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THE EFFECTS OF STAND DENSITY AND FERTILIZATION ON STAND DEVELOPMENT IN IMMATURE COASTAL DOUGLAS-FIR

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THE EFFECTS OF STAND DENSITY AND FERTILIZATION ON STAND DEVELOPMENT IN IMMATURE COASTAL DOUGLAS-FIR

Reid Carter and Rob Scagel

EXECUTIVE SUMMARY

120 dominant and codominant trees were selected and felled in fertilized and unfertilized 0.33 ha treatment plots spaced to 500, 750, and 1000 stems per hectare in a 32 year-old stand of coastal Douglas-fir. The sampled stands were spaced and fertilized with 225 kg N/ha as urea in 1977. Stem analysis was used to examine height, diameter, and volume response. Possible changes in stem form resulting from treatment were examined and the accuracy, precision, and repeatability of measurements was determined.

Initial density of the stand was approximately 1600 stems/ha. The stand had an MAI of approximately 10 m^3/ha and a site index of 33 m/50 years.

- Analysis of sample accuracy and repeatability found a sample of 10 trees was necessary to determine height and diameter within a treatment while 12 trees were necessary for determination of annual volume increment.
- Fertilization and stand density had no significant effect on stem form (taper).
- Response to fertilization was immediate and lasted 4 - 10^+ years. This fertilization effect was most pronounced in the 500 and 750 stem/ha treatments. Response to spacing was also quite rapid, however, the density effect was considerably smaller than the fertilization effect during the first 5 post-treatment years. Ten years after treatment the contribution of fertilization and density to the total variation in volume were approximately equal.
- Trees in the 500 and 750 stem/ha treatments had approximately the same volume on an individual tree basis 10 years after treatment. Total volume on a per hectare basis was approximately 50% greater in the 750 stem/ha treatment than in the 500 stem/ha treatment 10 years post-treatment. However, this stand is still relatively young and if these gains in the 750 stem/ha treatment are not realized through commercial thinning they will likely be lost to mortality.
- Fertilization, thinning and their interaction accounted for less than 8% of the total variation in volume. Pre-treatment volume accounted for approximately 90% of the within-treatment variation in volume. The largest trees showed the greatest response to thinning and fertilization. Thinnings should, therefore, carefully consider the size and form of remaining trees as these factors will strongly influence response to thinning and fertilization.
- Actual gains due to fertilization alone ten years after treatment ranged from 18.7 to 34.9 m^3/ha.

INTRODUCTION

Fertilization and thinning represent similar stand management strategies. Both operate under the premise that growth can be enhanced by relieving competition for nutrients. In addition, thinning assumes that competition for physical space, light, and moisture is also ameliorated.

To make economically sound decisions concerning fertilization and/or thinning, the independent and interactive effects of fertilization and thinning must be known on an areal and individual tree basis. The uniformity of treatment response among trees within a treatment and the possibility of a differential volume response within the stem must also be understood. This study examines the effects of fertilization and thinning on dominant and codominant trees in a thirty-two year-old plantation of Douglas-fir ten years after treatment.

Study Area

The study was carried out in the Juvenile Spacing Demonstration Area of Fletcher Challenge Canada's Courtenay Division. This Demonstration Area was established in 1977 in a 23-year-old Douglas-fir stand (SI/50=34m; MAI approximately 10 m^3/year). This plantation is located in the transition between the wetter Coastal Douglas-fir and Drier Coastal Western Hemlock biogeoclimatic subzones at an elevation of approximately 270m on flat to gentle sloping till-derived soils with an eastern aspect. The understory vegetation was dominated by salal. This site was selected as all treatment plots had approximately the same actual soil moisture and nutrient regime (Klinka *et al.* 1984). Restricting the study to such a homogenous situation partially assures that the treatments would not be differentially influenced by site.

Seven 2/3 ha blocks were established in March, 1977. Spacing treatments were applied to blocks (Figure 1) as part of a larger Juvenile Spacing Demonstration Project (Promnitz 1984). Following spacing, a fertilization treatment (225 kg N/ ha as urea; Figure 1) was applied to half of each block. As these areas were prepared for demonstration purposes, the treatments and spacing were applied more carefully than might be expected in an operational situation. Two 0.02 ha sample plots were established in each treatment for growth monitoring. Diameter of all plot trees was measured in the winter of 1977, 1978, 1979, and 1983. Height of subsampled trees was measured in the winter of 1977 and the winter of 1983 (Promnitz 1984). The current study is limited to the fertilized and unfertilized blocks mechanically spaced to 495, 740, and 988 stems/ ha.

A chronology of activities carried out in the demonstration area is as follows:

1954 - plantation planted to approximately 3000 stems/ha

1977 March

- seven 2/3 ha blocks were established
- spacing treatments were applied (Figure 1)
- fertilizer treatments were applied (Figure 1)
- four 0.02 ha sample plots were established in each block
- diameter of all plot trees and height of all subsample trees was measured

1978, 1979 - Winter

- diameter of all plot trees measured

1983 - Winter

- diameter of all plot trees and height of all subsample trees was measured

1986 - September

- sample trees were selected, felled, measured and analyzed.

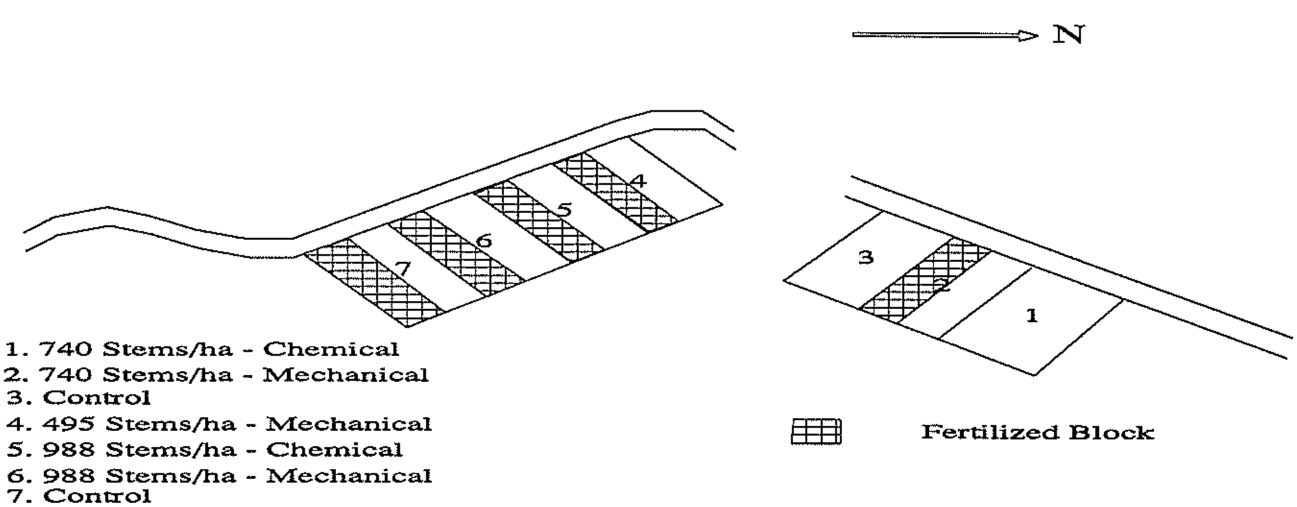

Figure 1. Layout of spacing and fertilization treatment plots in the Courtenay Juvenile Spacing Demonstration area.

