AN ABSTRACT OF THE THESIS OF

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Title: EFFECTS OF STAND DENSITY ON SITE INDEX IN THINNED STANDS OF DOUGLAS-FIR IN THE PACIFIC NORTHWEST.

Abstract approved: Signature redacted for privacy.
John F. Bell

In site index studies, the hypothesis that height growth of most conifers is independent of stand density is commonly accepted. However, some studies have shown height growth to be influenced by density particularly on medium to poor sites.

In this study two locations representing a high quality site (Hoskins area, Oregon) and a relatively lower site (Rocky Brook area, Washington) were selected to examine the effect of stand density on site index in natural stands of Douglas-fir which has been repeatedly thinned at different intensities. The data for the study were obtained from the periodic measurements of

the stand characteristics at the end of each thinning treatment period. The average height of the largest 40 trees per acre was used as basis for the comparison of height growth patterns among the different thinning regimes.

Simple linear regression was found adequate to describe height growth of the individual plots over the age range studied (20 to 36 years at the Hoskins and 27 to 44 years at the Rocky Brook). Covariance analysis using multiple regression was used to test differences in height growth within plots under similar thinning treatments. The coefficients of the height growth equations from individual plots were used in the analysis to test for differences in height growth among the different thinning regimes.

The results of the study indicated that on both sites, site index was not influenced by density over a wide range of stocking and within the age range studied.

EFFECTS OF STAND DENSITY ON SITE INDEX IN THINNED STANDS OF DOUGLAS-FIR IN THE PACIFIC NORTHWEST

by

Abdel Azim M.A. Zumrawi

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INTRODUCTION

Site quality refers to the relative timber producing capacity of a certain area for specific species. The productive capacity of an area enters into nearly every phase of forest management from regeneration to final harvest (Minor, 1964). Proper site quality evaluation is basic to the prediction of forest yields, growth potentials and general management practices.

Height growth of the dominant stand has been the most used index to site quality and the term site index is used to refer to the average height of some specified stand component at a specified reference age.

The reliability of height growth as a site quality index stems from the commonly accepted hypothesis that height growth of the dominant stand of most conifers is independent of stand density. However, in different site studies this has been shown not to hold under all conditions particularly on medium to poor sites (Lynch, 1958; and Alexander, 1967)

This study examines the effects of stand density on height growth in thinned stands of Douglas-fir at two experimental locations, the Hoskins study area (Oregon) on a high quality site (II) and the Rocky Brook study area (Washington) on a relatively poor site (IV).

LITERATURE REVIEW

Methods of Forest Site Evaluation

Different methods have been used to evaluate the site quality of forest lands. The ultimate objective has been to assess the productive capacity of forest lands for specific tree species or a mixture of species. Since the term "site" reflects the influence of many environmental factors, it's measurement has been complex and often inaccurate (Lynch, 1958).

Site classification methods used in forestry include:

Vegetative Indicator Method

Vegetative indicators are non-tree species that have been found to be associated with a particular quality of forest growth. This method was studied by Daubenmire (1961) as applied to ponderosa pine in Eastern Washington and Northern Idaho. He found strong correlation between the different habitat types and growth rate. Accordingly, he divided the habitat types into productivity groups on the basis of height growth. Because of the complexity of plant associations, only broad divisions of site quality can be made using this method.

Soil and Physiographic Factors as a Basis for Site Classification

Several soil-site investigations have been reported (Storie and Wieslander, 1948; Gessel and Lloyd, 1950;

Carmean, 1954; Lemmon, 1955; Copeland, 1958 and Steinbrenner, 1963). In these studies, soil factors such as depth, texture, available moisture and permeability were found to be significantly related to tree growth and productivity. Physiographic factors such as slope and aspect were also found to influence productivity but to a lesser degree.

Studying the relationship of certain soil properties to site index, Copeland (1958) reported strong correlation between easily measured soil characteristics and site index of western white pine. He concluded that his findings could provide a means of estimating site quality on areas where tree measurements can not be obtained.

In a forest soil-site survey, Gessel et al. (1950) indicated that land productivity for Douglas-fir growth could be predicted from measurable soil and other environmental characteristics.

Direct Measurement of Forest Growth as an Index to Site Quality

This is the most used method for site classification. Volume production is the variable of ultimate concern in site evaluation. The difficulty with volume as a measure of site is that it varies with factors that are not closely related to site quality such as stand density, composition and degree of utilization (Spurr, 1952). One of the determinants of volume productivity which was found to be most independent of stand factors and more reliable for site evaluation has been height growth.

In even-aged stands site quality is usually expressed as site index, which refers to the average height of some specified stand components at a specified reference age. Although this continues to be a useful measure of site, it has a number of limitations (Curtis, 1964; Avery and Burkhart, 1983). The most important one is that site index usually provides little information about ecological relationships which are the dominant factors that determine productivity. Other cited drawbacks include:

- Errors introduced due to difficulty in determining the exact stand age.
- Effects of stand density and other variables associated with volume are not directly considered.
- The concept of site index is well suited only for uniform, well-stocked even-aged stands.
- Site index may change periodically due to climatic variation.

In site index studies, the average height of the dominant portion of the stand is usually used in the height-age function. However, the average height of specified number of the largest trees per unit area has been suggested (Hush et al., 1982).

The stem analysis approach to the construction of polymorphic site index curves has been widely used (King, 1966). Different procedures and computational techniques have been described (Johnson and Worthington, 1963; Dahms, 1963; Stage, 1963; Curtis, 1964 and Heger, 1968). In constructing site index curves with stem analysis methods, the height growth of individual trees may not necessarily represent the height growth of stands. Dahms (1963) suggested a method for correcting the bias introduced (by the shifts in relative height of individual trees) into the height over age curves developed from height growth of individual trees.

Curtis et al. (1974) compared two possible regressions relating height and site index that can be calculated from stem analysis data. Their findings indicate that site index estimation curves corresponding to regression of the form:

Site index = f(Height, Age),

give a more precise estimate of site index than the conventional height growth curves corresponding to regression of the form:

Height = f(Age, Site Index).

