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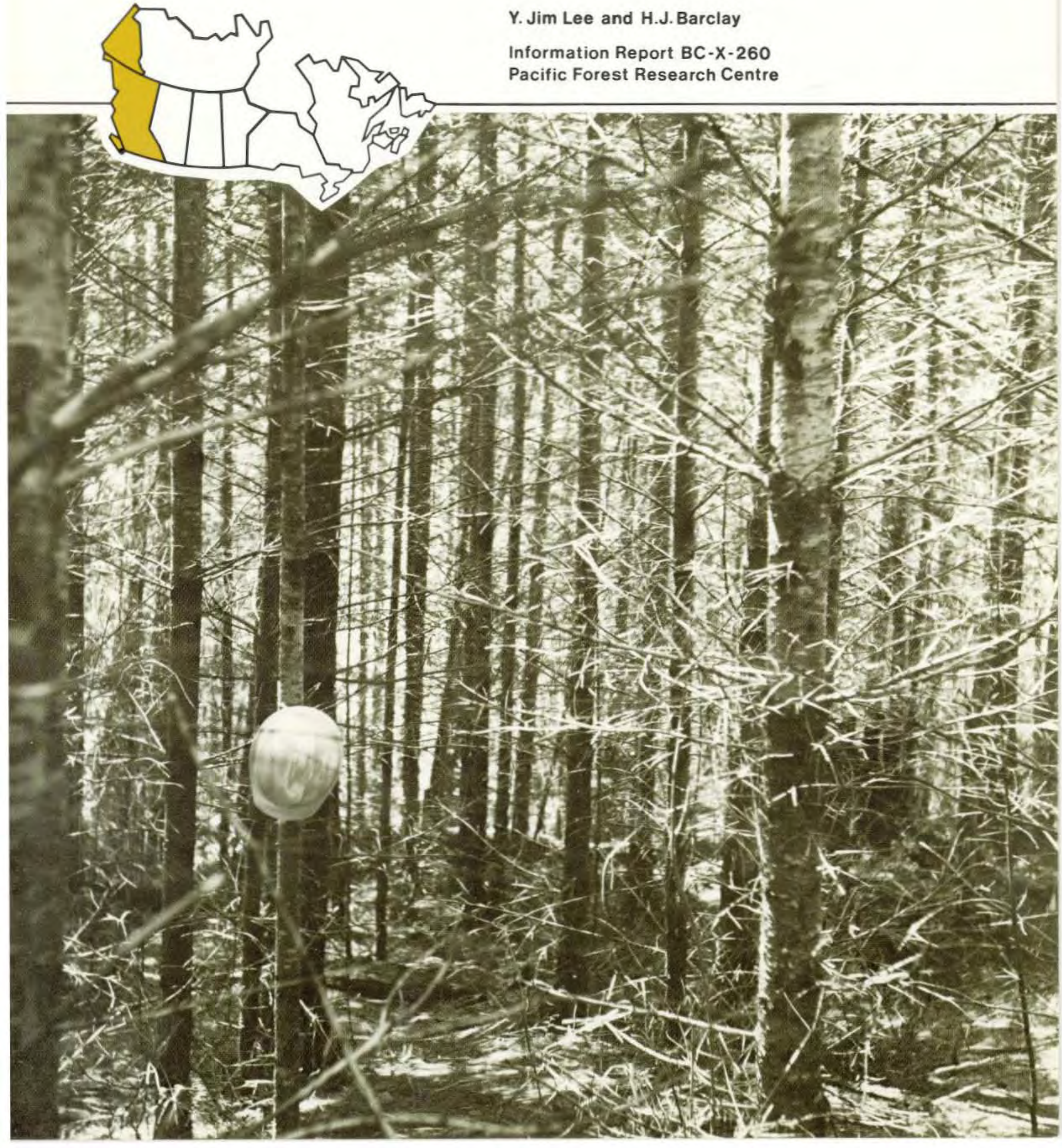

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Abstract

Ten-year growth responses to nitrogen fertilization and thinning are reported for experiments established in 25-year-old and a 55-year-old Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands of medium site quality. Four levels of nitrogen (0, 112, 224, and 336 kg N/ha), in the form of urea (46% N), were tested at two thinning levels in a randomized 4×2×2 factorial design replicated in two blocks. Fertilizer was applied in spring or fall, but the season of application had little effect on growth. Thinning almost doubled diameter growth by 10 years but affected only net volume growth; gross volume was only minimally affected by thinning. Fertilization in the 25-year-old stand increased mean dbh growth significantly in the second and third year and increased volume growth significantly in the first three years but the effect diminished thereafter. Fertilizer effect on the 55-year-old stand was inconsistent with different rates of application. Combined treatment of thinning and fertilization had the greatest growth response. In both stands the overall effect of 336 KgN/ha was to increase volume growth by about 20%. Thinning significantly decreased mortality, but the effect of fertilizer was negligible. Combined treatment had the greatest effect on the advancement of trees by the number of dbh classes. The effect of thinning and fertilization on the cumulative growth will probably continue after 10 years until the crowding of trees sets in.

Résumé

L'action de la fertilisation azotée et de l'éclaircie sur la croissance pendant dix ans a été étudiée dans des peuplements de douglas taxifolié (*Pseudotsuga menziesii* [Mirb.] Franco) de 25 et de 55 ans à des emplacements de qualité moyenne. Quatre doses d'azote (0, 112, 224 et 336 kg/ha), sous forme d'urée (46% N), ont été utilisées avec deux niveaux d'éclaircie dans an plan d'expérience factoriel 4×2×2 randomisé, répété dans deux blocs. L'engrais a été épandu au printemps ou à l'automne, mais la saison d'épandage a peu influé sur la croissance. L'éclaircie a presque doublé l'accroissement en diamètre en 10 ans, mais n'a eu un effet que sur l'accroissement en volume net; son effet a été suelement minimal sur le volume brut. Suite à la fertilisation dans le peuplement de 25 ans, le dhp moyen a augmenté de façon significative au cours de la deuxième et de la troisième année, ainsi que l'accroissement du volume, au cours des trois premières années, mais l'effet a été moindre par la suite. Dans le peuplement de 55 ans, la fertilisation n'a pas eu un effet constant pour différentes doses. Un traitement combiné d'éclaircie et de fertilisation a le plus stimulé la croissance. Dans les deux peuplements, la fertilisation à la dose de 336 kg/ha d'azote s'est traduite globablement par une augmentation d'environ 20% de l'accroissement en volume. L'éclaircie a diminué de façon significative la mortalité, mais l'effet de l'engrais a été négligeable. Un traitement combiné a eu le plus d'effet sur l'avancement des arbres en termes de classes de dhp. L'effet de l'éclaircie et de la fertilsation sur l'accroissement cumulatif se maintiendra probablement après 10 ans jusqu'à ce que les arbres se resserrent.