METHODS

Field Methods

Selection criteria

Stand dominant and codominant trees were selected as these represent future potential crop trees. Twenty trees were selected in each of the six density-treatment combinations for a total of 120 trees. Only trees without obvious defects were selected and trees growing in obvious depressions, on hillocks or adjacent to areas of *Phellinus weirii* were excluded. In the 750 and 1000 stem/ha densities the trees were generally sampled along transects. Owing to the lower density of the 500 stem/ha treatment, and a moist depression along one edge of the block, trees in this treatment were randomly distributed throughout the block.

A preliminary survey of the stands was conducted to identify stand structure and impose limits to sampling (i.e., identification of dominant and codominant trees). These measurements are summarized in Table 1. The surveyed and selected trees were completely independent samples.

The selected trees were chosen to fall within one standard deviation of the mean dbh of all the surveyed trees pooled over all densities and both treatments. The effect of selection is illustrated in Figure 2. The sample tree selection trimmed the lower tail of the total population and removed bivariate outliers.

As a group the sampled trees approximate a normal distribution. Within the separate densities and treatments, trees were not as normally distributed - particularly in the 1000 stem/ha density (Figure 3). The polymodal distribution in the 1000 stem/ha stand reflects the greater variation in the expression of dominance in this stand likely due to strong competition for light and possibly nutrients.

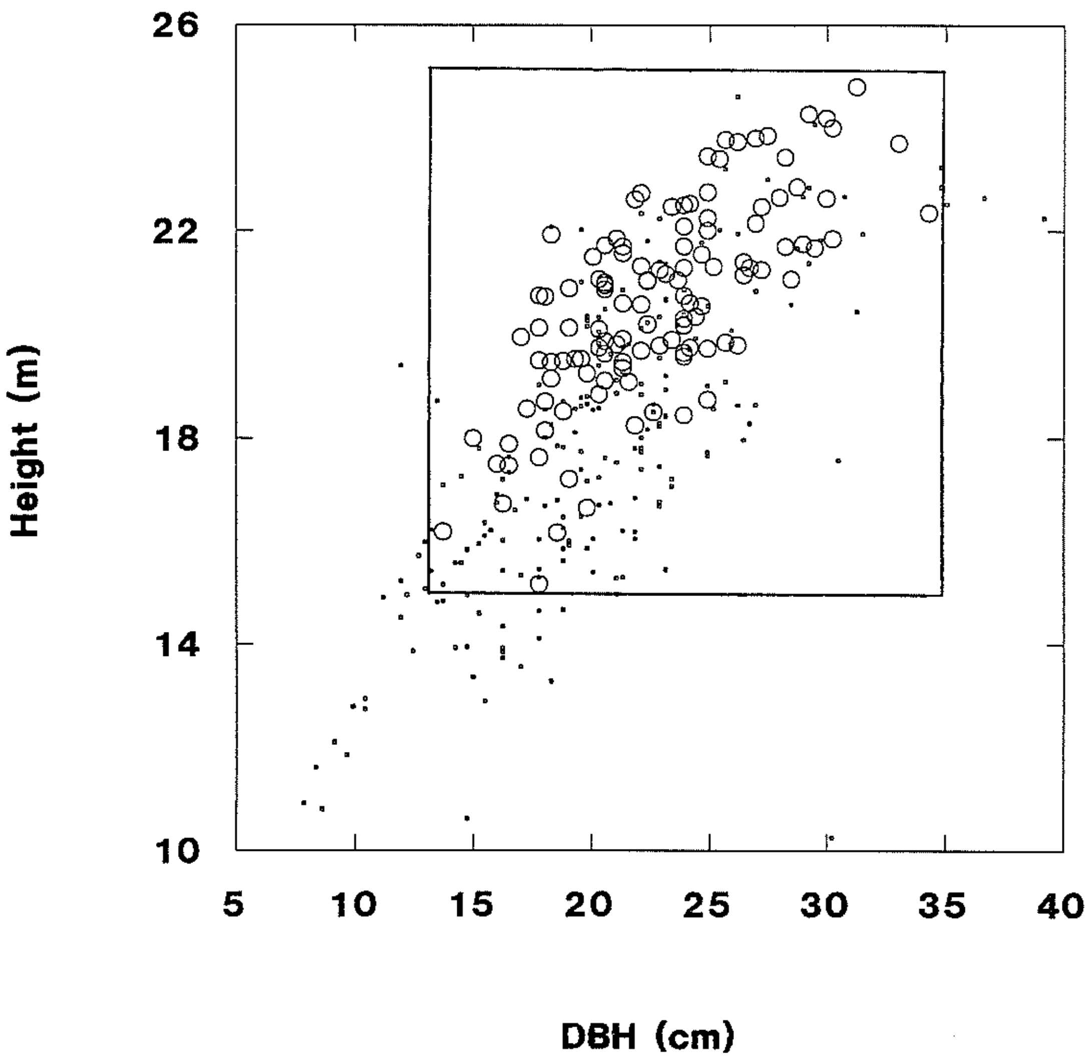

Figure 2. Height and diameter distribution of Survey (small squares) versus Selection (circles) trees across the six study plots. Lines indicate the extent of the selected trees in the sample population.

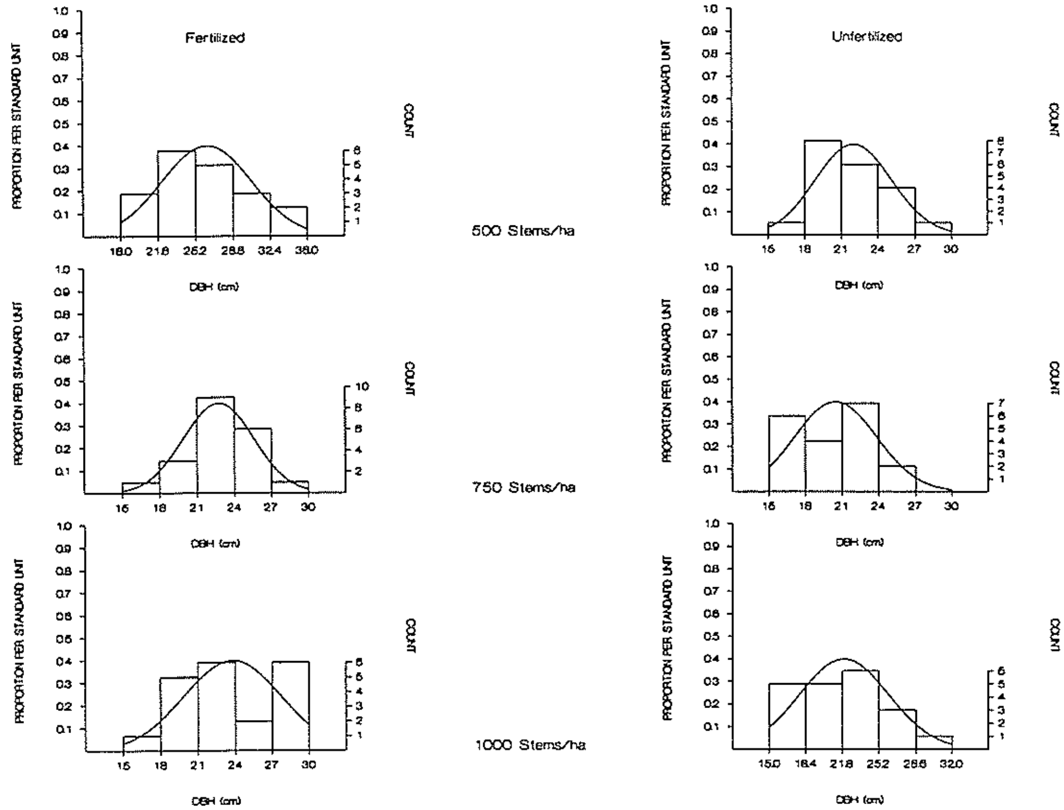

Figure 3. Diameter distribution of the selected trees in each stand density and fertilizer treatment. Note the greater mean diameter in the the fertilized treatments and the strong bimodal distribution in the fertilized 1000 stem/ha treatment.