However, a proper use of the latter would be in the construction of yield tables (Spurr, 1952).

The standard for Douglas-fir site classification is the site index curves prepared by McArdle (1930) and King (1966). McArdle (1930) used the average guide curve method in which the entire set of proportional height growth curves are based on a single guide curve of the average height of dominant and codominant stand over age. King (1966) used a stem analysis technique to prepare polymorphic site index curves based on regressions of the form:

$$\text{Height} = f(\text{Age, Site Index}).$$

Height Growth and Stand Density

Height growth of most conifers is believed to be independent of stand density over a wide range of stocking. This commonly accepted hypothesis is supported by several spacing studies in different species. However, other studies have reached opposite conclusions. Most of the height-density relationship studies (Eversole, 1955; Lynch, 1958; and Alexander, 1967) have indicated that the extent and direction of the density effect on height growth depend on both site quality and species characteristics.

Lynch (1958) studied the effect of density on height growth and site classification in natural stands of ponderosa pine. Height growth on adjacent stands of differing densities and apparently on the same site quality indicated that, on relatively poor sites, height growth is greatly reduced by dense stocking. He constructed site index curves adjusted for density to be used in ponderosa pine stands having various levels of stocking.

Alexander et al. (1967), found that the height growth of lodgepole pine in the western United States is reduced by density when the stand crown competition factor exceeds 125. He used a system similar to Lynch's (1958) paired-plot technique to develop adjusted site index curves for lodgepole pine stands growing under different density conditions.

According to a review by Sjolte-Jorgensen (1967), most experiments involving pines and other conifers in Europe have shown the mean height of the stand to increase with increasing spacing up to an optimum spacing for height growth. This optimum spacing, would of course, vary from one species to another. The mean height of the stand in some of these experiments was calculated as the height of the tree of the average basal area. However, in other cases it was the average height of specified stand component. Sjolte-Jorgensen (1967) pointed out that height growth differences between stands of different initial spacing may not be expected to remain constant until after a certain age.

The effect of density on height growth of natural slash pine stands was investigated by Collins (1967). Height growth of the dominant and codominant trees was found to be significantly reduced by increased density. Where at age 17 - 14 years after the thinning treatment - thinned stands were as much as 15 feet taller than the unthinned. He concluded that the dominant height of dense young stands of natural slash pine is not a true indicator of the site productivity.

In red pine stands planted at different spacings, Stiell (1964) found that at age 20 height growth was not affected by the level of stocking. He concluded that the live crown ratio was not reduced enough (even at the closest spacing of 7' x 7') to affect height growth. However, Evert (1971) cited (Ann. 1954) that "in red pine stands reduced height-growth has been found at high densities on dry sites."

In a review of spacing studies Evert (1971) concluded that the influence of density on height growth is evident in overly dense stands on poor to medium sites, where height growth is likely to increase with increased spacing. However, experiments involving wider spacings appear to have little effect on height growth.

Results from spacing experiment in Douglas-fir at Wind River, Washington (relatively low site) showed significant differences in height growth among spacings ranging from 4'x4' to 12'x12' (Eversole, 1955; Reukema, 1959 and 1970; Curtis and Reukema, 1970 and Reukema, 1979). Average heights for the entire stand, the dominant and codominant stand and the 100 largest trees per acre all increase as spacing increases from 5'x5' to 10'x10'. Differences in height growth have increased with advancing age. Reukema (1979) concluded that differences in site index among spacings are attributed to effects of different intensity of competition on height growth. The results from this study are exceptions to the general trends observed in other spacing experiments (Evert, 1971).

Stand density was not a factor in King's (1966) selection of stands for site measurement in Douglas-fir, but the selected stands included a wide range of stand densities. He stated that stand density apparently does not affect the shape of height growth trend and whatever effect it has on site determination must be expressed in the level of site index.

METHODS

Levels-of-Growing-Stock-Study In Douglas-fir (LOGS)

The levels-of-growing-stock-study in Douglas-fir is a regional cooperative study initiated in 1961. The objective of the LOGS study was "to determine how the amount of growing stock retained in repeatedly thinned stands of Douglas-fir affects cumulative wood production, tree size and growth-growing stock ratios." (Curtis, 1984) Nine experimental locations have been established in Oregon, Washington and British Columbia under the LOGS study program. Two of these locations were selected for the purpose of this study. The selected locations represent a high and low site quality. The objective was to evaluate the influence of stand density on height growth of Douglas-fir on different sites.

Description of the Selected Study Locations

1. Hoskins Study Area:

This study location was established in 1963 by the College of Forestry, Oregon State University. It is located 22 miles west of Corvallis, Oregon. The even-aged natural stand was uniform in stocking and 20 years old (13 years at b.h.) when the study was established. It occupies a high quality site (II). Elevation is about 1,000 feet. The aspect is southerly, with slopes ranging from 15 to 55 percent. (Williamson and Stabler, 1971) The soils are deep well-drained silty clay loams. (Curtis, 1984)

2. Rocky Brook Study Area:

This installation is located in the Olympic National Forest, Washington, at 2,500-foot elevation in the Olympic Mountains. The stand occupies a low quality site (IV), on gravelly, sandy loam soils. The aspect is south and a gentle slope averaging 10 percent. The study area was established in 1963 by the U.S. Forest Service in a stand planted in 1940 (Curtis, 1984). In 1969 spare plots were used to replace plots heavily damaged by snow (Williamson and Stabler, 1971).

Thinning Treatments

Each study location consists of eight different thinning regimes and an unthinned control. There are three 1/5-acre plots per treatment arranged in a completely randomized design. At the time of establishment, all the twenty-four treatment plots at each location were thinned to the same density. Following this calibration the treatment thinnings were applied when ever the average height growth of the selected crop trees comes closest to each multiple of ten feet. The purpose of the calibration thinning was to minimize the effects of variation in original density on stand growth.