Introduction

Thinning and fertilization are important silvicultural techniques used to increase productivity (Brix 1981; Barclay *et al.* 1982; Lee 1974; Weetman *et al.* 1979) of second growth Douglas-fir stands in the Pacific Northwest. Results from fertilizer trials may help to provide land managers with information necessary to develop guidelines in operational thinning and fertilization (Miller and Fight 1979).

In 1968, a study was initiated to investigate the growth response of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in three age classes to nitrogen fertilizer applied at four rates and in two seasons (Lee 1974). The study comprised three installations in three age classes: 0 to 20 years, 21 to 40 years, and 41 to 60 years, in uniform stands of medium site quality of 24.6 to 32.0 m at index age 50 (Anon. 1981). The study sites were located in the Greater Victoria Watershed Forest (Fig. 1), 24 km northwest of Victoria. One installation was established in each of three years commencing in 1968; the first installation for age class 21 to 40 years, the second for age class 41 to 60 years and the third for age class 0 to 20 years. Results of four-year basal area growth response for age class 21 to 40 years have been published (Lee 1974); both fertilization and thinning were shown to increase basal area growth. This paper reports ten-year growth response for the age class 21 to 40 years and 41 to 60 years. The growth response for the 0 to 20-year installation will be reported separately.

Materials and Methods

Study area

The first installation (21- to 40-year age class) was established in a uniform 25-year-old Douglas-fir stand and the second (41- to 60-year) in a 55-year-old stand. Elevation of the study area was approximately 300 m above sea level, and the terrain sloped 5 to 20% toward the southwest. Annual precipitation during the 10-year period ranged from 796 to 1663 mm and the average was 1319 mm (Anon. 1968-80). The soil was a well-drained sandy loam overlying till and was classified as a mini humo-ferric podzol (Anon. 1978). The predominant species was Douglas-fir with western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and other coastal tree species as minor components. Understorey vegetation consisted primarily of salal (*Gaultheria shallon* Pursh), with lesser amounts of Oregon grape (*Mahonia nervosa* (Pursh) Nutt.) and swordfern (*Polystichum munitum* (Kaulf.) Persl.).

Design and Treatments

For each installation, a randomized 4 × 2 × 2 factorial experiment, replicated in two blocks, was established. Each block consisted of four fertilizer levels, two thinning levels and two seasons of fertilizer application. Each installation consisted of 32 square 0.04-ha plots. Each plot was surrounded by a treated buffer zone about 6.1 m wide.

25-year-old stand. Eight plots in each block were thinned moderately to approximately 2.4 × 2.4 m from an initial spacing of 1.2 × 1.2 m. The residual basal area in the thinned plots ranged from 18.2 to 23.1 m^2/ha, with an average of 20.9 m^2/ha. The basal area in the unthinned plots ranged from 20.6 to 40.1 m^2/ha, with an average of 35.1 m^2/ha. The average diameters at breast height (dbh at 1.37 m) before fertilization for the thinned and unthinned plots were 11.7 and 6.4 cm, respectively. Four levels of nitrogen (0, 112, 224, and 336 kg N/ha), in the form of urea (46% N), were applied in spring or fall to thinned and unthinned stands. All plot trees were numbered, marked and measured for dbh, and heights of 40 trees in each plot were measured; 15 were from the suppressed and intermediate height classes, while the rest were dominants and codominants. Urea fertilizer was broadcast by hand to 12 of the 32 plots in September, 1968 and to the other 12 plots in April, 1969. Measurements of dbh were repeated in the summer of 1969 through 1978, except for 1977.

55-year-old stand. Establishment details and measurements for the 55-year-old stand were similar to those for the first installation, except that height measurements were only made on 15 trees per plot. Plots were thinned to remove suppressed trees, therefore no specific spacings were considered. The basal area removed by thinning ranged from 7.8 to 18.9 m^2/ha and the average was 14.5 m^2/ha. The remaining basal area ranged from 27.9 to 46.7 m^2/ha and the average was 38.5 m^2/ha. The fall fertilization was carried out in

