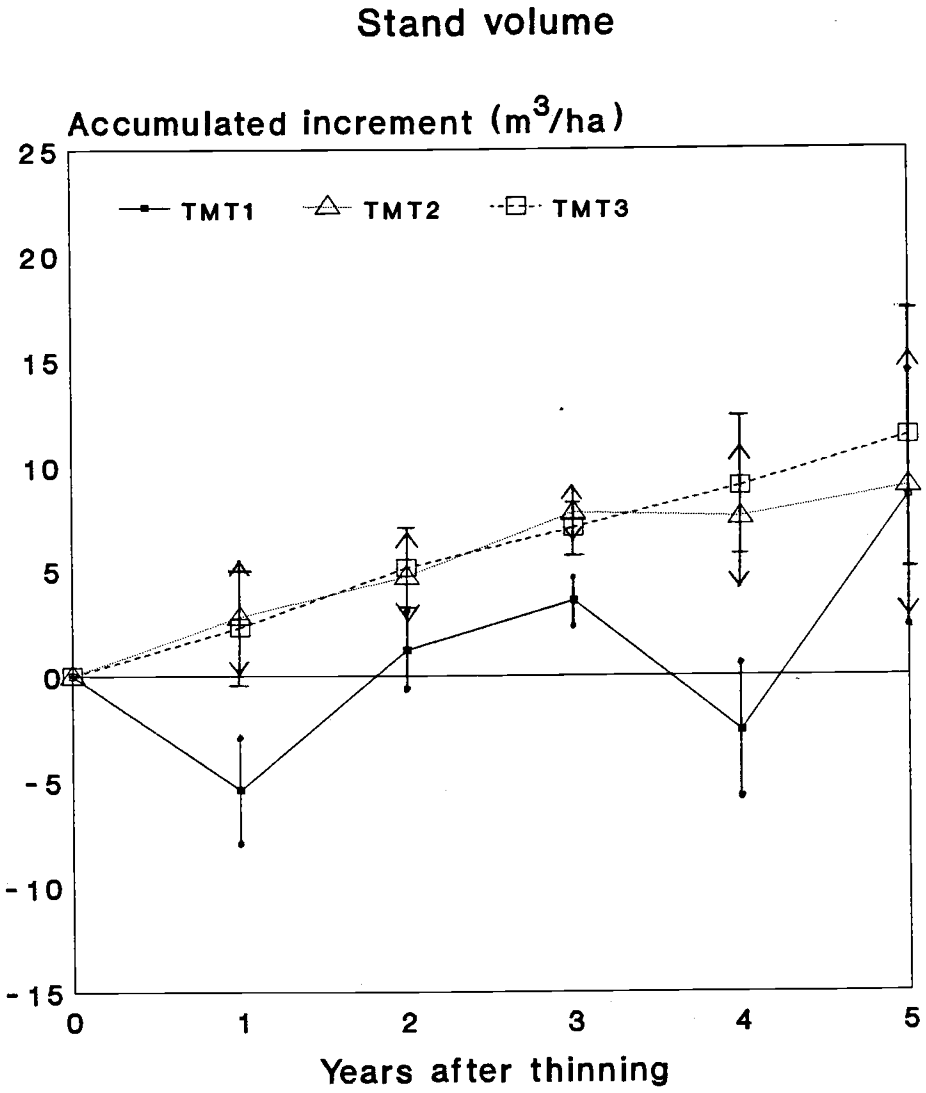

Figure 10. Stand volume increment of Pacific madrone accumulated over years after thinning. where TMT1(control stand): stem density 2290 trees/ha (SDI 1005.0), TMT2(lightly thinned stand): stem density 486 trees/ha (SDI 286.2) and TMT3(heavily thinned stand): stem density 264 trees/ha (SDI 203.2). Standard error is shown as a vertical bar.