The difference between the eight thinning treatments is in the amount of growing stock retained each time the thinning was done. The amount of basal area retained in the treated plots was a predetermined percentage of the gross basal area growth in the unthinned control plots since the last thinning. (Table 1.)

Table 1. Levels of growing stock study treatment schedule, showing percentage of gross basal area growth of control plots to be retained in growing stock by treatment and thinning period. From (Williamson and Stabler, 1971).

Thinning Period	Treatment 1	2	3	4	5	6	7	8
	percent							
First	10	10	30	30	50	50	70	70
Second	10	20	30	40	50	40	70	60
Third	10	30	30	50	50	30	70	50
Fourth	10	40	30	60	50	20	70	40
Fifth	10	50	30	70	50	10	70	30

Measurements And Available Data

Measurements of stand characteristics; diameter at breast height (b.h.) and height were made following the calibration thinning and at the beginning and end of each thinning period (at Hoskins diameters were measured annually). The (LOGS) study plan specified a minimum of eight trees per plot for height measurements, distributed over the range of diameters. It was also specified that about two-thirds of the measured trees be from the upper half of the diameter range. However, there was a variation among installations in the size of the height sample (Curtis, 1984).

Thinning treatments at each location can be divided into two groups according to the percentage of gross basal area growth retained on the thinned plots. There are the fixed percentage treatments (1, 3, 5 and 7) and the variable percentage treatments (2, 4, 6 and 8) (Table I.). Data from the fixed percentage treatments are used for the analysis in this study.

In the Hoskins study area, height measurements were taken after the calibration thinning and at the beginning and end of each of the following five treatment periods. These measurements cover the age range of 13 to 29 years at breast height. At the Rocky Brook area measurements were also taken after the calibration thinning and at the beginning and end of each of the following three treatment periods, i.e. before and after each treatment thinning. This has provided height measurements over the age range of 18 to 35 years at breast height. There are slight variations in the average heights measured before and after each treatment thinning. Since these variations are inconsistent and relatively small, only the before treatment measurements were used in this analysis.

Analysis of Height Growth-Density Relationship

Choice of The Height Statistic

The average height of the measured crop trees could be influenced by stand alterations such as the removal of crop trees in the thinning particularly in the later treatment periods. Removal of crop trees is expected to result in a greater increase in the average height than the change due to actual growth. For consistency with previous site index studies and to avoid changes in the average height which are not a direct result of actual growth, the average height of the largest forty trees per acre has been suggested as a height statistic.

Marshall and Bell (1982) estimated the average height of the largest forty trees per acre (H40). The method used involves the use of the quadratic mean diameter (QMD) and the average volume of the eight largest trees per plot (1/5-acre), to solve Bruce-Demars volume equation for height. The estimated average heights of the largest forty trees were found adequate to describe the stand height growth when compared to the average height of the measured crop trees. The values of the (H40) are used in this study as basis for the comparison of height growth patterns.

Form of Height Growth Equation

The first step was to select a regression model that expresses stand height as a function of age. The inspection of height-over-age graphs from the different plots and treatments average indicates that the relationship is linear over this age range (Figures 1 and 2). Simple linear regression of the form:

$$H - 4.5 = b_1 + b_2A \qquad (1)$$

was found adequate to describe the height growth function, where H is the total height, A is the age at breast height and b_1, b_2 are parameters to be estimated.

Comparison of Height-Growth Patterns

The analysis of variation in the height growth functions were performed separately at each of the two selected study locations.

Indicator variables were used in a general linear model to test whether the height growth regression functions on plots under the same thinning regime are identical. The comparison of the three plots under each treatment was made by testing the regression coefficients of the general linear model of the form:

$$H - 4.5 = b_0 + b_1A + b_2X_1 + b_3X_2 + b_4AX_1 + b_5\ AX_2 \qquad (2)$$

where H, A are as defined in equation (1), X_1, X_2 are indicator variables representing the three plots under