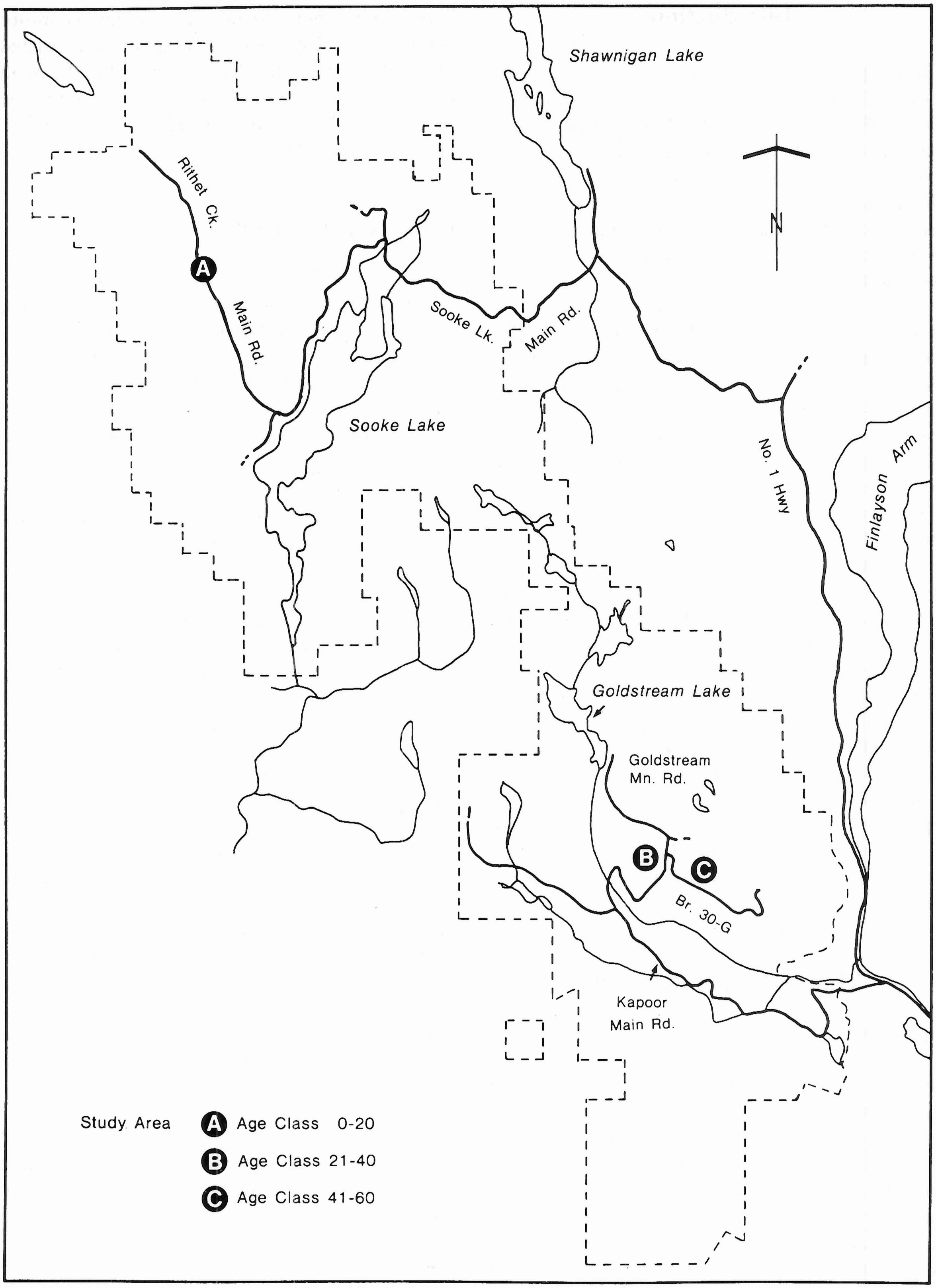

Fig. 1. Location of study areas in the Greater Victoria Watershed Forest.

September, 1969 and the spring fertilization was carried out in April, 1970. Measurements of dbh were repeated in the summer of 1970 through 1979, except for 1977 and 1978.

Volume Calculations

For both age classes, dbh in centimetres and height in metres of the sample trees were measured 5 and 10 years after establishment. For each treatment level, these measurements were used to calculate local height-dbh equations in the form of

$$\log (H) = a + b \log (D)$$
where H = Tree height in metres
D = dbh in centimetres

Tree heights were then calculated for all trees using these equations. The Shawnigan tree volume equation (Hall *et al.* 1980) was used to calculate volume for all trees, since tree form is probably not affected much by the minor site differences between Shawnigan and Greater Victoria Watershed Forest.

$$\log V = -4.21248 + 1.95836 \log D + 0.882447 \log H$$
where V = volume in cubic metres.

Statistical Analysis

The effect on mean dbh growth, volume growth and, mortality in terms of volume per hectare and in terms of trees per hectare were subjected to analysis of variance (random blocks design) for the determination on the significant difference for various treatments (thinning, fertilization and season of fertilizer application). Analyses were carried out yearly as well as for cumulative treatment effect.

Results

25-year-old stand

Season of Application. As reported by Lee (1974), fall application resulted in significantly better basal area growth response (142%) than that of spring fertilization in the first growing period. Analysis of variance indicated that significant differences in yearly mean dbh increment due to season of application were found in the first two growing periods, and for volume growth only in the first year. No significant effects were found yearly or cummulatively thereafter. A small amount of growth may be attributed to an extended growing period during September and October in the fall fertilized stands. In addition, the rate of photsynthesis may also have been increased in the dormant season and resulted in slightly better gorwth the following spring (Brix 1971). However, with respect to overall growth response, the timing of fertilization had very little effect.

Thinning. Averaged across all fertilization regimes, thinning increased mean dbh growth significantly both yearly and cumulatively throughout the 10-year period. Mean dbh increment in thinned plots was twice that in the unthinned plots (Fig. 2a). On a per unit area basis, thinning reduced net volume growth in the first two growing periods but net yield increased significantly thereafter (Fig. 2b). Thinning increased cumulative net yield by about 35 m^3/ha; however the elimination of the loss due to mortality of approximately 30 m^3/ha (Fig. 2c) over the 10-year period almost balanced this gain in volume. Since the 10-year volume increments were calculated as final volume minus initial volume, virtually all of the gain in volume increments due to thinning can be attributed to loss to mortality in the unthinned plots. Thus thinning increased net volume growth but not gross volume growth.

The mortality of the unthinned plots was extremely high due to excessive initial overstocking. The mean initial stocking for the unthinned and thinned plots were 8441 and 1827 stems/ha respectively for the 25-year-old stand. Most of the thinned trees were in the suppressed and intermediate height classes, thus thinning not only removed those likely to die anyway but also increased the mean tree size remaining in the thinned plots.

