EFFECTS OF THINNING ON CROWN STRUCTURE, STEM FORM AND WOOD DENSITY OF RADIATA PINE

by

G.R. Siemon

Thesis submitted for the degree of Doctor of Philosophy in the Australian National University.

25th October, 1973

ORIGINALITY OF THE THESIS

Except where specific reference is made to assistance by another person, the design, analysis and presentation of this research is original and was done without collaboration.

G R Siemon

G.R. Siemon

25th October, 1973

ACKNOWLEDGEMENTS

This project was undertaken during the tenure of a Commonwealth Postgraduate Scholarship.

I wish to thank my supervisor, Dr G.B. Wood, for his interest and valuable advice and criticism throughout the project. Dr W.G. Forrest of the New South Wales Forestry Commission, at present Senior Forester, L.A.R.P., provided considerable assistance during the field sampling and later gave extremely useful comments during the writing phase.

The New South Wales Forestry Commission generously allowed sampling in a thinning trial in the Green Hills State Forest, near Batlow, and provided assistance during the field work.

Professor J.D. Ovington is thanked for providing the use of technical assistance for most of the field work and allowing the use of Department of Forestry facilities throughout the project.

Statistical advice was generously given by Mr W. Müller and Mr R.G. Forrester of the Division of Mathematical Statistics of CSIRO, for which appreciation is expressed.

Various staff members and postgraduate students of the Department of Forestry were of great assistance through discussions, and by providing computer programs for data analysis.

CORRIGENDA

page	
5	Insert "(Forrest, 1969)"after "crown" in 2nd last line.
7	Change "green volume of wood" to "volume of green wood" in 5th last line.
13a	Insert "The star indicates a plot considered unsuitable for the thinning trial" above the caption.
14	Insert "from below" after "thinned" in 2nd line below the table.
26	Change "Table 3.4" to "Table 3.3" in 9th line.
32a	Insert "(as percentages)" at end of caption.
52a	Change "Thinning Treatment" to "Diameter Class" and place "<" before "20" at the axis intersection in Fig.4.
61	Change reference 3rd line to "Elliott, 1970a)."
76	Insert (Will, 1964) after CO_2 in 4th last line
79	Change "valves" to "values", in 7th line.
88	Change " lass" to "class" in 8th line.
92	Insert "(Forrest, pers.comm.)" after "developed" in 4th last line.
93	Insert another "0.22" after "0.21" in 7th last line.
94	Insert "merchantable" before "volume" in 5th line.
95	Delete "co" at end of 8th line.
107	Insert subscript "B" to give "D_B" in 4th column.
117	Insert "(cm)" after "treatment" in caption.
120	Change 2nd last reference to Doerner, Karl Jr.

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

CHAPTER 2

MATERIAL AND GENERAL METHODS

Page

CHAPTER 3

EFFECT OF THINNING ON CROWN STRUCTURE

CHAPTER 4

EFFECT OF THINNING ON STEM FORM

CHAPTER 5

EFFECT OF THINNING ON WOOD DENSITY

CHAPTER 6

INTERRELATIONSHIPS AND GENERAL DISCUSSION

LIST OF TABLES

LIST OF FIGURES

Page

LIST OF APPENDICES

LIST OF ABBREVIATIONS

The following abbreviations are used in the text of the thesis:

B.A.	basal area
B.H.	breast height
D_B	stem diameter at base of green crown
D.B.H.	diameter breast height
D.B.H.O.B.	diameter breast height over bark
d.o.b.	diameter over bark
d.u.b.	diameter under bark
s.p.ha	stems per hectare
N.S.	not significant at $p = 0.05$
*	significant at $p = 0.05$
**	significant at $p = 0.01$
***	significant at $p = 0.001$

ABSTRACT

Radiata pine (Pinus radiata D.Don) is the most important exotic conifer in Australian plantations. However, no major studies had been made of the concomitant effects of thinning on crown and stem parameters and on wood density even though this silvicultural treatment is widely practised in management for sawlog production.

The study area is a 23-year-old stand on a uniform site in the Green Hills State Forest, N.S.W., in which a thinning trial of four replications of six treatments was established in 1962. Sampling was undertaken in 1970, eight years after the initial treatment was applied.