Table 1. Comparison of dbh (cm) in the surveyed trees and field and laboratory measurements of dbh in the selected trees.

Density	Treatment	Field		Lab
		Survey	Selection	Selection
1000	UnFert.	18.01	22.02	22.00
	Fert.	19.09	23.47	26.26
750	UnFert.	19.54	22.06	20.73
	Fert.	20.60	22.81	22.90
500	UnFert.	21.26	21.90	21.95
	Fert.	24.27	26.19	24.08

Field Repeatability and Sample Size Study

Examining precision and repeatability of measurements aids in distinguishing practical differences from trivial but statistically significant differences. The repeatability and precision of all measurements used in this study were examined indicating the accuracy of our results and providing direction for future studies.

Selection of sample trees relied on the accurate measurement of diameter and height. Measurement error can influence tree selection. Additionally, the variability of measurements in a stand also influences the number of samples necessary to arrive at a stable estimate of central tendency and provide a standard error that is less than the measurement repeatability.

Experimental errors can occur in two places. In the field, errors associated with measuring diameter and height as well as inadvertent bias in tree selection, and in the lab, where errors associated with measurement and identification of increments occur. The errors associated with both lab and field measures are indicated for this study. For future studies the repeatability estimate is a realistic expectation of measurement error.

Repeatability of diameter and height measurement was performed on a group of 20 trees. Two observers repeated these measurements on three occasions. The overall model used was:

measurement = tree + observer + e

(n = 120 + 20 + 2)

The standard error over both observers and all trees was 0.6 cm in diameter and 1.5 m in height (or about 3% of the average tree diameter and 7.5% of the average tree height). The associated $Eta_{observer}$ are very small (0.5 %). Since dbh, relative to height, is a more precise field measurement it was used as the basis for selection.

The sample size for height, diameter, and annual-volume increment was assessed using the techniques of Scagel *et al.* (1985) and Dallal (1988). A minimum of 10 (height and diameter) or 12 trees (annual volume increment) per treatment was necessary to assure a stable mean and achieve a standard error less than the repeatability error (Table 2). The sample size of 20 trees used in this study was more than adequate (Figure 4). These results should not be applied universally as mixed age stands, stands originating naturally, and stands that have been operationally treated may require a larger sample than recognized here.

Sampling technique

General guidelines for field sampling follow Herman *et al.* (1975). Following selection, the trees were numbered and marked. Trees were felled in a manner to minimize damage to the crowns and then inspected for defects that were not obvious during the selection reconnaissance. The falling cut was made at 30 cm. Five cm thick disks were cut from the bole of the tree at 0.6 m and breast height (1.3 m). The length of the remainder of the bole was measured and 8 regularly spaced disks were cut.. Each disk was individually numbered on the lower side. All disks from a single tree were stored together in a numbered bag. A total of 1200 disks were cut.

In addition to cutting disks from the bole, the length of live crown was measured as was the length of the largest live branch at the base of the live crown. Annual height increment was also measured for each of the past 12 years (1975-86). These measurements describe general canopy form and served to supplement other measurements of height.

Table 2. Number of samples required for s.e. to be less than measurement repeatability for dbh, height, and 1981 volume increment.

Variable	Measurement error	Repeatability	Sample Size
dbh	$\pm$ 0.50cm	$\pm$0.60cm	10
Height	na[1]	$\pm$1.14m	10
Vol '81	$\pm 0.005m^3$	$\pm 0.006m^3$	12

[1]Measurement error increased with tree height.

Analytical Methods

Axis selection and measurement.

The longest and shortest radii on each disk were selected, marked, measured, and then averaged as the quadratic mean of the two radii. This technique avoids under-estimation of both average surface area at the whorl and calculated volume (Husch *et al.* 1982). 2400 measurement transects were made.

Bark thickness, radial increment for each of the outer twelve growth rings (1975-1986), and distance to the pith was measured on each axis of the disk using a Parker Digital Ring Width Analyzer - Model 3 in combination with a 10x binocular microscope. This gives a total of 14 measurements per disk transect. All measurements were made by a single observer.

Sample size

Three observers measured the same disk three times along the longest and shortest dimensions. The dimensions to be measured were clearly marked before measuring, thus minimizing variability caused by dimension selection. Twelve trees per treatment were necessary to stabilize the mean and minimize the standard error for a given increment (Table 2). The sample of 20 trees for each treatment is well in excess of the minimum sample size.

Stem eccentricity

Stem eccentricity was also examined. Eccentricity is defined as the difference between the largest and smallest radii for a given disk. At breast height the average eccentricity pooled over all treatments was 2.8 cm. Generally, stem eccentricity and individual increment measurement error increased toward the lower part of stem. Figure 4 suggests that eccentricity effects can be minimized by measuring diameter at 3 m rather than at breast height. Although sampling still higher on the stem would yield even less eccentricity, the occurrence of branches may prohibit effective measurement. Sampling at this height also avoids the thicker bark found at breast height.

Data analysis

Total bark volume, annual volume increment for each year (1975-1986), and the inner core volume (pith to 1974) were calculated using the Tree Ring Analysis Program (**TRAP**) of Emanuel and Carter (1986). This program calculated annual volume between each disk sample height as a linear function and summed the total volume across all sample sections. All volume measurements were based on a 30 cm stump height and a 7.5 cm top diameter.

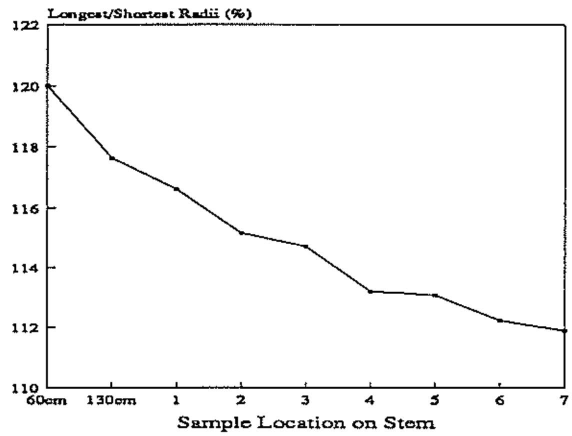

Figure 4. Decline in the ratio of longest to shortest stem radii (expressed in percent) with increasing height on the stem.

All additional analyses were performed using Lotus Symphony and SYSTAT statistical software. Graphics were prepared using Symphony, Harvard Graphics and SYGRAPH. The analyses focus on annual increment, crown form, and volume on an individual tree and stand basis. Details of specific statistical analyses are provided in the results. Analyses carried out in this project emphasize the size of the various effects rather than their significance. Since examining the size of an effect may be an unfamiliar approach, a brief description is provided below.

Statistically insignificant effects are, relative to the total variation, small effects. With large sample sizes statistical significance is easily attained for very small effects. The deciding factor in critically examining significant effects is their relative size (e.g., percentage of the total variation explained by the effect).