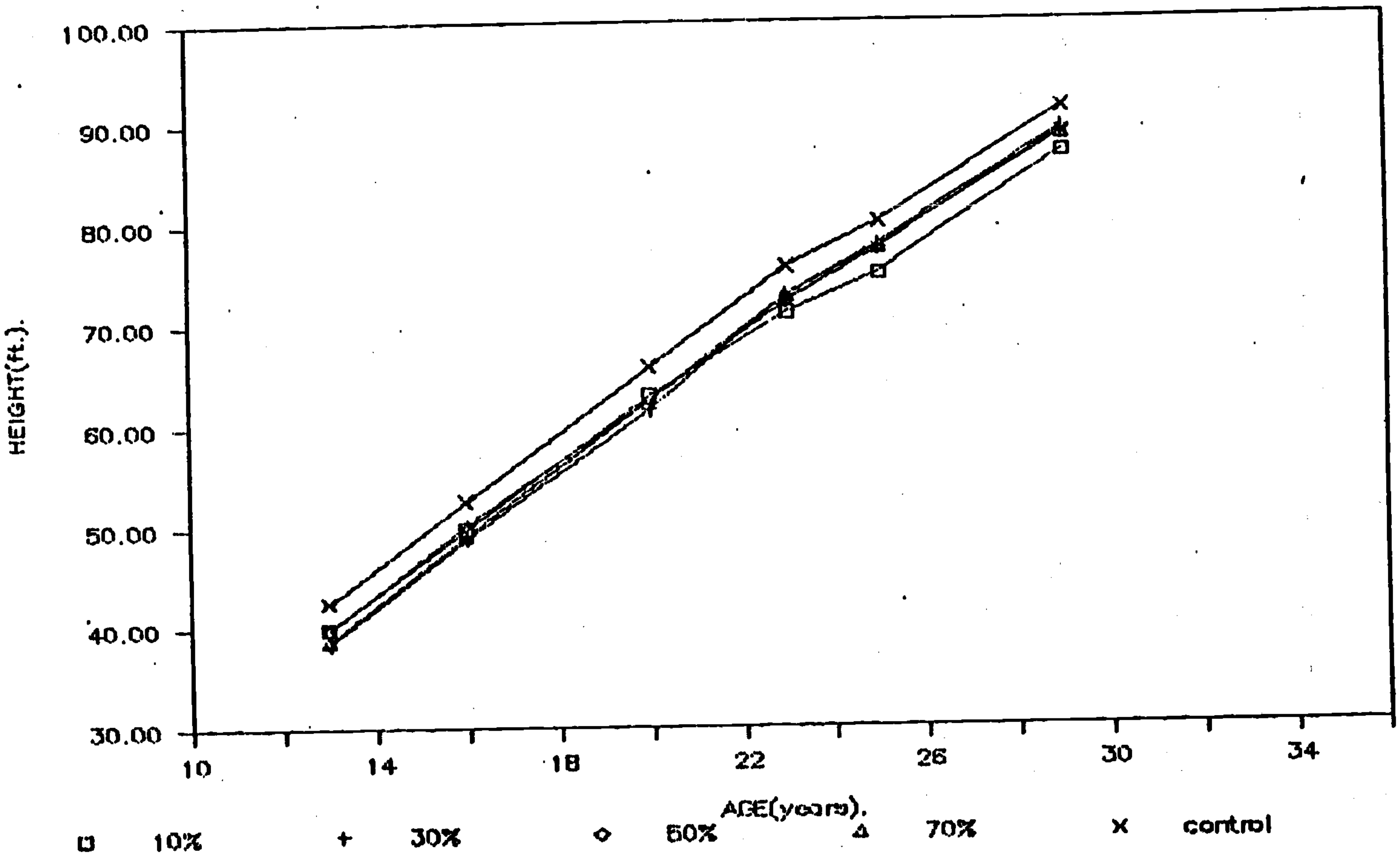

Figure 1: Height-Age Relationship by Treatment (Hoskins Area).

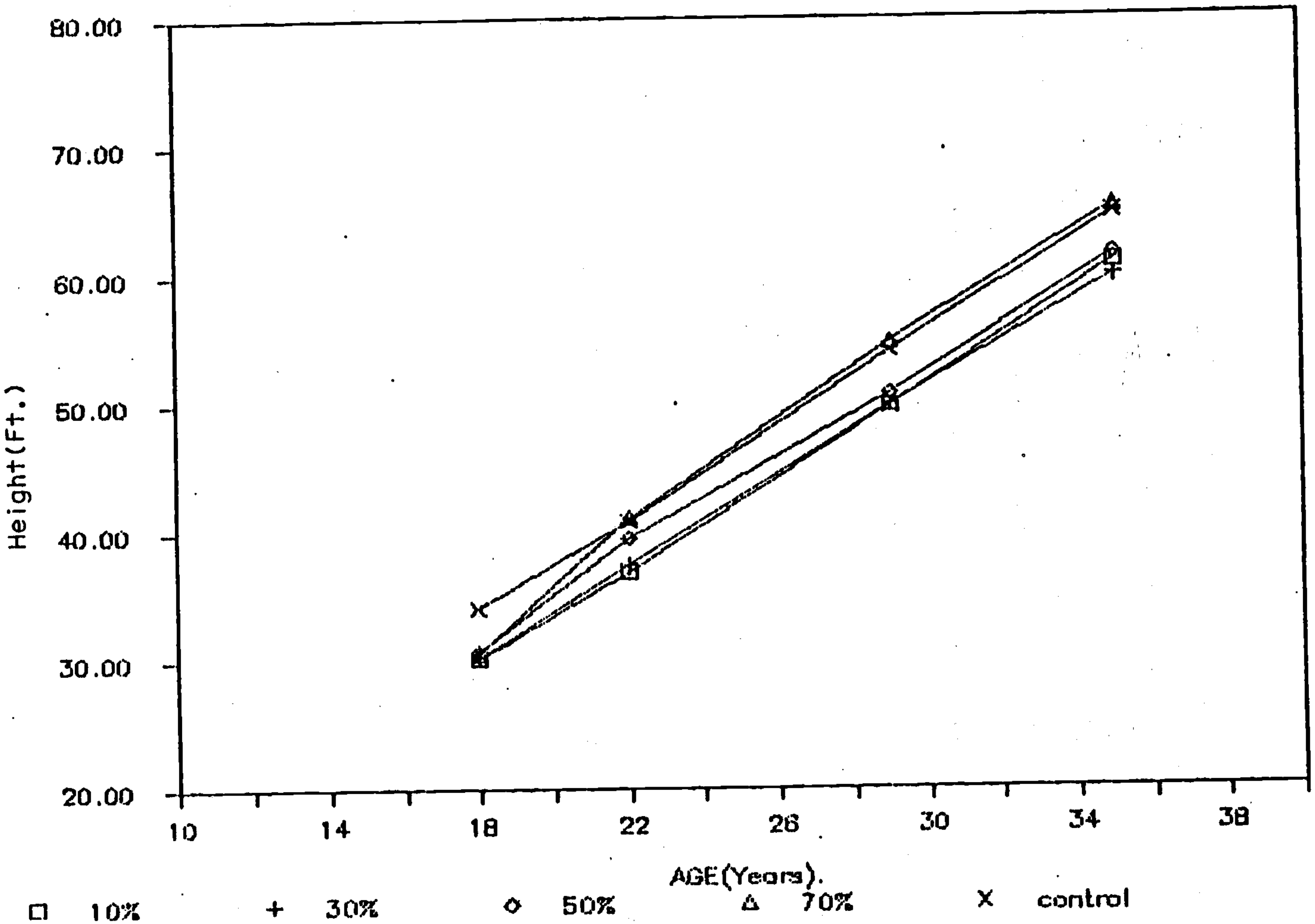

Figure 2: Height-Age Relationship by Treatment (Rocky Brook Area).

each treatment and b_1 to b_5 are parameters to be estimated (Neter et al., 1983).