Selected crown and branch parameters were compared between treatments and a gradation of values found with increasing intensity of thinning. Foliage weight by age classes was related to branch cross-sectional area using the allometric equation, and the relationship used to estimate foliage weight in the crown and the relative distribution of foliage at different stand densities. These data were associated with stem D.B.H.O.B. to estimate foliage biomass per hectare and annual productivity of needles. Foliage biomass increased significantly with increasing stand density.

The effect of thinning on stem form and taper was examined using stem analysis data. Stem form changed little after treatment while taper changed considerably in the most heavily thinned treatment. The shape of the stem was a second degree paraboloid in more than 80% of the profiles examined, and the mechanistic theory explains a considerable amount of the variation found in stem shape.

Wood density variations after thinning were compared using the X-ray densitometry technique. Thinning reduced mean density, percent latewood, and density range, while ring width was substantially increased after treatment. The major effect was found below the green crown and outside the juvenile core.

The interrelationships between selected crown, stem and wood density variables indicate a strong interaction between the crown and stem. In the general discussion the results of the study are summarized and the implications of the crown-stem relationship discussed in relation to the effect of thinning. The implications of the findings and their usefulness to forestry practice are considered.

CHAPTER 1

INTRODUCTION

Radiata pine (Pinus radiata D.Don) is one of the most important exotic species used in afforestation and reforestation projects in a number of countries having a temperate sub-humid climate e.g. New Zealand, Australia, South Africa, Chile. The popularity of the species for plantation establishment is due to its remarkable rate of growth over a range of environments, its ease of propagation and the general utility of its timber. The species has been extensively planted in Australia, the total area of government and private plantations by March 1971 being 294,000 ha (Commonwealth Year Book, 1972).

Radiata pine plantations are managed under intensive silvicultural regimes which involve control of initial spacing, tending, mineral fertilizing, pruning, thinning and other cultural treatments of generally lesser consequence. The treatments considered to have major effects on tree growth and wood properties are initial spacing, mineral fertilizing and thinning (Paul, 1963; Elliott, 1970a).

The yield and quality of both wood fibre and solid wood products from either conifer or hardwood stands depend largely on wood density and other wood properties. Whilst the wood-using industries have constantly changing requirements for raw material (Anon, 1970), their efficiency requires an intimate knowledge of the raw material. Consequently quantitative measures of the effects of silvicultural treatments on wood properties, and tree and forest growth are essential.

McKinnell (1970) studied the effects of mineral fertilizing on wood density in radiata pine and found that changes in density resulting from fertilizer application are no greater than the natural variation within the species: he concluded that fertilizing will not affect the utilization of the species. The State Forest Services and the Forest Products Laboratory, CSIRO, have also investigated the effects of fertilizing on radiata pine but McKinnell's study is the most detailed to date.

Thinning is a very common treatment in plantations managed for sawlog production, the regimes applied varying considerably depending on the objects of management and the general management philosophy. Different regimes may have considerable effects on wood properties. These effects have not been studied in detail for radiata pine despite their great importance to the wood-using industries.

1.1 Thinning Practice

Thinning is defined as "a felling made in an immature crop or stand in order primarily to accelerate diameter increment but also, by suitable selection, to improve the average form of the trees that remain, without - at least according to classical concepts - permanently breaking the canopy" (Ford-Robertson, 1971).

The theory of thinning is based on the forest stand regarded as an ecological unit and dominated by trees which continually need more growing space to remain healthy and to develop stem, crown and roots proportionally. For example Day (1966) defined three stages in a forest stand in relation to change in population density. During the first stage from planting to canopy closure, trees grow as individuals. In the second stage the stand becomes a unit, with total growth balanced and distributed between its members. A light to medium grade of thinning is prudent at this stage. Fairly rapid canopy closure follows and rethinning is then required to alleviate further competition for light, space, soil moisture and nutrients. Height growth continues and so has a marked effect on crown extension. The third stage occurs when the high canopy cannot be maintained because of physiological limitations: foliage density decreases in dominant trees and canopy gaps are difficult to fill because of a reduced rate of crown extension. Thinning then has progressively less effect on tree growth.

1.2 Effects of Thinning on Crown and Stem Morphology and Wood Density

1.2.1 Crown Morphology

The effect of thinning on various crown parameters has been widely studied but the results obtained often differ. This is partly because the base of the green crown has been defined in various ways, the most common definitions being the level of the lowest green whorl, of the lowest green branch, or halfway between these two levels (Ford-Robertson, 1971). Another definition is where the first green leaves occur (Ward, 1964). The more complex definitions by Czarnowski (1961) and Beekhuis (1965) involve some mathematical calculation and are largely impractical.