Fertilization rate. In the second and third growth periods, averaged across all thinned plots, fertilized plots yielded significantly greater mean dbh growth in the second and third growth periods than the unfertilized control (Fig. 3a) . This difference was not significant thereafter, but cumulative mean dbh growth was significantly greater than that of the unfertilized control for the second through the sixth growing periods (Fig. 3a). Fertilizer treatment resulted in short-term

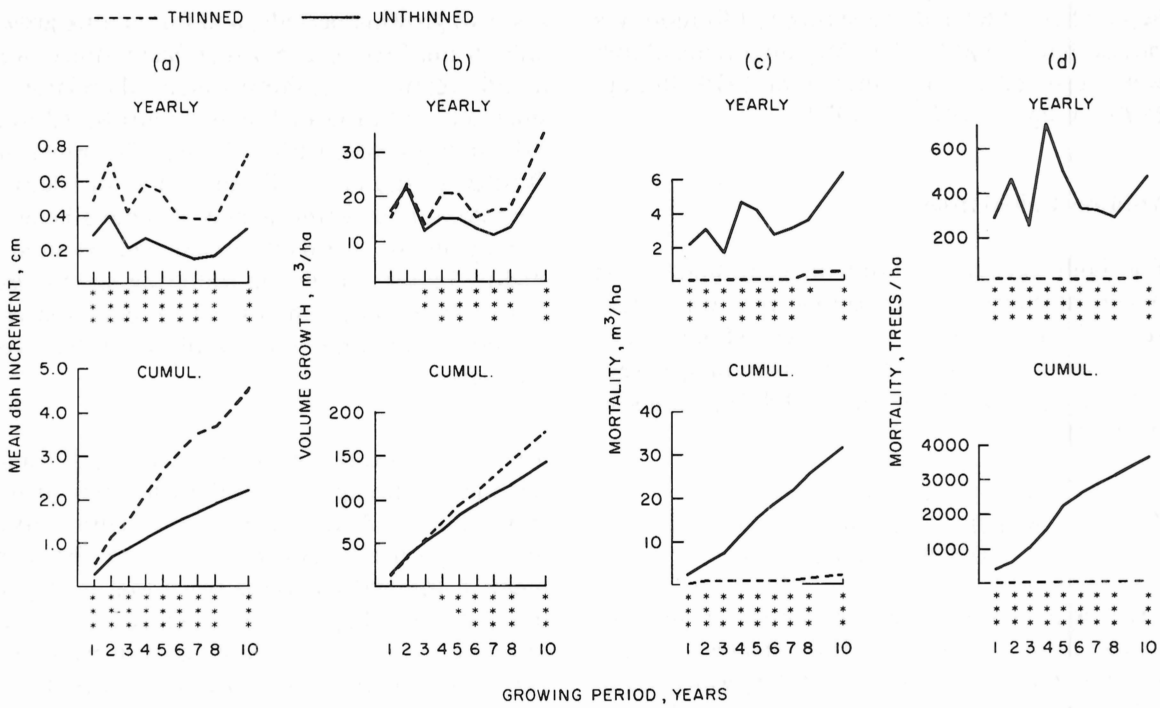

Fig. 2. Effects of thinning on mean dbh increment, net volume growth, and mortality in a 25-year-old Douglas-fir stand over a 10-year period. Significant differences at the 5.0%, 1.0%, and 0.1% levels are indicated by 1, 2, and 3 vertical asterisks, respectively.

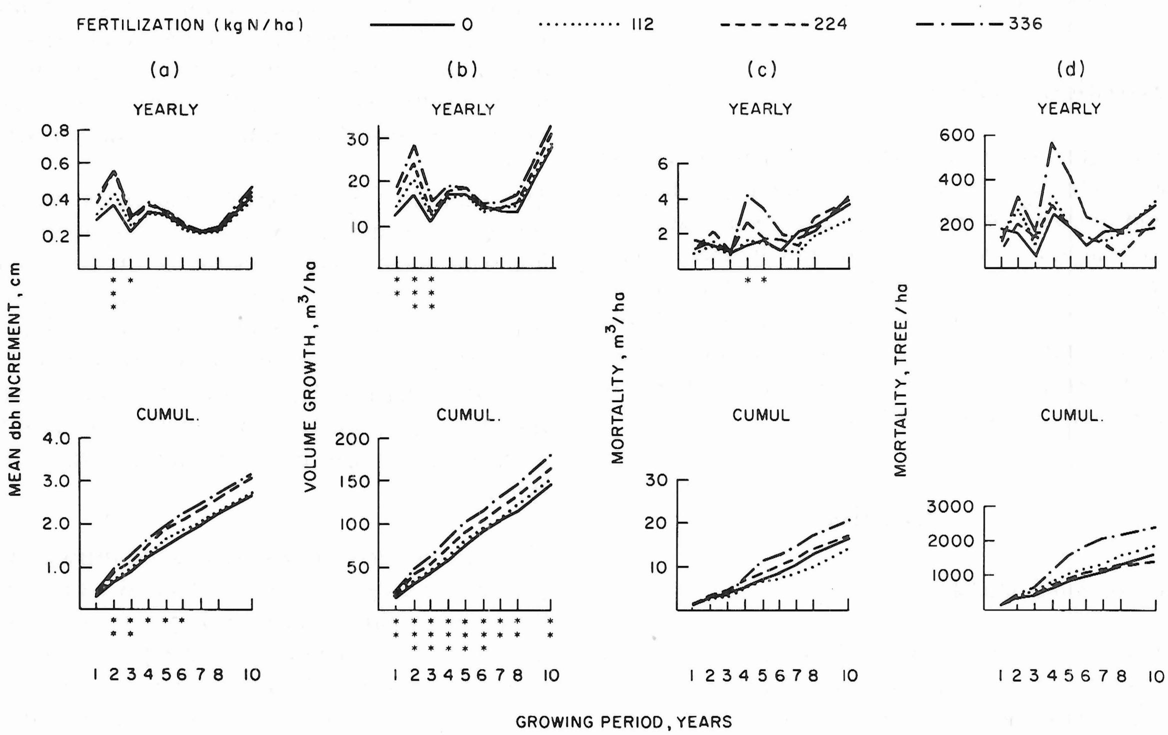

Fig. 3. Effects of urea fertilization on mean dbh increment, net volume growth and mortality in a 25-year-old Douglas fir stand over a 10-year period. Significant differences at the 5.0%, 1.0%, and 0.1% levels are indicated by 1, 2, and 3 vertical asterisks, respectively.