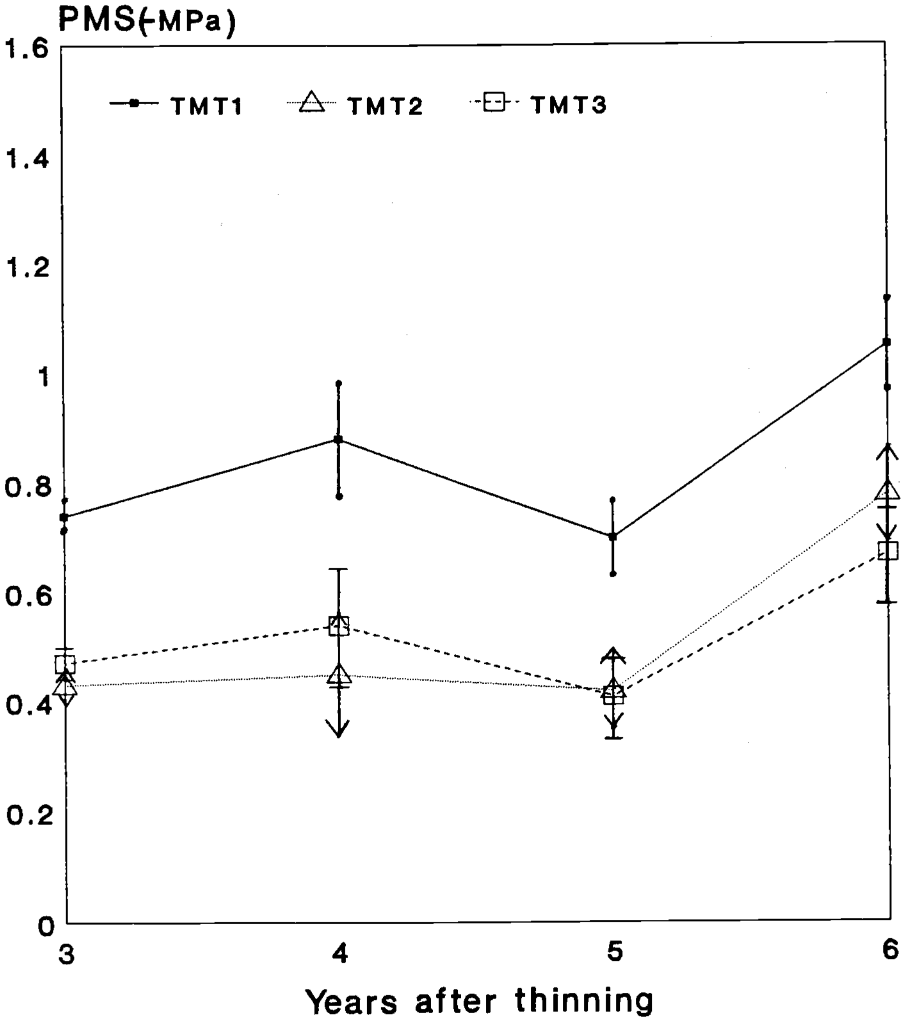

Figure 11. Plant moisture stress (PMS) of Pacific madrone stand over years after thinning. where TMT1(control stand): stem density 2290 trees/ha (SDI 1005.0), TMT2(lightly thinned stand): stem density 486 trees/ha (SDI 286.2) and TMT3(heavily thinned stand): stem density 264 trees/ha (SDI 203.2). Standard error is shown as a vertical bar.