Beekhuis (1965) found for New Zealand-grown stands of radiata pine that crown length remains nearly constant after full canopy closure, height to the lowest green whorl increasing at approximately the same rate as total height. A similar finding was made by Stiell (1966) in P. resinosa Ait.. However, if the stand is thinned crown length will vary. Beekhuis (1965) concluded ". . . , to obtain a reliable estimate of crown depth under different thinning regimes, both stand density and stand height have to be taken into consideration."

Neither crown length nor crown length ratio (the ratio of green crown length to total height of the tree) were found to vary when Keister, Crow and Burns (1968) compared the effects of four classical methods of thinning on 40-year-old P.elliottii Engelm.. The most efficient crown length ratios are .45 to .50 according to Holsoe (1950) and Ward (1964) but these values could vary with species, age and stand density.

Under a constant stand density with repeated light thinnings, crown length ratio decreases with increasing stand height (Kramer, 1966) because crown length remains relatively constant (Beekhuis, 1965; Stiell, 1966).

Thinning also has effect on crown diameter, though in radiata pine the response may be less than for crown length (Van Laar, 1963). Field determination of crown diameter is generally difficult because of the physical problems in making direct measurements and the irregularity of the crown outline (Walters and Soos, 1962). Crown diameter may be estimated from stem diameter(Ilvessalo, 1950; Smith and Bailey, 1964). Conversely it is used to estimate the stem diameter and volume of trees on aerial photographs (Husch, 1947; Spurr, 1960).

For a given stand density, crown diameter tends to stabilize (Stiell, 1966). Honer (1971) developed equations for Abies balsamea Miller. and Picea mariana (Miller) Britt., St. & Pogg., relating crown radius at any level in the crown to variables incorporating total tree height and the length along the bole from the tree tip to the level at which crown radius is measured. He concluded that portions of crowns above the maximum crown radius have similar growing conditions in both forest- and open-grown trees of the same species and height.

A major long term affect of reasonably heavy thinning is an increase in both crown width and length so that a released crown retains a particular shape (Curtin, 1968). Although general descriptions of crown shape are common, quantitative descriptions are not. Quantitative measures are important in studies of productivity because of the relationship between crown size and rate of tree growth (Honer, 1971).

Crown volume and surface area are affected by thinning through the effects on length and diameter. Kramer (1966) found that while heavy thinning results in increased crown surface area and volume per tree, wood production per unit area depends on total crown surface area. However, crown surface area and volume are difficult to assess accurately because of irregularities caused by variations in branch size, angle and distribution, and by competition effects (Stiell, 1966).

Besides affecting external dimensions of the crown, thinning affects the development of individual branches, even down to the lowest green branch (James and Tustin, 1970). Because thinning modifies the depth of the green crown but not height growth, the branches at the crown base of trees in thinned stands will be older and receive more light so, on average, they will be longer and thicker than those in unthinned or denser stands.

Needle persistence in conifers is affected by the intensity of light reaching the crown. The crowns of trees expand annually and so the quantity of light reaching the older needles is reduced with increasing plantation age. Thinning temporarily arrests this process and thereby affects needle persistence and the distribution of foliage age classes in the crown. In general, the photosynthetically efficient crown forms a sheath which moves upward with increasing age at a rate depending on the relative spacing between trees.

1.2.2 Stem Form and Taper

Stem "form" refers to the shape of the tree stem and "taper" to the rate of decrease in diameter with increasing height up the stem (Ford-Robertson, 1971).

Larson (1963a) concluded that any change in crown development resulting from thinning will be reflected by a change in stem form, but this is not supported by the research of Stiell (1964) and Bassett (1969) on two different coniferous species.

In a review of the effect of growing space on the growth of conifers, Jorgensen (1967) concluded that spacing affects stem taper, and that taper increases with increasing stem D.B.H.O.B. e.g. see Klem (1952) and Cromer and Pawsey (1957).

Jacobs (1954) suggested that in heavily thinned stands of radiata pine a considerable proportion of the rapid diameter growth of the bole occurring immediately after thinning can be attributed to adjustment of tree form. However, this increased diameter growth following thinning may or may not change the stem profile. It depends on stem shape before thinning and the regularity of changes in diameter growth along the length of the bole after thinning. Larson (1965) found these changes were largely determined by the size and vigour of the live crown.