The percentage of the total variation explained by an effect is frequently reported in regression and correlation analysis as an r^2 value. Size effects in ANOVA are given as Eta^2 values, although they are rarely reported. Eta^2 and r^2 are identical in their calculation and interpretation. They are bounded by 0 and 1. Smaller values are smaller effects. Values closer to 1 are larger effects. Just as an r^2 of 0.63 expresses the result that 63% of the total variation in the data in a regression is accounted for, an Eta^2 of 0.63 expresses the result that 63% of the total variation in an ANOVA is accounted for.

As there were initial height, diameter and volume differences between the blocks (Table 3) it was necessary to remove the effects of these differences from the ANOVA. This was accomplished with analysis of covariance (ANCOVA). Pre-treatment height, dbh, and volume were used as covariates for these analyses. As with the use of ANOVA in partitioning variation, ANCOVA was also used to partition variation in the data.

RESULTS

Annual Height and Diameter Increment

Figure 5 gives *Eta*^{2} from ANCOVA for cumulative height increment since treatment. This figure shows the total variance accounted for by fertilization, density, and their interaction. Fertilization and the density-fertilizer interaction account for most of the explained variation while stand density is a minor component and has had a declining influence since treatment. Only about 5% of the total variation in height can be assigned to treatment effects, while the largest source of variation is related to pre-treatment height (Figure 6). This dominant effect of pre-treatment height has shown a continual decline since treatment but, 10 years after treatment, still accounts for over 70% of the observed variation.

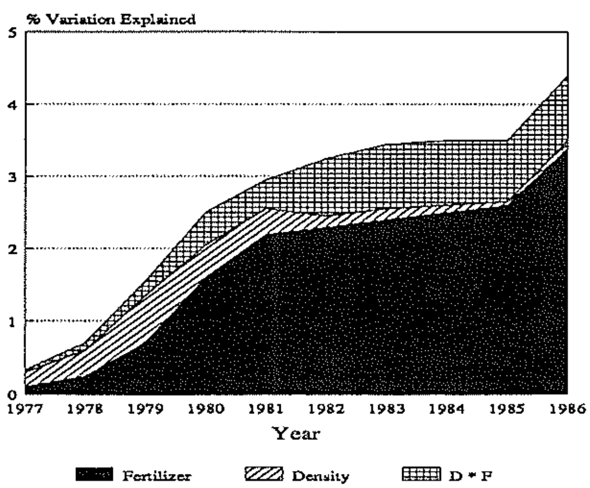

Figure 5. Percentage of total variation explained by density, fertilization, and the D*F interaction.

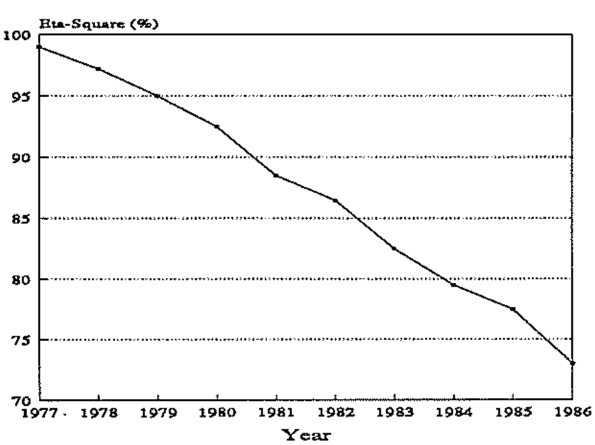

Figure 6. Contribution of pre-treatment height (covariate) to variation in cumulative height between 1977 and 1986.

Stand mean height and diameter characteristics are given by treatment in Table 3. Annual height increment for the two pre-treatment years and 10 post-treatment years are given in Figure 7. Site index is also given in Table 3, and ranges from 32-35 m/50 years (Mitchell and Cameron 1985). Due to differences in site index between treatments, covariance analysis (ANCOVA), using total height in 1976 as the covariate was used for height comparisons. These initial differences in height (Table 3) are larger than the measurement error associated with field height estimation.

Although significant differences in cumulative height and annual height increment were found between treatments, few of these differences for annual height are consistently related to either stand density or fertilizer treatment. The stand density effect is the largest of the hypothesized effects in the ANOVA model prior to treatment simply reflecting site differences prior to the 1977 treatment. However, by 1979 the fertilizer effect had become the major factor. There were differences in annual height increment between treatments - these differences were most apparent during the first five post-treatment years (1977-1981; Figure 7). During the last five years (1982-1986) the lowest density showed a greater average annual height increment than the higher density blocks.

The effects of density and fertilization on annual diameter increment (both inside and outside bark) were not as pronounced as for height. Differences between treatments and densities were significant but accounted for only a small amount of the total variation. On a cumulative basis, density and fertilization are major factors and are about equally weighted in their contribution to hypothesized effects (Figures 8 and 9). Pre-treatment diameter is a very strong factor in the cumulative model, accounting for greater than 80% of the total variation 10 years after treatment.

Crown Form

Stand density effects figured significantly in accounting for live crown length. Stand density accounted for 10% of the total variation in the data. Fertilized blocks had longer live crowns than unfertilized, and length of live crown increased with decreasing stand density. Although fertilization and density-fertilization interactions were not significant there were easily observed differences between the treatments that were reflected in the foliar characteristics of the crown. The unfertilized blocks appeared to have a much lower leaf area, greater light penetration, and had much more lichen on the stem and lower branches than the fertilized blocks.

Table 3. Height and diameter characteristics of trees within each stand density and fertilizer treatment.[1]

Treatment	N	Tree height 1986 (m)	Tree height 1977 (m)	Dbh 1977 (cm)	Qdbh[2] 1986	LLC (m)	Site Index	Annual Height Increment 1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
Fert-500	20	21.9	13.9	10.3	26.6	12.6	35	0.81	0.81	0.77	0.86	0.93	0.96	0.92	0.86	0.73	0.76	0.59	0.63
		1.7	-	1.7	-	2.4	1.6	0.17	0.11	0.15	0.17	0.16	0.13	0.15	0.2	0.11	0.1	0.08	0.1
UnFert-500	20	20	13	8.7	22.2	11.7	33	0.77	0.76	0.75	0.73	0.63	0.76	0.84	0.68	0.69	0.68	0.56	0.68
		1.7	-	1.2	-	2.1	1.8	0.12	0.12	0.19	0.27	0.3	0.17	0.1	0.15	0.13	0.12	0.18	0.09
Fert-750	20	20.5	12.8	9	22.9	11.7	34	0.83	0.83	0.88	0.87	0.9	0.85	0.93	0.7	0.79	0.67	0.54	0.61
		1.6	-	1.1	-	1.7	1.4	0.15	0.18	0.16	0.18	0.2	0.26	0.21	0.19	0.18	0.16	0.09	0.13
UnFert-750	20	19.2	11.9	8.1	20.7	10.8	32	0.76	0.85	0.83	0.74	0.82	0.79	0.85	0.75	0.73	0.66	0.54	0.57
		1.7	-	1.3	-	2.3	1.2	0.11	0.09	0.11	0.11	0.09	0.14	0.14	0.16	0.13	0.12	0.09	0.14
Fert-1000	20	21.5	14	9.4	24.1	10.7	34	0.8	0.9	0.87	0.88	0.92	0.86	0.91	0.62	0.69	0.67	0.54	0.55
		1.3	-	1.5	-	1.6	1.7	0.17	0.12	0.1	0.11	0.12	0.11	0.12	0.12	0.11	0.13	0.1	0.14
UnFert-1000	20	20.8	13.7	8.6	22.4	10.1	34	0.85	0.94	0.92	0.85	0.78	0.81	0.86	0.63	0.69	0.63	0.46	0.5
		2	-	1.6	-	3.3	1.9	0.18	0.17	0.14	0.29	0.24	0.14	0.14	0.14	0.18	0.14	0.12	0.18

[1] Top number is mean; bottom number is standard deviation.
[2] Quadratic mean diameter.
[3] LLC - Length of live crown.