In comparing the height growth regressions among the different thinning treatments, the 15 regression lines obtained by fitting equation (1) to the data from each plot were treated as random samples of size 3 from each thinning treatment (Beck, 1971). The slope of the regression function and the estimated height at the stand age when the study was established were used in the analysis of variance.

RESULTS AND DISCUSSION

When equation (1) was fitted to the data for each of the 15 plots at each study location, it proved highly efficient in describing the height-age relationship of individual plots. At the Hoskins study area the mean-root-square residuals ranged from .58 to 2.05 feet, more than 80 percent were less than 1.5 feet. For the Rocky Brook area the mean-root-square residuals ranged from .37 to 2.08 feet with more than 85 percent less than 1.5 feet. The coefficients of determination obtained are always high. Graphs of estimated versus observed heights showed no evidence of bias. Residual plots also showed no evidence of systematic pattern in the deviations around the fitted regression lines. It seemed reasonable to assume that the height-growth patterns of the individual plots was adequately described by the two parameters of equation (1). The height growth rate and the estimated heights at the stand age when the study was established are summarized in Tables 2 and 3 for the Hoskins and Rocky Brook areas, respectively.

Tests of the coefficients of the covariance model (2) showed that height-growth rates on plots under the same thinning treatment at the Hoskins study area are not significantly different at the .05 level. However, the levels of the height-age regressions of the plots in treatment 1, 5 and 9 (controls) are significantly different at the .05 level. Since any minor site differences among plots treated alike could have affected the rate of growth, differences in the level of growth functions could be attributed to variations in the original stands before the establishment of the study or to variations introduced by the calibration thinning.

In the Rocky Brook study area, results of the tests of differences among plots treated alike showed the following:

a - Plots in Treatments 1, 7 and the controls showed no significant differences in their height growth rates, but are significantly different in the level of their height-growth functions at the .05 level.

b - Plots in Treatments 3 and 5 showed significant differences in both the level and slope of their height-growth functions.

Differences in (a) above could be attributed to variations in the original stands or variations introduced by the calibration thinning. The differences among plots in Treatments 3 and 5 could be attributed to minor site differences under the assumption of no inconsistencies in the application of the thinning treatments.

Table II

Height Growth Rate and the estimated height at age 13 (at b.h.) obtained by fitting equation (1) to individual plot data (Hoskins study area).

Treatment	Plot	Height Growth Rate (ft/year)	Estimated Height at Age 13 (ft)
	3	2.89	35.4
1	8	2.81	38.7
	20	3.01	35.7
	7	3.09	36.4
3	11	3.22	34.2
	21	3.31	33.6
	9	3.14	37.8
5	24	3.17	36.1
	27	2.87	34.9
	12	3.08	35.7
7	14	3.19	35.4
	19	3.16	34.8
	10	2.94	37.7
9	22	3.16	41.9
(control)	26	3.11	37.7

Table III

Height Growth Rate and estimated heights at age 18 (at b.h.) obtained by fitting equation (1) to individual plot data (Rocky Brook study area).

Treatment	Plot	Height Growth Rate (ft/year)	Estimated Height at Age 13 (ft)
	24	1.83	24.0
1	32	1.79	29.9
	36	1.84	35.8
	11	2.06	30.1
3	16	1.45	31.1
	40	1.72	30.0
	9	1.54	32.2
5	15	2.00	31.1
	21	1.79	30.8
	25	1.79	29.3
7	38	2.19	32.0
	39	2.06	34.2
	14	1.62	31.5
9	27	1.86	38.9
(control)	29	1.97	31.3

In the Hoskins study area the results from the analysis of variance performed on the coefficients obtained by fitting equation (1) to the data from individual plots are shown in Tables 4 and 5. Table 4 shows the contribution of the thinning treatment and the different plots within treatment to the total variation in the slope of the height-age regression function - height-growth rate. The height-growth rates - slopes of height - age regressions are not significantly different. However, at a lower level of significance of .1, there is a significant difference between the initial heights of the control plots and the treatment plots. The average height-growth rate and the stand initial height by treatment are shown in Figures 3 and 4.

Under the assumption that the stand was uniform at the time the study was started, (a criterion for the stand selection) it could be that the top height of the treatment plots has been reduced by the calibration thinning.

As would be expected differences in the estimated site indices (King, 1966) between the control and the treatment plots are due to variations in the initial heights after the calibration thinning. After the fifth thinning treatment, there was a 5-foot difference in the

Table IV

Analysis of variance indicating the contribution of the different sources to the total variation in the slope of the height-growth function-rate of growth (Hoskins study area).

Source of variation	SS	DF	MS
Thinning treatment	.155	4	.0388
Plots within treatment	.132	10	.0132
Total	.287	14	

F value = 2.93 with 4 and 10 D.F.

Table V

Analysis of variance indicating the contribution of the different sources to the total variation in the estimated height at age 13 (at b.h.). (Hoskins study area)

Source of variation	SS	DF	MS
Thinning treatment	33.92	4	8.48
Plots within treatment	26.89	10	2.692
Total	60.81	14	

F value = 3.15 with 4 and 10 D.F.