Elliott (1970b) has suggested that more even ring widths up the stem could be achieved by the selective application of thinning treatment. This will involve a change of shape if the bole resembles a second degree paraboloid, but not a conoid, before thinning.

Carron (1968) stated: ". . . , whether variation in (stand) density affects diameter growth along the stem, to what extent (and) under what circumstances, is a matter on which there is considerable but conflicting evidence. This is one of the largest and most critical gaps in our knowledge of the behaviour of trees."

The increase of diameter growth of trees remaining in a stand after thinning has been attributed to more available growing space for the green crown, less competition for soil moisture and nutrients, and increased light to the intermediate branches (Forward and Nolan, 1961). In radiata pine stands, trees of all dominance classes may respond to thinning, the increase in diameter growth being proportional to tree size. The growth response is greatest in young stands soon after canopy closure and decreases with stand age (Shepherd and Forrest, in press).

1.2.3 Wood Density

Specific gravity (the ratio of the oven-dry weight of a sample to the weight of a volume of water equal to the volume of the sample at some specific moisture content) and basic density (density based on the oven-dry weight and green volume of wood), as defined by Ford-Robertson (1971), are often used synonymously in the literature.

The basic density of wood has been intensively studied because it is easily determined and is correlated with many other wood properties e.g. strength, machinability, weight, and pulp quality and yield. A comprehensive review of the literature on wood density of conifers covering measurement, variation in and between trees, and the effects of heredity and silvicultural treatments, was compiled by Elliott (1970a). Earlier reviews include those by Spurr and Hsiung (1954), Larson (1957) and Goggans (1961).

Initial spacing and thinning are similar in that both are designed to give trees adequate growing space. Their effects on basic density are somewhat controversial. Paul (1963) in a comprehensive review of the literature concluded that close initial spacing increases density, but later researchers claim a negligible effect (Hamilton and Matthews, 1965; Fielding, 1967b; Maeglin, 1967).

Initial spacing is of major importance to stand development until first thinning is applied. Close spacing reduces branch development (Fielding, 1967b) and it has been suggested that consequently stem taper will be reduced (Boyd 1967). Close spacing also reduces the size of the juvenile core (Kleuters, 1964).

Thinning after canopy closure can have a considerable effect on wood density. Larson (1963b) reported a fall in basic density following thinning due to a greater production of earlywood. In later years, the production of earlywood and latewood becomes more balanced and basic density increases again (Larson, op.cit.; Paul, 1963). Thinning of overcrowded stands releases trees from conditions favouring latewood formation, and one would expect a fall in basic density. However, Keister (1967), Zobel, Roberds and Ralston (1969) and Bassett (1969) found thinning had no effect on wood density in southern pines.

Thinning has little effect on the wood density of trees in senescent stands because the crowns are receded and are a considerable distance from the zones of wood production (Spurr and Hsiung, 1954; Larson, 1957).

1.3 Relationships between Crown, Stem and Wood Density

In forestry practice, the concept of a crown-stem relationship is often overlooked (Larson, 1969). Reukema (1961) suggests that the history of crown development of a tree is possibly more important in explaining stem growth than the size of the crown at a given time. He is supported by Smith (1963) who advocates control of the crown as the basis of growing forest tree crops for a particular end use.

The most efficient crowns for wood production are those which produce most wood for the space they occupy (Brown and Goddard, 1961). Large crowns and branches do not necessarily make a tree a more efficient producer of wood. In general, long narrow crowns are regarded as more efficient in exploiting available light than short wide crowns (Reukema, 1961; Hamilton, 1969).

Kramer and Kozlowski (1960) consider the ability of an individual tree to produce bole wood is a function of: (i) the average efficiency of the photosynthetic material, (ii) the total photosynthetic area contributing to the production of carbohydrates, (iii) the duration of photosynthetic activity both daily and annually and (iv) the propensity of the tree to store its photosynthetic products in the bole in preference to the branches and roots.

The formation of wood on the bole is regulated by the growth and development of foliage in the crown (Larson, 1969). The relationship is particularly well expressed in the young tree whose stem is fully enclosed by the green crown.