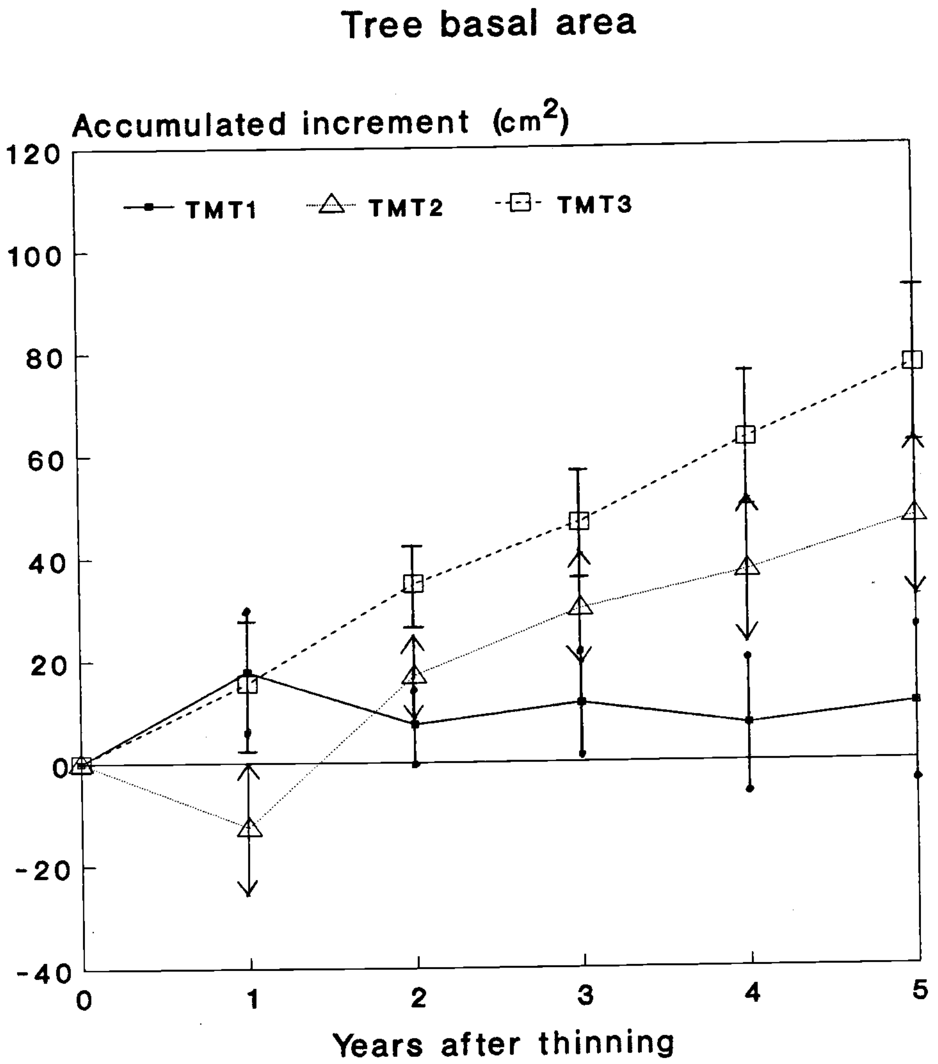

Figure 12. Tree basal area increment of Pacific madrone crop trees accumulated over years after thinning. where TMT1(control stand): stem density 2290 trees/ha (SDI 1005.0), TMT2(lightly thinned stand): stem density 486 trees/ha (SDI 286.2) and TMT3(heavily thinned stand): stem density 264 trees/ha (SDI 203.2). Standard error is shown as a vertical bar.

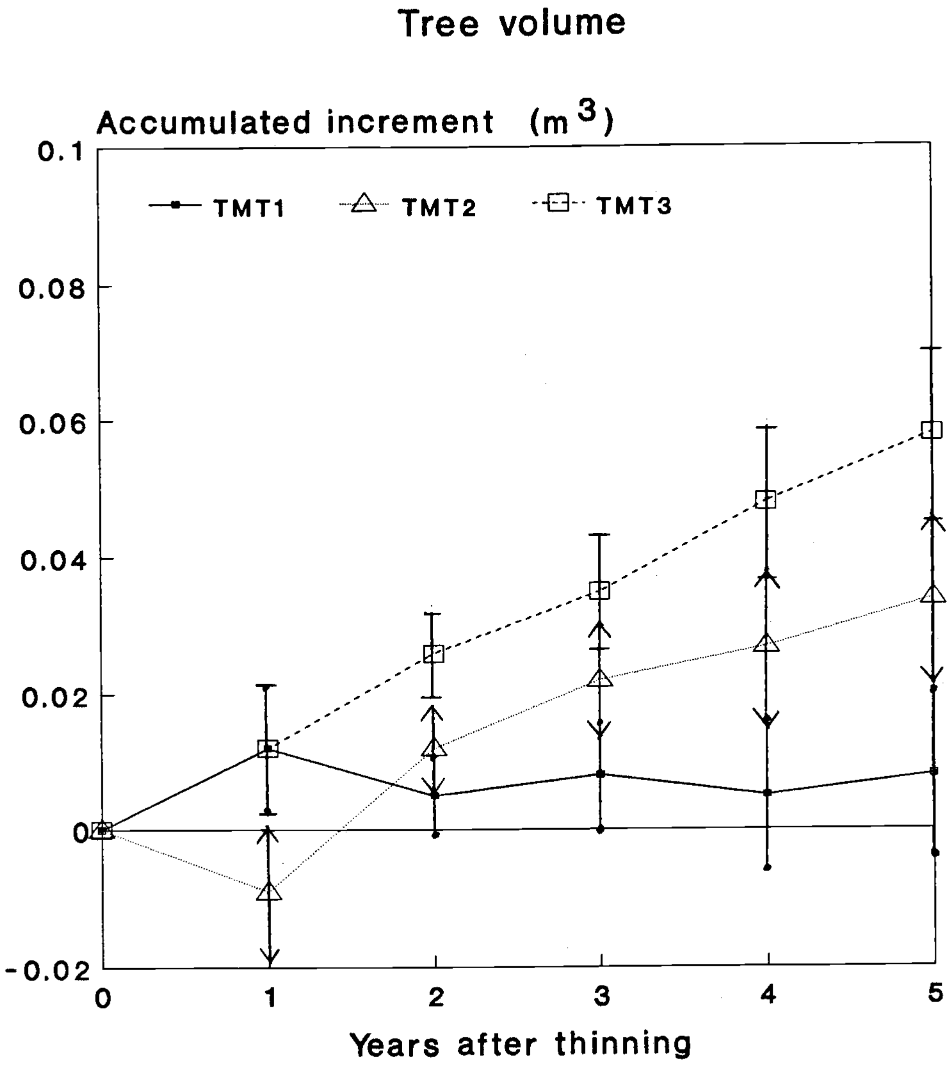

Figure 13. Tree volume increment of Pacific madrone crop trees accumulated over years after thinning. where TMT1(control stand): stem density 2290 trees/ha (SDI 1005.0), TMT2(lightly thinned stand): stem density 486 trees/ha (SDI 286.2) and TMT3(heavily thinned stand): stem density 264 trees/ha (SDI 203.2). Standard error is shown as a vertical bar.