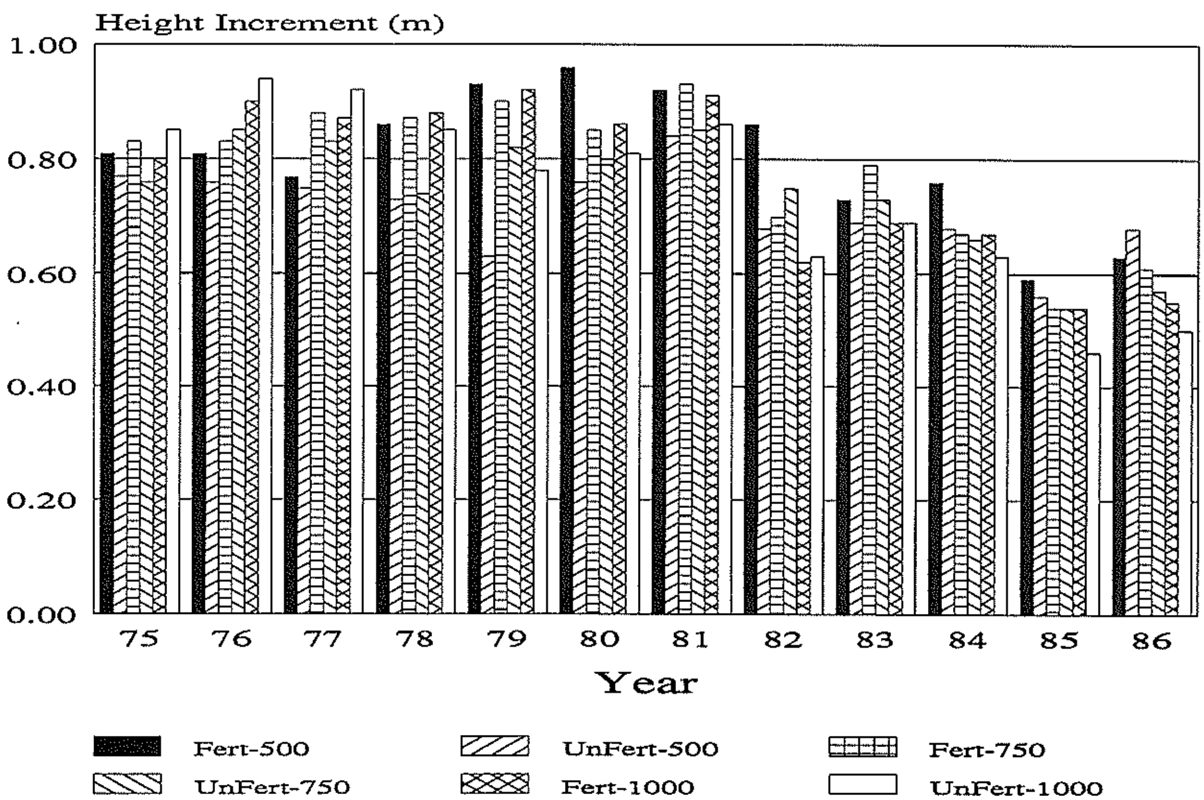

Figure 7. Annual height increment (m) during the two pre-treatment (1975-1976) and nine post-treatment (1978-1986) years. Notice the greater for the fertilized treatments during the first five post-treatment years.

Mortality

Exact mortality figures for each year were not available. When examining these treatments in 1984, Promnitz (1984) found "mortality was generally highly erratic without any apparent relationship to either type of spacing (chemical or mechanical) or fertilization". Similar results were found in this study. Therefore, in order to calculate volume on an areal basis (m^3/ha) mortality was considered to be the same for both the fertilized and unfertilized stands within each density level. Mortality was calculated as a linear reduction in stocking from the number of stems/ha in 1977 through 1986. The values used for each year are given in Table 4.

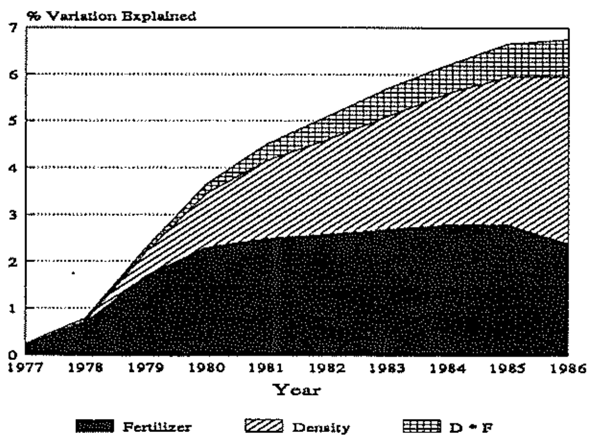

Figure 8. Changes in the total amount of variation in dbh explained by density, fertilization, and the D*F in-

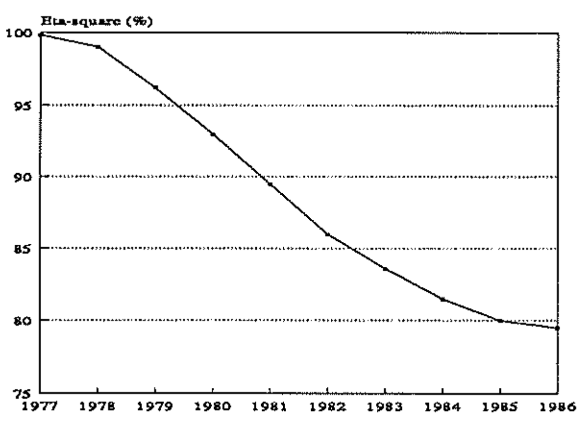

Figure 9. Change in the amount of variation in cumulative dbh explained by pre-treatment dbh (covariate) between 1977 and 1986.

Volume

Current Annual Increment (CAI)

Current annual increment of individual trees (CAI) and on a per ha basis (CAI/ha) are given for each treatment in Tables 5 and 6 and illustrated in Figures 10 and 11. These CAI measurements were calculated on an adjusted basis. Pre-treatment volume in each treatment was set equal to the volume for the fertilized 500 stem/ha treatment and all later annual increments were adjusted by the same factor.

CAI on an individual tree basis showed no consistent pattern between treatments during the pre-treatment period, although trees in the 500 and 1000 stems/ha block appeared to have somewhat higher CAI's (Table 5). Following spacing and fertilization, the relative volume production of individual trees changed appreciably between treatments. The fertilized blocks had significantly higher CAI's within one growing season after fertilization. The lower density stands (500 and 750 stems/ha) had the largest initial response to fertilization, a relative response that continued 10 years later (Figure. 10).

The CAI per hectare data presented in Table 6 and Figure 11 are only approximates as the annual mortality data was calculated rather than measured (Table 4). CAI/ha peaked approximately 2 to 4 years after treatment reaching a maximum of 26 m^3/year in the fertilized 1000 stem/ha block. This large CAI/ha in the 1000 stem/ha block throughout the post-treatment period is due to the greater number of stems.