The juvenile wood or core wood in the stem of conifers is generally characterized by low specific gravity, low percent latewood, short tracheids, wide micellar angle and high longitudinal shrinkage (Fielding, 1967b). It often includes substantial amounts of spiral grain and compression wood. Larson (1963b) suggested the juvenile wood should be defined as the wood formed in the live crown. The term aptly describes the type of wood formed in a young tree: the same or a very similar type of wood is also produced in the rings nearest the pith at all heights in the stems of older trees.

Within the crown, the percentage of earlywood produced in the bole is comparatively large because earlywood formation is favoured by close proximity to the foliage. The percentage of latewood in each growth ring gradually increases with increasing distance below the crown. Latewood is initiated at or near the stem base in trees of all ages and proceeds upward as the growing season continues. The width of the latewood zone therefore tapers more than the annual sheath, and near the stem apex, formation of latewood ceases. This pattern of latewood development is a function of age and distance from the active crown, both of which increase simultaneously (Larson 1969).

Percent latewood has a considerable effect on wood density, more so than percent earlywood. In many studies the density of latewood is reported to be more than twice that of earlywood (Elliott, 1970a).

Effects of growth rate on the tree stem are complicated by the interaction of age of the tree, position in the trunk and genetic variation; in addition, the wide variation in environmental factors influencing trees during their long life are significant (Fielding, 1967b). Ring width depends on growth rate, but there is considerable evidence that ring width accounts for only a small part of the variation in basic density across a stem (Elliott, 1970a). Partitioning the stem by age classes from the pith but excluding the juvenile core can result in significant correlations between ring width and basic density (Keith, 1961).

In this discussion the relationships between the crown and wood formation processes have been indicated. Thinning generally has most effect on the green crown, and any modifications to the crown may be reflected by changes in wood density. Indirect effects of thinning include changes in branch size, branch longevity, the proportion of live and dead whorls and branch angle; these factors determine the size and nature of knots, whether green or dry, which in turn affect peeling quality, veneer appearance, pulp quality and the strength properties of sawn timber (Wright, 1971).

While the green crown is important because it governs the patterns of tree growth and cell characteristics, and hence wood density (Larson, 1969), crown parameters also affect stem shape. Changes in the crown resulting in variation of ring width at different heights in the stem may cause variations in stem form. A relationship between stem shape and wood density is therefore conceivable.

Trendelenberg (1932, 1935), Volkert (1941), Schniewind (1962) and Doerner (1964) have shown that a tree may meet strength requirements by producing a smaller volume of high density wood or a larger volume of low density wood. McKinnell (1970) has shown a statistically significant relationship between stem taper and wood density in radiata pine, therefore it seems likely that stem taper would differ between trees containing wood of these two types.

1.4 Aims of the Study

Radiata pine is of great importance in Australia, yet no major studies have been made of the concomitant effects of thinning on crown and stem parameters and on wood density of plantation trees.

This study was undertaken to determine these effects and to examine the nature of any interrelationships.