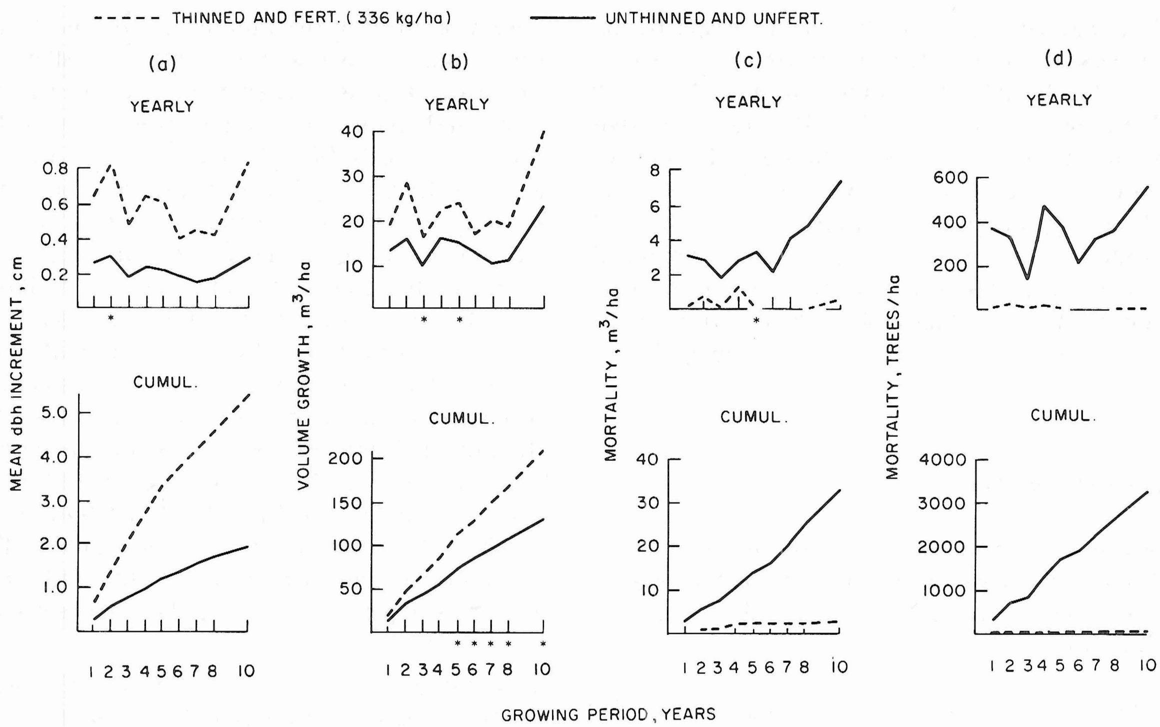

Fig. 4. Combined effects of thinning and urea fertilization (336 KgN/ha) on mean dbh increment, net volume growth and mortality in a 25-year-old Douglas-fir stand over a 10-year period. Significant differences at the 5.0%, 1.0%, and 0.1% levels are indicated by 1, 2, and 3 vertical asterisks, respectively.

yearly increase in volume per unit area and in significant cumulative increase of 33.9 m^3/ha (23% greater than with no fertilization) over the 10-year growing period (Fig. 3b). The 10-year volume increments were 145.8, 150.9, 166.0 and 179.7 m^3/ha with fertilization rates of 0, 112, 224 and 336 Kg N/ha respectively. The effect of fertilization on mortality in terms of volume or number of trees per hectare was not as dramatic as that of the thinning effect. Only during the fourth and fifth growing period was the yearly volume loss per unit area due to mortality significant ($P < 0.05$, Fig. 3c). However the 336-kg N/ha treatment did show a higher mortality rate in terms of both volume and number of trees per hectare over the other treatments both yearly and cumulatively (Fig. 3c and d).

Combined effect of thinning and fertilization. The combined effect of thinning and the 336-kg N/ha fertilizer treatment gave the highest mean dbh and net volume growth. This treatment combination also gave the lowest mortality in terms of both volume and number of trees per hectare, though this was not always statistically significant (Fig. 4). The mean dbh growth for the treated plots was three times greater than those of the untreated control over the 10-year period, both yearly and cumulatively (Fig. 4a). However, in terms of volume per hectare, the growth was only 1.5 times as great (Fig. 4b). This combined treatment gave the least mortality, both in terms of volume and number of trees per hectare, compared to the unthinned and unfertilized stand, i.e., one sixteenth in cumulative mortality.

Splitting the fertilized plots into unthinned and thinned, the net volume increments were 133.4, 147.1, 146.0 and 149.7 m^3/ha for 0, 112, 224 and 336 kg N/ha respectively in unthinned plots, and 158.2, 154.8, 186.0 and 209.7 m^3/ha for 0, 112, 224 and 336 kg N/ha respectively in thinned plots. Thus, except for the lowest fertilizer rate, the response was least in thinned stands.

Advancement of trees by dbh classes in ten years after treatment. Ten years after treatment, the combined effect of thinning and urea fertilization (336 kg N/ha) resulted in 12, 23, 39, 25 and 1% of live trees per hectare that have advanced 4, 3, 2, 1 and zero 2.5-cm dbh classes respectively, whereas the unthinned-unfertilized control only 1, 4, 13, 29 and 53% advanced by 4, 3, 2, 1 and 0 dbh classes respectively (Fig. 5). This means that almost all the live trees in the treated stand advanced more than a single dbh class in the 10-year growing period, whereas more than half of the live trees in the untreated stand remained in the same dbh class over the 10-year growing period (Fig. 5). Therefore the combined treatment produced larger trees, thus reducing the rotation period.

55-year-old stand

Season of Application. Analysis of variance indicated that season of fertilization had no significant effect in growth response either yearly or cummulatively.