Fertilizer response examined using the adjusted data appears to have lasted only 4 - 6 years in the 750 stem/ha treatment while the 1000 stem/ha treatment appeared to last for 6 -7 years and the 500 stem/ha treatment continued to show a response to fertilization 10 years after treatment. The 750 stem/ha treatment has had the greatest CAI/ha (adjusted basis) of the three treatments during the 6 to 10 year post-treatment period.

Table 4. Number of stems/ha following mortality - calculated as a linear reduction in stocking between 1977 and 1986.

Treatment	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
1000	1620	1600	988	970	951	933	914	895	877	860	845	830
750	1620	1600	750	748	746	744	742	740	737	735	732	730
500	1620	1600	495	495	493	491	488	485	483	480	476	472

Table 5. Mean and standard deviation of annual volume production characteristics of individual trees within each treatment using standardized pre-treatment volumes.

Treatment	N	Core	Pretreat	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	Total Bark	Total Vol(ib)
								Volume (m^3)									
500-Fert	20	0.072	0.102	0.013	0.017	0.018	0.026	0.034	0.038	0.039	0.027	0.032	0.031	0.027	0.030	0.065	0.404
		0.029	0.048	0.005	0.007	0.007	0.010	0.012	0.013	0.014	0.010	0.011	0.011	0.009	0.010	0.024	0.140
500-Unfert	20	0.071	0.102	0.013	0.017	0.018	0.017	0.023	0.028	0.028	0.020	0.025	0.025	0.020	0.024	0.054	0.330
		0.032	0.048	0.005	0.006	0.006	0.006	0.007	0.010	0.010	0.007	0.010	0.010	0.008	0.010	0.020	0.121
750-Fert	20	0.069	0.102	0.015	0.019	0.020	0.026	0.033	0.036	0.037	0.028	0.036	0.033	0.025	0.029	0.070	0.407
		0.021	0.034	0.004	0.005	0.005	0.008	0.009	0.011	0.012	0.009	0.012	0.012	0.008	0.009	0.017	0.115
750-Unfert	20	0.069	0.102	0.017	0.018	0.020	0.020	0.023	0.028	0.033	0.030	0.037	0.033	0.025	0.030	0.072	0.381
		0.030	0.050	0.012	0.007	0.007	0.008	0.008	0.010	0.013	0.012	0.013	0.013	0.010	0.013	0.032	0.142
1000-Fert	20	0.072	0.102	0.012	0.017	0.018	0.022	0.028	0.031	0.031	0.021	0.025	0.021	0.020	0.022	0.057	0.345
		0.024	0.037	0.004	0.005	0.005	0.006	0.008	0.009	0.009	0.006	0.007	0.008	0.007	0.007	0.018	0.101
1000-Unfert	20	0.067	0.102	0.015	0.018	0.020	0.018	0.022	0.026	0.026	0.018	0.023	0.022	0.018	0.020	0.052	0.313
		0.026	0.046	0.008	0.008	0.009	0.008	0.010	0.012	0.013	0.009	0.011	0.011	0.010	0.011	0.022	0.122

1 Top number is mean: bottom number is standard deviation.

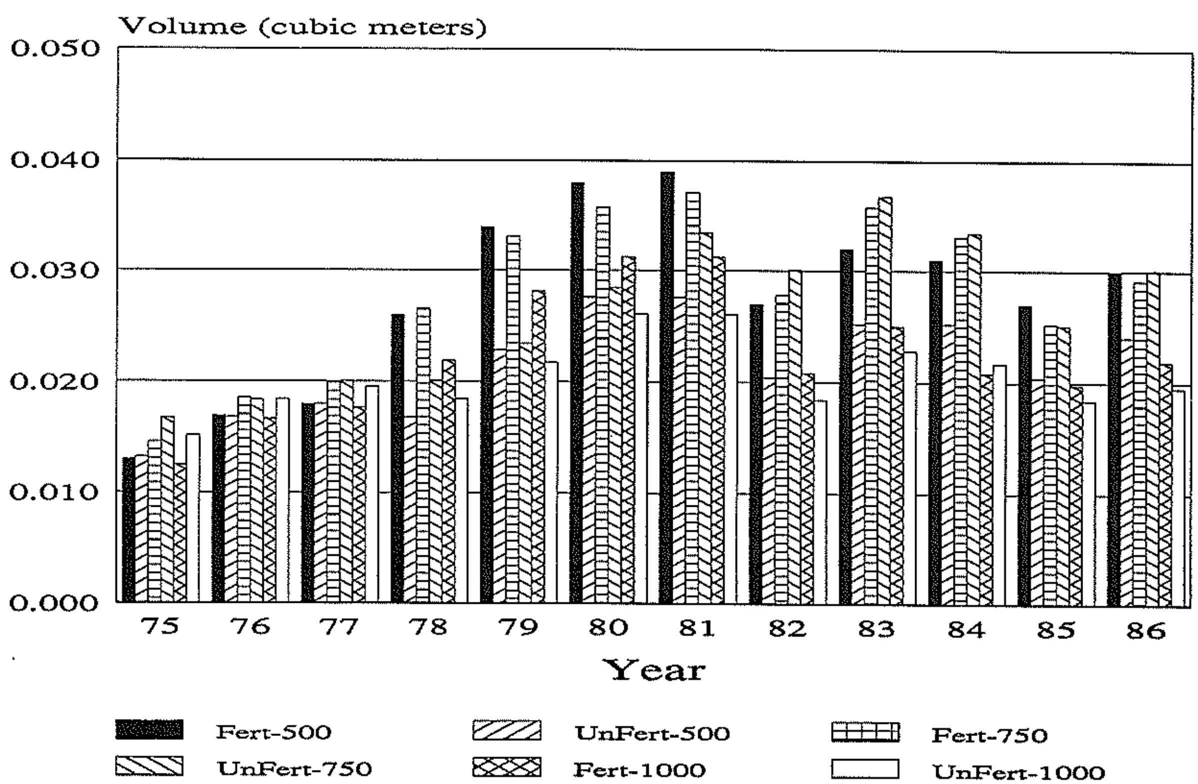

Figure 10. Annual volume increment of individual trees between 1975 and 1986 for fertilized and unfertilized trees at each density.

Table 6. Mean and standard deviation for current annual increment (m^3/ha) using standardized pre-treatment volumes.

Treatment	Core	Pretreat	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	Total
							Volume (m^3/ha)								
500-Fert	116.6	164.9	21.1	27.2	8.9	12.9	16.8	18.7	19.0	13.1	15.5	14.9	12.9	14.2	191.2
	47.0	66.3	8.1	11.2	6.9	9.7	11.4	12.1	12.8	9.0	9.6	9.5	7.6	8.3	113.6
500-Unfert	114.7	163.0	21.4	26.9	8.9	8.3	11.2	13.6	13.5	9.9	12.2	12.1	9.7	11.3	155.7
	52.5	69.9	7.8	9.6	3.0	3.0	3.5	4.7	4.7	3.5	4.6	4.6	4.0	4.5	59.7
750-Fert	111.6	164.9	23.6	29.7	14.9	19.8	24.7	26.6	27.5	20.6	26.4	24.3	18.4	21.3	296.7
	34.3	49.3	6.4	8.5	4.0	5.9	6.9	7.9	8.8	6.9	8.8	8.8	5.8	6.8	92.1
750-Unfert	111.1	167.6	27.1	29.4	15.0	15.0	17.5	21.1	24.8	22.3	27.1	24.6	18.4	22.0	281.5
	48.8	78.4	19.0	10.7	5.0	6.3	6.2	7.5	9.9	8.7	9.9	9.8	7.3	9.8	115.1
1000-Fert	116.3	163.2	20.2	26.6	17.5	21.2	26.7	29.1	28.5	18.6	21.9	17.9	16.7	18.1	282.5
	38.8	53.9	6.7	8.3	5.1	6.1	7.9	8.7	8.6	5.6	6.4	7.2	6.2	6.0	90.1
1000-Unfert	109.0	163.1	24.6	29.5	19.3	17.9	20.6	24.3	23.8	16.5	20.0	18.7	15.6	16.2	261.1
	42.2	66.6	12.3	12.2	8.6	7.4	9.3	11.1	11.9	7.8	9.5	9.3	8.3	9.0	119.2

[1] Top number is mean: bottom number is standard deviation.