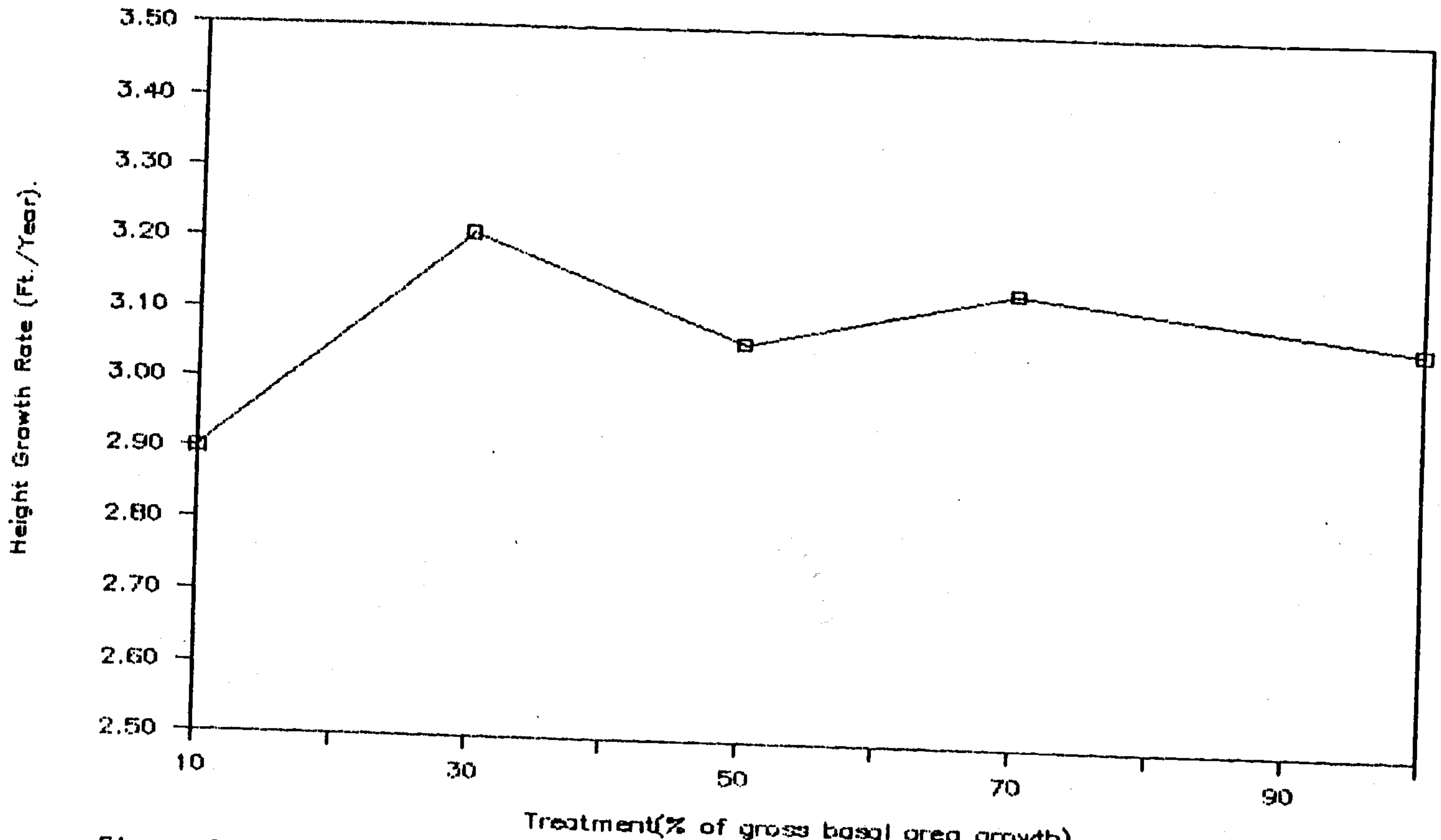

Figure 3: Height-Growth Rate by Thinning Treatment (Hoskins Area).