Thinning. The effect of thinning on the 55-year-old stand was not as great as the effect on the 25-year-old stand. Thinning almost doubled the dbh increment both yearly and cumulatively over the 10-year growth period (Fig. 6a). Net

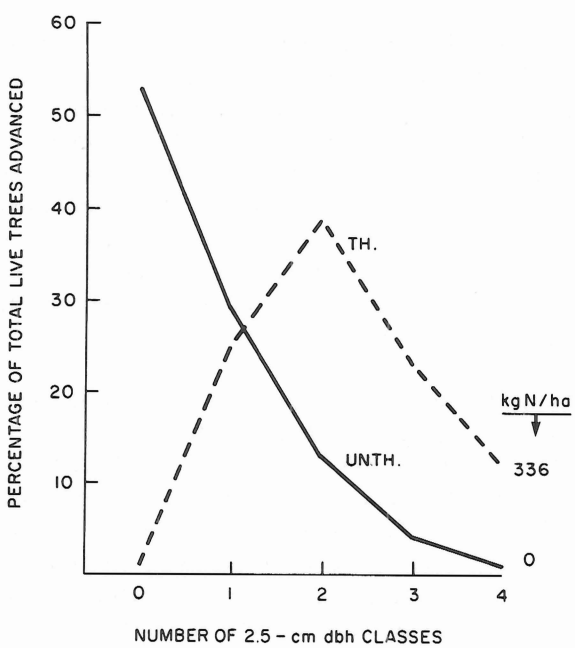

Fig. 5. Combined effects of thinning and urea fertilization (control and 336 Kg N/ha) on the percentage of live trees advancing through 2.5-cm dbh classes over a 10-year growing period in the 25-year-old Douglas-fir stand.

volume growth in the thinned stand was significantly higher than that of the unthinned stand for the third, sixth and the seventh years on a yearly basis, and significant differences were found for the third, fourth, fifth, sixth and seventh year on a cumulative basis (Fig. 6b). Mortality in terms of volume per hectare varied from year to year and was cumulatively greater for the unthinned stand. At the end of the tenth year, cumulative mortality was 50 m^3/ha for unthinned but only 27 m^3/ha for the thinned stand (Fig. 6c). Mortality in terms of the number of trees per hectrare was significantly greater for unthinned than for the thinned stand (Fig. 6d). The cumulative mortality in trees per hectare was about 30 for the thinned and 435 for the unthinned stand, again yielding little effect on gross volume growth. The mean initial stems per hectare for the unthinned and thinned plots were 1637 and 631 respectively.

Fertilization rate. Cumulative mean dbh increment was significantly greater than that of the unfertilized control for the second through the seventh growing periods after treatment (Fig 7a) with an increase of 50% for the 336 Kg N/ha rate. The 112 kg N/ha treatment yielded greater mean dbh increment than that of the 224 kg N/ha fertilized stand. Significant differences were found on volume growth per unit area among the four treatments on some years (Fig. 7b) with the heavily fertilized plots growing 21.4 m^3/ha (20%) more than unfertilized plots. The volume growth response was not consistent with rate of fertilization. This was probably due to heavy tree mortality in terms of volume per hectare for the 224-kg N/ha and 336-kg N/ha treatments (Fig. 7c). This was perhaps due to the death of trees with larger dbh in these two stands, i.e., a greater number of dead trees yearly and cumulatively (Fig. 7d) for the 112-kg N/ha treatment and the untreated control, yet less mortality in terms of volume per hectare (Fig. 7c). It appeared that the death of a few large trees would affect the treatment growth response greatly in an older stand.

Combined effect of thinning and fertilization. The combined treatment effect of thinning and the 336-kg N/ha treatment more than doubled the mean dbh increment of the unthinned-unfertilized stand yearly and more than tripled the cumulative dbh increment (Fig. 8a). However, due to heavy mortality in terms of volume per ha (Fig. 8c) in the seventh through tenth period, yearly volume growth per hectare was similar for

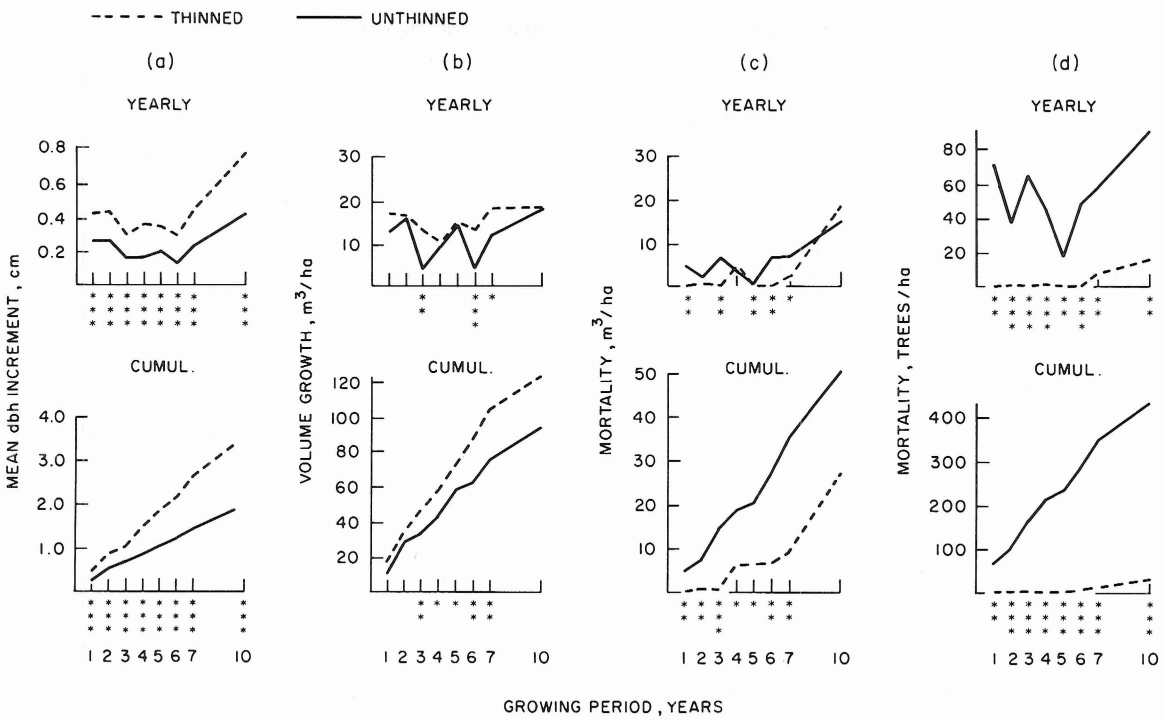

Fig. 6. Effects of thinning on mean dbh increment, net volume growth, and mortality in a 55-year-old Douglas-fir stand over a 10-year period. Significant differences at the 5.0%, 1.0%, and 0.1% levels are indicated by 1, 2, and 3 vertical asterisks, respectively.