CHAPTER 2

MATERIAL AND GENERAL METHODS

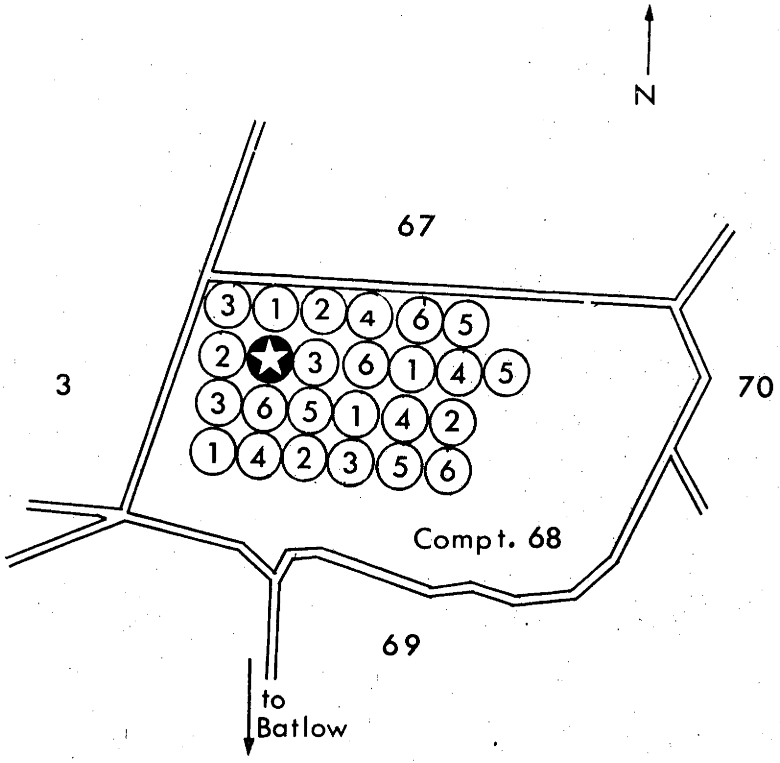
2.1 The Experimental Area

In order to examine the hypothesis that the external profile and internal structure of trees are mutually dependent on the stand density at which the trees are grown, it is desirable to examine trees in a forest where stand density is the only variable. Suitable stands were available in an experimental thinning trial located in the Green Hills State Forest near Batlow on the Southern Tablelands of N.S.W. (Figure 2.1).

The experiment and forest area have been described in detail by Shepherd and Forrest (in press). Briefly, the experimental area is part of Cpt. 68, planted with 1/0 radiata pine seedlings in 1947 at a nominal spacing of 2.4m x 2.4m (1736 stems ha^{-1}). The seedlings used were from seed collected from various silvicultural thinnings in older plantations, so the full genetic variability of the original plantation is retained in the study area.

The stand is situated on a broad, gently sloping site: the soil is a red loam clay derived from old weathered granites and is adequately drained. Nutrient availability is adequate to support high quality plantations (Shepherd, 1967).

All trees were pruned to 3.0m in 1956 and the best 400 trees ha^{-1} were pruned to 6.1m by 1960. The compartment was thinned for the first time in 1962 at age 15 years and this was a commercial thinning. The experiment was established



Randomized block design
Four replications of six treatments

Thinning Treatment	Nominal Basal Area
1	11.5-18.4 m^2ha^{-1}
2	15.0-21.9 "
3	18.4-25.3 "
4	23.0-29.9 "
5	27.6-34.5 "
6	Control - "unthinned"

FIGURE 2.1 Layout of the study thinning trial in Green Hills State Forest, N.S.W.

at this time to provide reliable growth data on which to base future management of the pine plantations.

The experiment is a compact block of six treatments randomised within each of four replications. The treatment plots are 0.25 ha square, and each contains a circular, one-tenth ha measured sub-plot.

The experimental treatments were planned so that a wide range of stand density conditions could be maintained. The basal area limits specified for each treatment are:

Treatment	B.A. Limits (m^2 ha^{-1})
1	11.5 - 18.4
2	15.0 - 21.9
3	18.4 - 25.3
4	23.0 - 29.9
5	27.6 - 34.5
6	Control ("unthinned")

When the experiment was established in 1962, each plot was thinned to the relevant lower basal area. All plots were rethinned to the prescribed lower limits in 1964 and again in 1967, since on each occasion stand densities had reached the specified upper limits. The control plots were lightly thinned in 1967 to forestall mortality and maintain stand hygiene.

The fourth experimental thinning was done in 1970 and the tree material used in this study was drawn from it. By 1970 the top height of the tallest 50 trees ha^{-1} was 27.6m.

2.2 Sample Tree Selection

In general the techniques described in the literature for sampling, particularly for wood properties, are subjective and liable to bias, samples tending to be confined to dominant and co-dominant trees. Pearson (1952) considered that sampling was only valid when the distribution of values of each wood property in the sample represented the distribution of values in the population.

Greater precision is usually obtained from a larger number of trees even if fewer samples are taken per tree. Kralumer and Snodgrass (1967), Harris (1967) and Wolski (1965, 1968) devised suitable sampling techniques. Wolski recommended selection of sample trees based on D.B.H. and weighted according to frequency in each diameter class; he did not specify whether selection within a stratum should be subjective or objective. This method is commendable if the individual trees are randomly sampled, but requires complete enumeration of the stand.

A faster method is to estimate the number of trees required from an estimate of the population variance, and a specified allowable error, using the equation;

$$n = \left(\frac{ts}{e}\right)^2$$

where n = required sample size

t = Student's "t" value for small samples

s^2 = estimate of population variance of a variable

e = required precision of estimate of the population mean value.

McIntyre (1952) suggested a "ranked-set" sampling technique which requires a minimum number of samples and is easily applied in the field. Although developed originally for studies of pasture or annual crop yields, the method has good possibilities in studies of wood properties (McKinnell, 1970).