V. SYNOPSIS

Discussion

Effects of thinning varied with species and crown class. Average red alder plot trees of the thinned stands did not grow significantly more than those of the control stand, though crop trees did (Table 5). For Pacific madrone, however, average plot and crop trees of the heavily thinned stand grew more than those of the control stand (Table 10). Pacific madrone crop trees in the heavily thinned stand grew 589% more for tree basal area than those in the control stand, while red alder crop trees grew 66% more. Considering the growth rate and thinning intensities, it was evident that slow-growing Pacific madrone was more benefited by thinning than red alder. In correlation analysis, Pacific madrone tree growth was significantly correlated with plant moisture stress (Table 8, 9). This might be the reason why the effect of thinning was so marked for Pacific madrone, especially for crop trees.

There were no significant differences in total height and merchantable height growth for both species, although red alder total height of the heavily thinned stand increased less than that of the control stand when the initial total height was included as a covariate.

Hibbs et al. (1989) also noted that although a reduction in height growth after thinning is not common among hardwood species, but it is not unusual for red alder. Total height and merchantable height growths of both species were seldom affected by plant moisture stress or stem density (Table 3, 4, 8, 9).

There were no significant differences in stand growth among the treatments for both red alder and Pacific madrone. Stand growth was not significantly correlated with plant moisture stress, crown cover or stem density, though red alder stand growth was positively related to stand basal area (Table 3, 8).

The effect of thinning on PMS might be more evident for Pacific madrone on a dry site (range of PMS: -0.41 - -1.05 MPa, annual precipitation: about 500 mm) than for red alder on a wet site (range of PMS: -0.24 - -0.40 MPa, annual precipitation: 1700-2000 mm). At present, it is difficult to answer how thinning effect was different between the two species because of the missing data. The only evidence was that Pacific madrone trees in the thinned stands grew at more rapid rates than red alder trees and that tree growth of Pacific madrone was significantly correlated with plant moisture stress but that of red alder was not.

Conclusion

The effect of thinning on tree growth was more marked for slow-growing Pacific madrone than for rapid-growing red alder, although the absolute differences in growth among the treatments were about the same. For tree basal area, red alder crop trees in the heavily thinned plot increased annually 66% (13.1 cm^2) more than those in the control plot, while Pacific madrone crop trees grew 589% (13.2 cm^2) more.

Crop trees of both species were more benefited than average plot trees. Tree basal area and volume of average red alder plot trees in the heavily thinned stand did not grow significantly more, while those of crop trees grew more. For Pacific madrone crop trees in the heavily thinned stand, tree basal area grew 6.9 times as fast as that in the control stand, while it grew 3.9 times for average plot trees.

The growth rates of the thinned stands were almost constant over years after the thinning treatments for both species. That is, thinning responses appear to have been immediate rather than gradual.

There were no significant differences in the increases of total height and merchantable height for both species. For red alder, however, PAI's of total height of the heavily thinned plot were significantly less than those of the control plot when the initial heights were included as covariates. The increases of total and merchantable height were not significantly affected by plant moisture stress or stem density.

Stand growth was not significantly different among the treatments for both species. So, if the management objective is to facilitate growth of crop trees without loosing stand productivity, the stands can be managed at the low density range. The relative stand basal area growth rates of the heavily thinned stands were higher than those of the control stands for both species. The stand growth was not significantly correlated with plant moisture stress or any density measure.

PMS was significantly correlated with tree growth of Pacific madrone and response of crop trees was greater than that of average plot trees. For Pacific madrone, PMS's of the thinned plots were 37-42% lower than that of the control plot in the third and sixth year after thinning. However, PMS was not significantly correlated with red alder and there were no differences among the treatments. These differences in PMS might be the reason why the effect of thinning on tree growth was so marked for Pacific madrone, especially for crop trees.

For Pacific madrone, crown cover did not increase as light availability increased after thinning, i.e., no significant difference in crown growth was found between the control and the thinned stands. It was not significantly correlated with tree growth, while water potential was. Crown growth might not be so important a factor for tree growth as water availability in a dry region.

VI. LITERATURE CITED

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