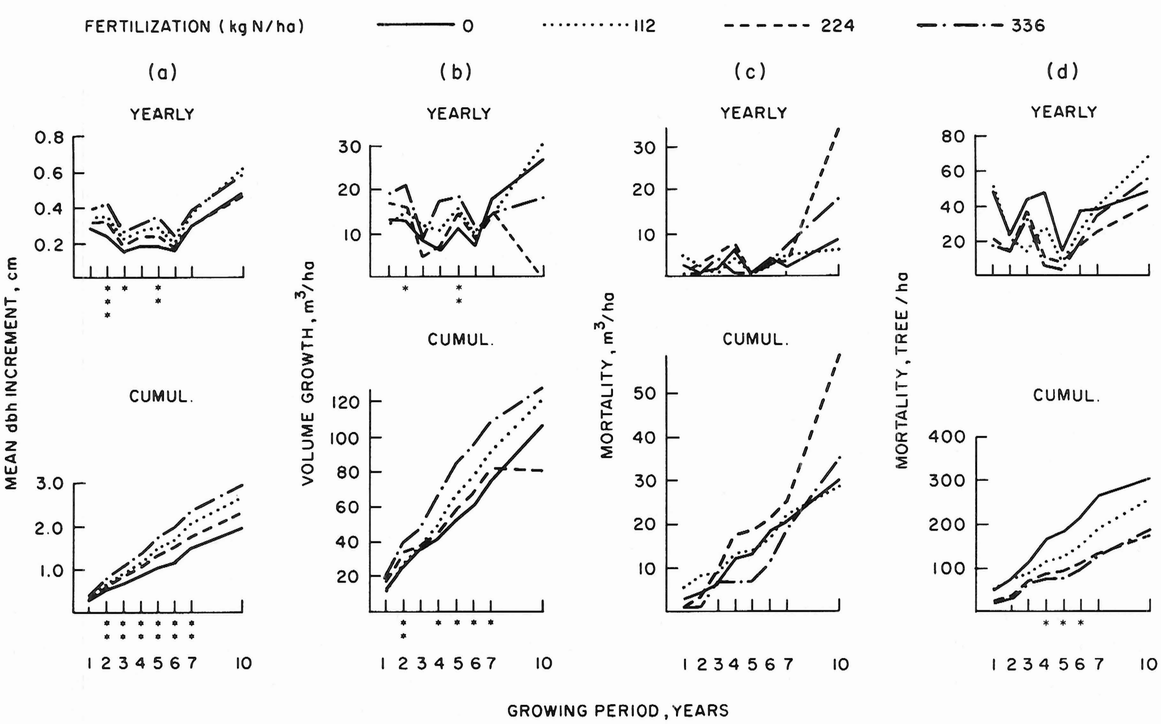

Fig. 7. Effects of urea fertilization on mean dbh increment, net volume growth and mortality in a 55-year-old Douglas-fir stand over a 10-year period. Significant differences at the 5.0%, 1.0%, and 0.1% levels are indicated by 1, 2, and 3 vertical asterisks, respectively.

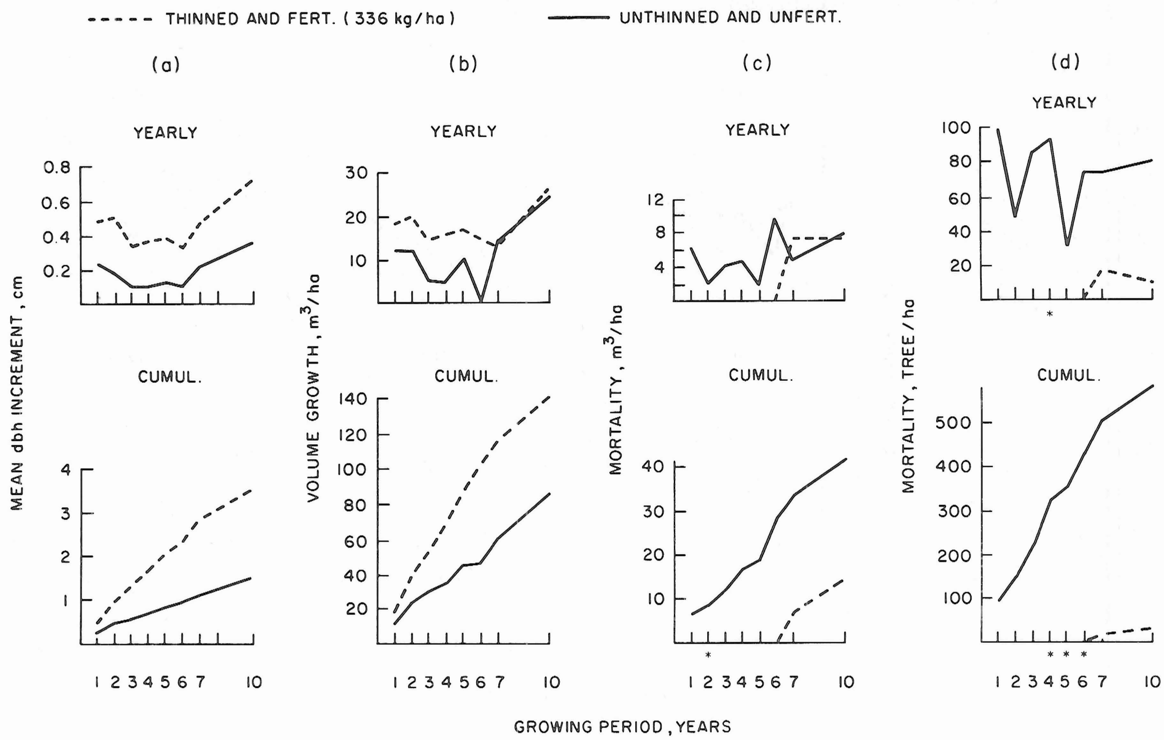

Fig. 8. Combined effects of thinning and urea fertilization (336 KgN/ha) on mean dbh increment, net volume growth and mortality in a 55-year-old Douglas-fir stand over a 10-year period. Significant differences at the 5.0%, 1.0%, and 0.1% levels are indicated by 1, 2, and 3 vertical asterisks, respectively.

this period, but cumulative growth response was still one-third greater for the treated plots than that of the untreated control (Fig. 8b & c). Most of this difference is attributable to higher mortality in the unthinned plots.