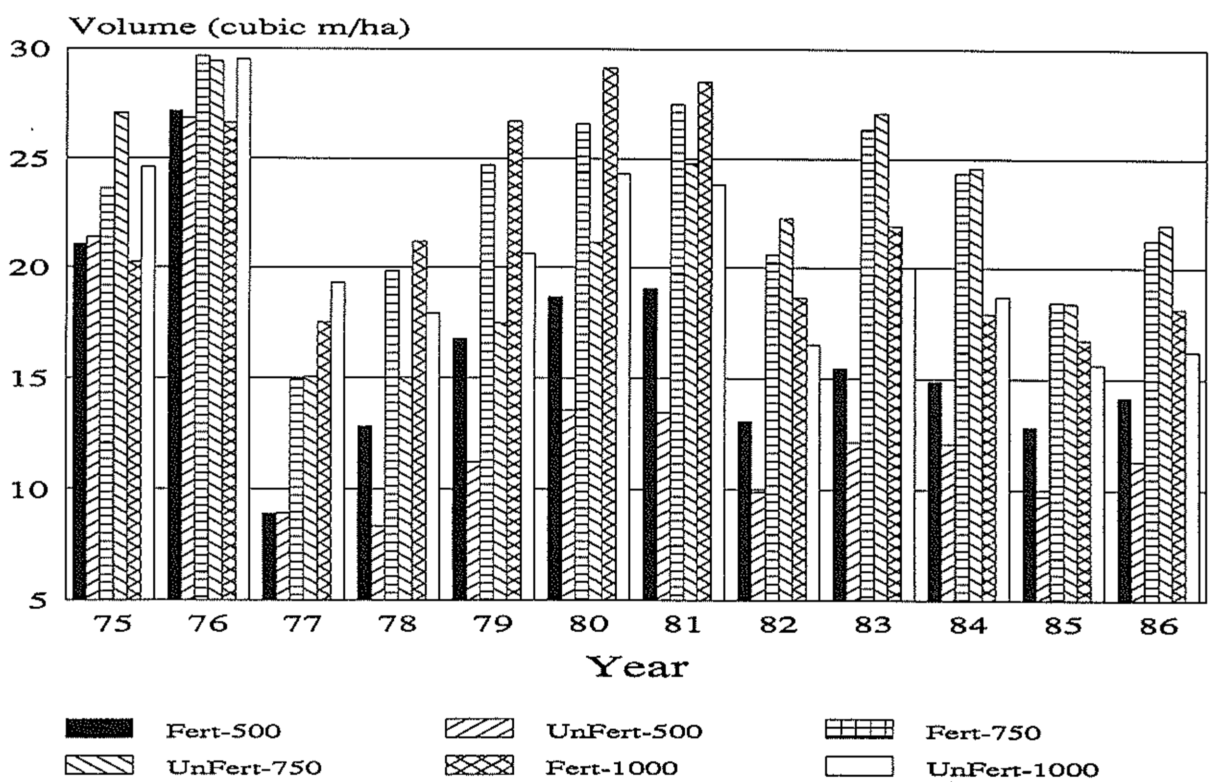

Figure 11. Annual volume increment on a per hectare basis between 1975 and 1986 for fertilized and unfertilized treatments at each density.

Cumulative annual increment (CUMAI)

Changes in CAI attributable to treatment effects (fertilization, density, and the fertilization-density interaction) were examined using repeated measures ANCOVA (Milliken and Johnson 1984) with pre-treatment volume as the covariate. The F-values from mean contrasts from this analysis for the fertilizer, density and interaction effects are presented in Appendix 1. The fertilization effect was very large and started immediately following treatment. This effect showed increasing domination of the explained variation over time. Density effects also started very soon after treatment; however, they were initially much smaller than the fertilizer effect. The density effect became more significant than the fertilizer effect around the seventh or eighth post-treatment year. The density effect continued to increase 10 years following treatment. The interaction of density and fertilization was generally much smaller reaching a maximum six to eight years post-treatment when the density and fertilizer effects were approximately equal.

The complete model (density, fertilization, and the D*F interaction) accounted for, at most, 8% of the total variation in CAI. The covariate, pre-treatment volume, accounted for the largest source of variation. The size of the covariate continued to account for greater than 75% of the total variation 10 years after treatment. This decline paralleled that shown earlier for diameter (Figure 9).

A graphical presentation of adjusted cumulative volume for individual trees (CUMAI) and on a per hectare basis (CUMAI/ha) is given for each of the past 12 years in Figures 12 and 13. The largest CUMAI is exhibited by individual fertilized trees in the 500 and 750 stem/ha blocks. The unfertilized 750 stem/ha block appears to have a similar slope although at a lower total volume.

Examination of CUMAI on a per ha basis (Figure 13) indicates that all treatments and densities displayed a parallel trend. CUMAI/ha is initially greatest in the fertilized and unfertilized 1000 stem/ha blocks as would be expected due to the greater number of stems and standardized initial volumes. However, ten years after treatment both the fertilized and unfertilized 750 stem/ha blocks have a greater total volume than the fertilized 1000 stem/ha block. Individual trees in the fertilized 750 stem/ha treatment have approximately the same CAI as the fertilized 500 stem/ha treatment. This treatment has approximately 50 percent more volume due to the greater number of stems. The unfertilized 750 stem/ha treatment has outperformed the unfertilized 500 stem/ha treatment resulting in both a greater total volume per hectare and larger piece size.

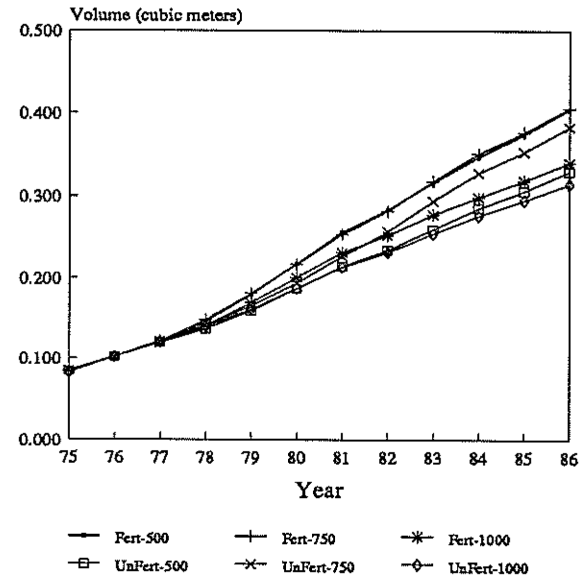

Figure 12. Cumulative annual volume increment of individual trees within each treatment between 1975 and 1986.