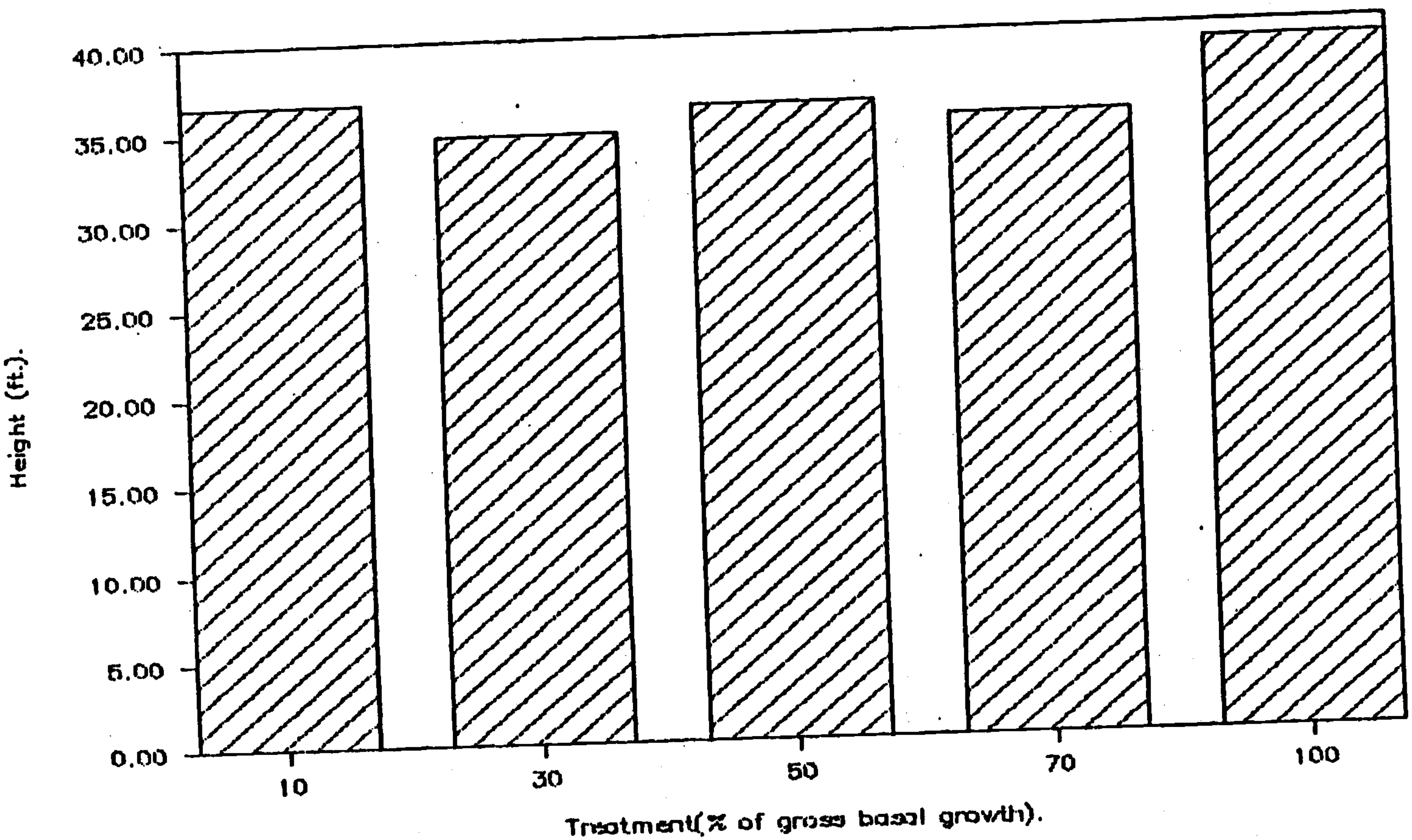

Figure 4: Stand Initial Height After the Calibration Thinning by Treatment (Hoskins Area).

estimated site index of the control plots and the treatment plots.

These results indicate that at the Hoskins study area (Site Class II) height growth has not been significantly influenced by the stand density within the range of densities represented in the study and within the age range studied. The average relative density (Curtis, 1982) of the treatment plots ranged from 20 for plots in treatment (1) to 38 for the plots in treatment (7) and was 89 for the control plots. Although the control plots has a much higher relative density it has evidently not influenced the height growth.

Evert (1971) in a review of spacing studies concluded that the influence of density on height growth is evident in overly dense stands on poor sites and has little or no effect on height growth on higher sites.

For the Rocky Brook study area the analysis of variance of the height-growth rate and the estimated height at age 18 are shown in Tables 6 and 7 respectively. The initial heights of the treatment and the control after the calibration thinning showed no significant differences at the .01 level. The height growth rates are also not significantly different at this level of significance. The average height growth rate and the initial stand

Table VI

Analysis of variance indicating the contribution of the different sources to the total variation in the slope of the height-growth function (Rocky Brook area).

Source of variation	SS	DF	MS
Thinning treatment	.132	4	3.31
Plots within treatment	.442	10	4.42
Total	.574	14	

F value = .75 with 4 and 10 D.F.

Table VII

Analysis of variance indicating the contribution of the different sources to the total variation in the estimated height at age 18 (at b.h.). (Rocky Brook area)

Source of variation	SS	DF	MS
Thinning treatment	29.07	4	7.27
Plots within treatment	121.41	10	12.14
Total	150.48	14	

F value = .60 with 4 and 10 D.F.

height by treatment are presented in Figures 5 and 6, respectively.

It is also evident from these results that at the Rocky Brook study area (Site Class IV), stand density has not affected height growth within the range of densities represented in the study. The average relative density of the treatment plots ranged from 18 for the plots in treatment (1) to 28 for plots in treatment (7) and was 67 for the control plots. In the spacing experiment in Douglas-fir at the Wind River, Washington (Site Class IV), differences in height growth occurred between spacings ranging from 4 x 4 feet to 10 x 10 feet (Curtis and Reukema, 1970 and Reukema, 1979). Although the Rocky Brook area occupies a similar low site, the 4 x 4 and 5 x 5 feet spacings at the Wind River are more dense compared to the closest spacing (control) at the Rocky Brook area (approximately 6 x 6 feet). This comparison, however, is made having in mind that the growth trends in plantations may differ from those of thinned natural stands (King, 1966).