No mortality occurred on the thinned and fertilized (336 kg N/ha) stand until the seventh year, thereafter the cumulative number of dead trees per hectare was forty times greater for the untreated control than that of the thinned and fertilized (336 kg N/ha) stand (Fig. 8d).

The net volume increments in unthinned, fertilized plots were 87.3, 89.6, 86.5 and 111.7 m³/ha for 0, 112, 224 and 336 Kg N/ha respectively. The net volume increments for thinned, fertilized plots were 124.2, 151.5, 74.2 and 142.6 m³/ha for 0, 112, 224 and 336 kg N/ha, respectively.

Advancement of trees by dbh classes in ten years after treatment. Ten years after treatment, the combined effect of thinning and urea fertilization (336 kg N/ha) resulted in 8, 33, 52 and 7% of live trees per hectare advancing 3, 2, 1 and zero 2.5-cm dbh classes respectively, whereas in the unthinned unfertilized control, 0, 9, 37 and 54% advanced by 3, 2, 1 and 0 dbh classes respectively (Fig. 9). This means that 92% of the live trees in the treated stand have moved up one or more dbh class within the ten-year treatment period, whereas one-half of the live trees in the untreated stands did not grow more than 2.5 cm (a single dbh class) over the 10-year treatment period (Fig. 9).

Discussion

This study indicates the value of applying nitrogen fertilizer to thinned younger stands if the objective is to produce greater volume, trees with larger dbh, and shorter rotation. Trees on thinned plots grew more than those on unthinned plots, but this net volume growth difference is explainable on the basis of greater tree mortality in unthinned plots.

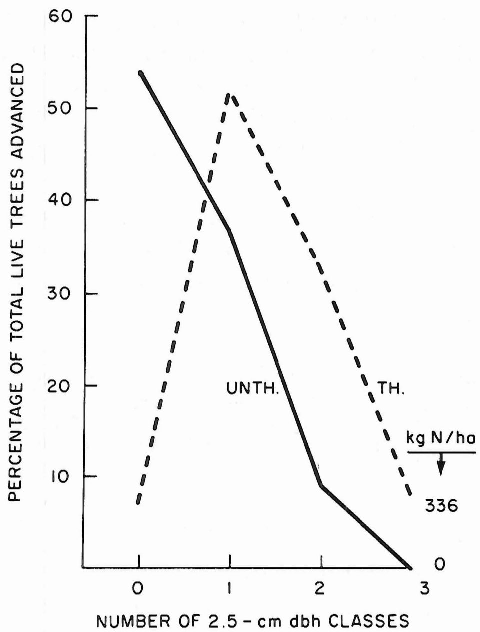

Fig. 9. Combined effects of thinning and urea fertilization (control and 336 Kg N/ha) on the percentage of live trees advancing through 2.5-cm dbh classes over a 10-year growing period in the 55-year-old Douglas-fir stand.

Fertilization increased growth significantly in the first three years but the effect diminished thereafter. This contrasts with the results from the Shawnigan experiment (Barclay *et al.* 1982) in which the dbh and volume increments in fertilized plots still exceed those in control plots nine years after treatment. This is likely due to the lower site quality at Shawnigan (21 m at index age 50 (Anon. 1981)) than in the Victoria watershed (25 to 32 m at index age 50), which would enhance the response to fertilizer. In addition, the heavy stocking of the watershed trees would reduce the degree and duration of the response (Brix 1983). This effect of site quality on level of volume response has been noted elsewhere but is of relatively short duration; differential response effects due to site class do not generally persist much longer than four years in coastal Douglas-fir (Anon 1982).

In both the 25- and 55-year-old trees, the effects of fertilization on individual tree growth were evident sooner than were the effects of thinning. In addition, the effects of fertilizer on increment diminished much sooner than those of thinning. In some previous experiments, the difference between volume increments of control plots and those fertilized with urea at 224 Kg N/ha became insignificant after eight years in both thinned and unthinned Douglas-fir stands (Anon 1982).

The combined treatment had a strong effect on growth response. Response to fertilization by individual trees is likely to be greater in a thinned stand, as results showed for the 25-year-old stand, because light conditions are improved and foliar nitrogen concentrations are higher, enhancing foliage growth (Brix 1983). Low light intensity is likely to limit growth response to nitrogen fertilizer in unthinned plots (Brix 1971).

Conclusions

(1) Thinning increased mean dbh growth immediately and consistently, but its effects on volume growth were not immediate and become evident only after three years in both the 25-year-old and the 55-year-old stands. Thinning increased net volume growth but had little effect on gross volume growth.

(2) Fertilization increased mean dbh growth significantly in the second and third year and increased both net and gross volume growth significantly in the first three years but the effect diminished thereafter in the 25-year-old stand. The effect of fertilizer on the 55-year-old stand was less consistent for different rates of application.

(3) The combined treatment of thinning and fertilization had the greatest effect on growth response on both the 25-year-old and the 55-year-old stand.

(4) Mortality in the unthinned stand was substantially greater than that in the thinned stand for both the 25-year-old and the 55-year-old stand. However, the effect of fertilization on mortality was negligible.

(5) The advancement of trees by dbh class for the combined treatment was greater for the 25-year-old stand than for the 55-year-old stand, indicating that a greater gain is obtainable by thinning a young stand rather than an older one.

(6) The thinning and fertilization effect on the cumulative growth may continue after this 10-year observation period until the crowding of trees sets in. A second thinning operation may then be required.

(7) The season of application of fertilizer had no significant effect on growth in either the 25-year-old or the 55-year-old stand.

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