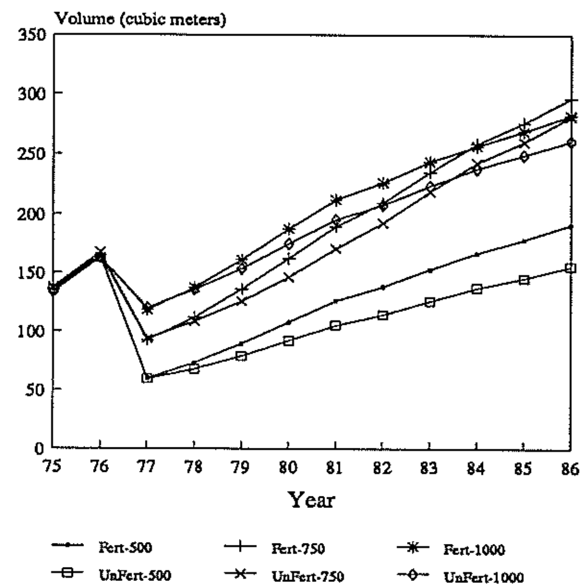

Figure 13. Cumulative annual volume per hectare for each treatment between 1975 and 1986.

The efficiency of nitrogen fertilization, measured as stem volume response (m^3) per kiligram of N applied (Barclay and Brix 1985a) was calculated for each treatment. Volume response attributable to fertilizer was-determined using the difference in the control and fertilized treatments within each density. Fertilizer efficiencies were 0.158, 0.067, and 0.095 m^3/ha per kg N in the 500, 750 and 1000 stem per ha treatments, respectively. These efficiencies are somewhat lower than those cited by Barclay and Brix (1985a) who found efficiencies ranging from 0.18 - 0.20 m^3/ha per kg N. This is likely attributable nitrogen being more limiting at the Shawnigan Lake site studied by Barclay and Brix (1985a) than in the stand examined in the current study.

Within-tree total volume distribution

The location of maximal volume production within the stem and the effects of stand density and fertilization on stem form were examined. Relative total volume, post-treatment volume, and annual volume increment were examined in the lower, middle, and upper third of the bole. No significant change in the within-tree distribution of volume was found for any of these measures. Approximately 40, 32, and 28 percent of the total volume was found in the lower, middle and upper sections of the stem for each treatment, respectively.

The percentage of total and post-treatment volume in each third of the bole was surprisingly consistent between treatments. The distribution of annual volume production within the stem was also quite uniform between treatments with any differences appearing to be random. Growth along the bole appeared to be uniformly enhanced by fertilization with no measurable change in stem form occurring as a result of treatment. These results agree well with Johnston (1980).

DISCUSSION AND CONCLUSIONS

Cumulative height and volume growth continue to show a positive treatment effect 10 years after fertilization and thinning. The fertilizer effect had the greatest influence on volume production during the first four to six post-treatment years while the density effect became more dominant seven to eight years post-treatment.

Our results showed a marked trend: the lower density treatments (e.g., 750 and 500 stems/ha) had a larger and/or longer to response due to fertilization. When all treatments were adjusted to standardized pre-treatment volumes the size of response to fertilization on an individual tree basis appeared to be the same for the 500 and 750 stem/ha treatments while the response in the 1000 stem/ha treatment was considerably lower. This agrees well with results found by Barclay and Brix (1985b) in a Douglas-fir stand at Shawnigan Lake, B.C. However, this stand is still relatively young, likely only half-way through its rotation. If the greater volume in the 750 stem/ha treatments is not harvested through commercial thinning these apparent gains will likely be lost to mortality. If commercial thinnings are anticipated a density of 750 stems/ha is likely the most economic. If not, the 500 stem/ha treatment may be more appropriate.

These results may differ from those expressed in other studies as a result of this studies emphasis on crop trees, rather than all trees in the stand. The uniformity of the stand and the careful application of fertilizer and spacing may also contribute to these differences (Strand and Promnitz 1979).

The recognition of such a large and persistent factor as pretreatment size is important when considering the management of stands and individual trees. Although treatment response could be detected on both an individual tree and an areal basis, the amount of the response that could be explained by treatment was relatively small. Ninety-two percent of the within-block variation in the data was unexplained by treatment effects. However, 90% of this within-block variation could be accounted for by pre-treatment tree size. The larger the pre-treatment size of the tree, the larger the size 10 years later and the greater the response of that tree to treatment. On a crop basis there has been a net gain attributed to fertilization. This response is larger than thinning alone and continues to increase 10 years after treatment.

Recognizing that after 10 years fertilization effects only account for 5% of the total variation there are several important conclusions concerning fertilization. First, there was an immediate response to fertilization. Second, the effect was most pronounced in the lower density blocks. Third, the annual effect of fertilizer peaked during the first three to four years after treatment. Fourth, fertilization had no measurable effect on stem form, although the length of the live crown increased with fertilization and declining density. Fifth, cumulative fertilization effects continue to increase 10 years after treatment.

A crude economic comparison of fertilizer effects alone can be made by subtracting the volume/ha in the unfertilized blocks of each density from the volume of the fertilized blocks. A scaling factor was used to adjust the volume of the fertilized and unfertilized blocks at each stand density level to the same pre-treatment levels. Actual gains due to fertilization ten years after treatment ranged from 18.7 to 34.9 cubic m/ha (Table 9). These values are very similar to those found by Miller *et al.* (1988) for coastal Douglas-fir in southern Oregon. If current log values (at age 32) are considered to be equal in each of the three densities the economics of the fertilizer treatment alone can be evaluated at each density. If the log value for immature Douglas-fir at age 32 is placed at \$32/m^3 the return on the fertilization investment at age 32 would range from \$599./ha (750 stems/ha) to \$1117.7/ha (500 stems/ha). Although this price of \$32/m^3 likely overstates the current value of the wood produced in the 1000 stem/ha treatment and understates the current value of wood produced in the 500 and 750 stem/ha treatments, these values represent a compounded annual rate of return (over 10 years) ranging from 14.1% in the 750 stem/ha treatment to 21.5% in the 500 stem/ha treatment on an initial fertilization investment of $160/ha. This rate of return will, of course, decline with time.

Research Recommendations

This study suggests two areas for further research: explanations for differential response of individual trees within treatments; and, the interaction of fertilization response over a broad range of stand conditions. In particular, the following should be considered:

1. Sample size necessary in operationally fertilized stands and uneven aged, mixed, and naturally established stands.

2. Further work should be devoted to understanding the nature of the within stand component of variation in pre-treatment stand structure and post-treatment response. This would suggest studies which examine individual tree response on a microsite basis. Significant gains might be obtained by further study of this very large variation within site.

Management Considerations

1. Priority for fertilization should be given to fully stocked, medium to low density stands. The 750 stem/ha stand in this study showed the largest response to fertilization.

2. The large fertilizer response found in the 750 stem/ha treatment may not be realized if a commercial thinning is not planned. If following fertilization, the stand is to be left untreated until final harvest, treatment densities should be closer to final harvest densities to avoid losses to mortality (e.g., 500 stems/ha).

3. Thinnings should carefully consider size and form of the remaining trees as these factors will strongly influence the response to fertilization.

4. Fertilizer effects will be measurable on an individual tree basis soon after treatment. However, realized gains will be a function of cumulative response which include treatment effects on the stand's diameter distribution,rotation length and losses due to mortality.

5. If response to fertilization is to be evaluated there is a requirement for systematic description of initial stand conditions, careful monitoring during application, establishment of representative control plots, and careful long-term monitoring.

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