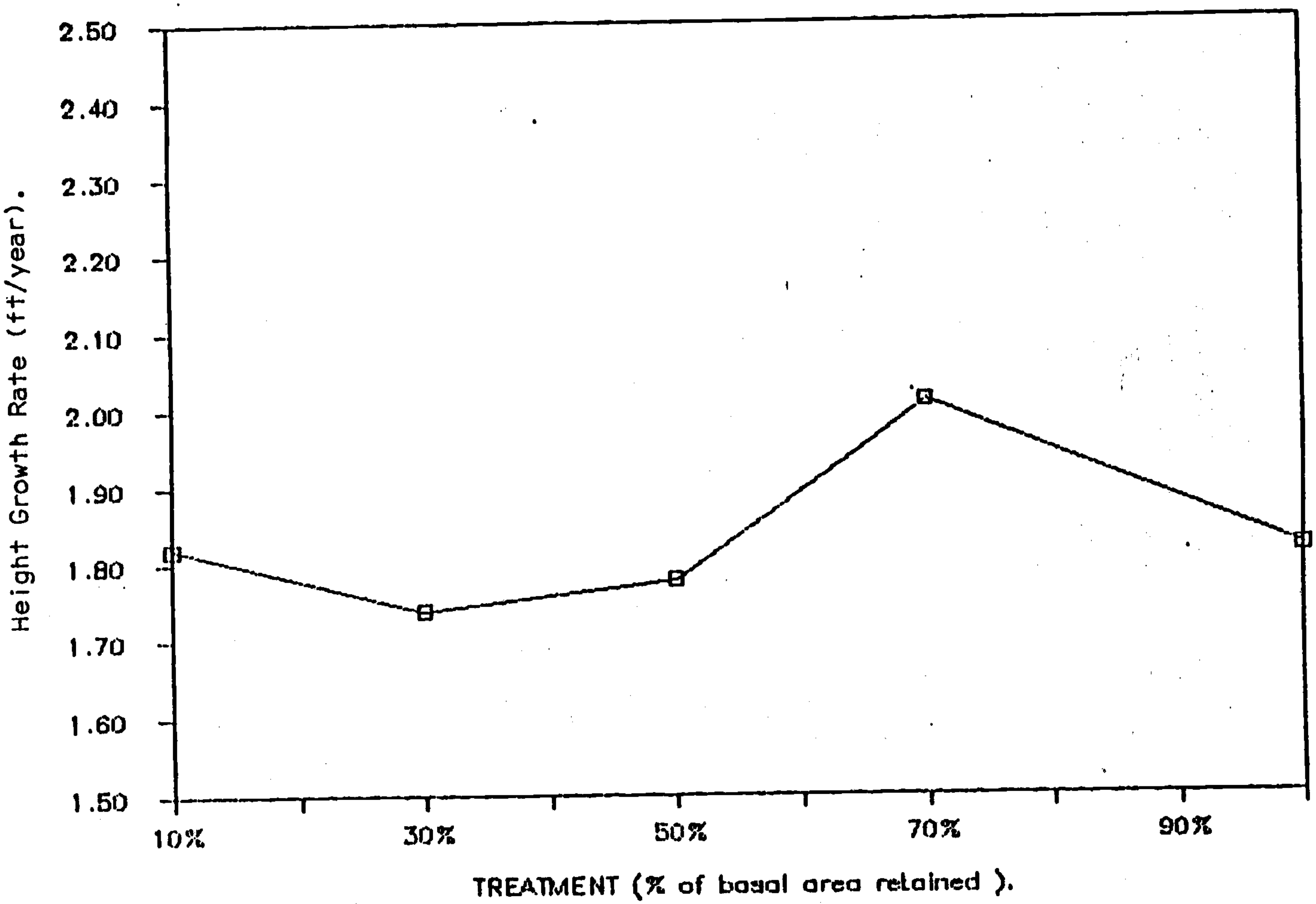

Figure 5: Height-Growth Rate by Thinning Treatment (Rocky Brook Area).

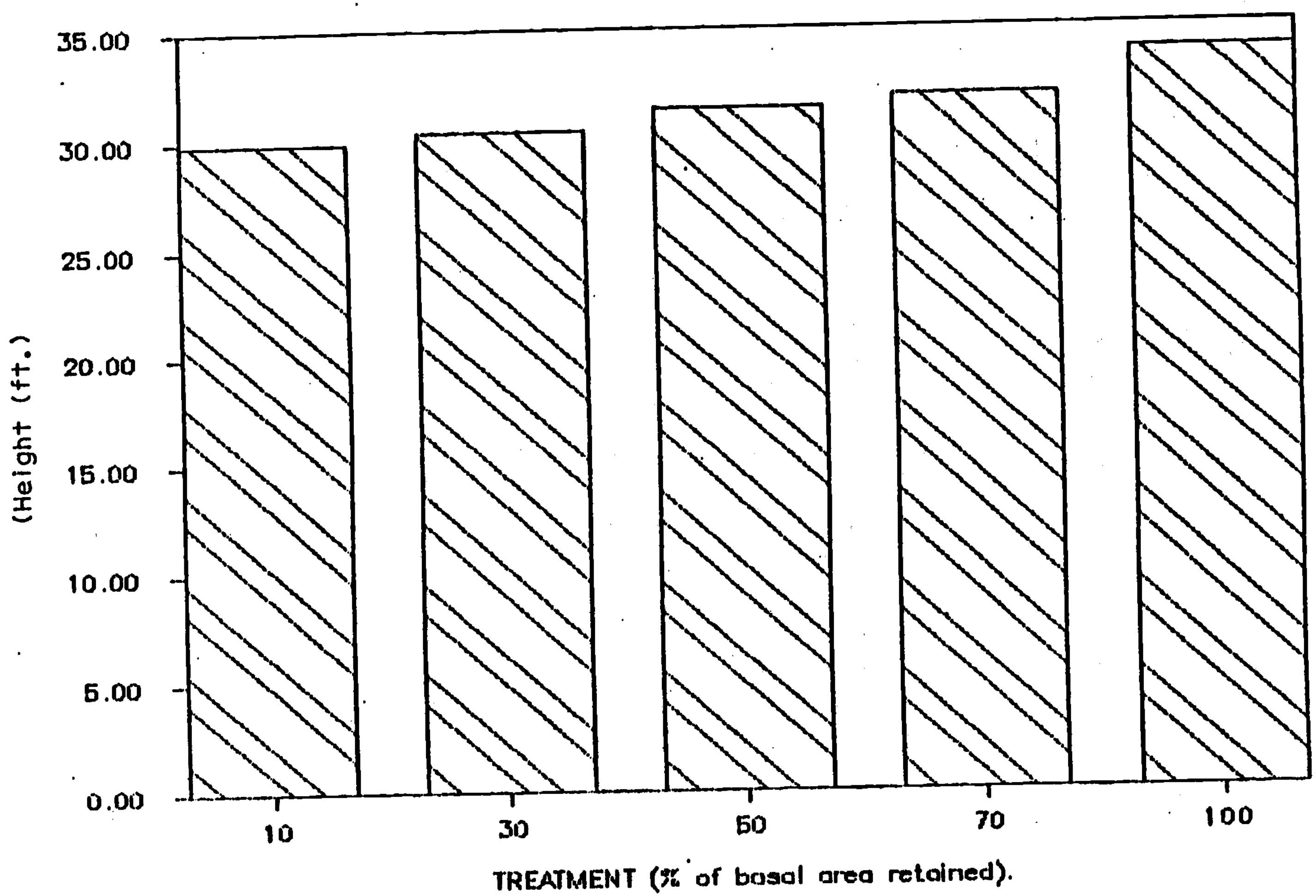

Figure 6: Stand Initial Height After the Calibration Thinning by Treatment (Rocky Brook Area).

CONCLUSIONS

The principal objective of this study was to examine the influence of stand density on height growth and site index at two locations representing a high quality site (II) and a relatively lower quality site (IV). The results of the study indicated the following:

1. On high quality site (class II), height growth was not influenced by stand density over a wide range of stocking within the age range studied (20 to 32 years). The relative density (Curtis, 1982) ranged from 20 to 89. Differences in site index occurred only as a result of the heavy initial thinning which altered the stands top height.
2. On the relatively low quality site (class IV), the relative density ranged from 18 to 67 and no significant differences in site index were detected over this range of stocking and within the age range studied (27 to 44 years). It could not, however, be shown if higher densities--similar to those on the other site--would affect height growth on such a poor site as other studies in Douglas-fir has indicated.

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