In the selected study area, evidence from growth data and observation suggested that Treatment 2 (15.0 to 21.9 m^2ha^{-1})

would not add appreciably to any comparison, so was excluded. In addition, two replicates of the control treatment were discarded because of severe wind damage.

From considerations of variability within the stands, previous experience and practicality, a total sample size of approximately 50 trees was thought adequate to give reliable information on growth and development under the different thinning treatments.

It was desirable for statistical reasons to sample a uniform proportion of the trees in the experimental treatments to be compared, rather than a uniform number of trees per treatment. The number of trees per plot varied from 9 in Treatment 1 to 73 in Treatment 6; consequently 10% of the trees in each plot were selected at random, though a minimum of two trees and a maximum of six trees per plot were specified. This resulted in the following distribution of sample trees - the total number of trees per replicate is given in brackets:

	Replicate				
Treatment	A	B	C	D	Total Sample
1	2	2	2	2	8
	(9)	(12)	(13)	(9)	(43)
3	2	2	2	2	8
	(24)	(20)	(22)	(20)	(86)
4	3	3	3	3	12
	(29)	(25)	(28)	(26)	(108)
5	4	4	4	4	16
	(40)	(36)	(38)	(44)	(158)
6	+	+	6	6	12
			(60)	(73)	(133)

+ Excluded from study because of wind damage.

The selection of sample trees was based on the 1962 emuneration of the D.B.H.O.B. of trees still standing in June 1970. The trees in each plot were arranged in descending order of diameter and then stratified into groups of equal size, the number of groups depending on the number of trees required per plot (cf. Wolski, 1965, 1968). One sample tree plus two reserve trees were then selected at random from each group.

All sample trees were inspected in the field in June 1970 when defective trees (double or multi - leaders, damaged trees, and trees with severe leans or sweeps) were replaced by one of the reserve trees. A total of 10 trees was replaced due to defect. An additional six trees were replaced on the selection list because the Forestry Commission considered their removal was silviculturally undesirable, bearing in mind the experiment was to be continued beyond 1970. This factor prevented the use of McIntyre's "ranked-set" method.

2.3 Sampling, Collection and Storage of Sample Material

Sample selection and collection were undertaken in July and August, 1970. During these months radiata pine in the Batlow area grows at a minimal rate and may be virtually dormant (W. Forrest, pers.comm.). The D.B.H.O.B. of each sample tree was measured before felling and the north point was marked on each bole at breast height.

After felling, the stem tips were reconstructed and the following parameters were measured:

(i) total height (m)

(ii) height from ground to lowest green whorl (defined as having a minimum of two live branches)

(iii) diameter overbark immediately below the lowest green whorl (cm)

(iv) diameter of each branch in each green whorl measured at a distance of 5cm from the junction with the stem (cm).

2.3.1 Sampling for Stem Profile Description and Wood Density

Sampling the wood properties of trees requires a knowledge of patterns of variation within trees and the factors affecting these properties. The general pattern in conifers is for density to increase from stem apex to base, and from pith to bark at any given height in the tree (e.g. Elliott, 1970a). In many earlier studies, the standard method of sampling was based on the removal of samples at fixed positions along the stem, but this does not take into account the systematic variation in wood properties along the stem as do the sampling systems described by Duff and Nolan (1953), Richardson (1961) and Balodis (1966).

Duff and Nolan (1953) described three sequences to represent variations in wood density patterns. The horizontal sequence traces the radial change in density from pith to bark, with each ring from the pith outwards produced by a cambium of increasing age. In the oblique sequence, an individual growth increment sheath is traced from stem apex to base with the cambial age increasing downwards. The vertical sequence traces density values down the stem, from internode to internode, at a constant number of rings from the pith.

Richardson (1961) recommended that wood density samples be located by reference to the number of internodes from the apex of the tree, and be taken from the centre of each internodal section. Where correct definition of internode age was difficult, he suggested sampling at fixed percentages of total tree height. Jacobs (1936) suggested a technique for identifying the growth stages in the crowns of mature radiata pine after felling, but this is usually laborious. In addition, the internodal positions are difficult to detect along the clean section of the bole.

The method of sampling wood density described by Richardson (1961) was found to be impractical because of problems in identifying the spring whorls. Sampling based on the percentile height system was necessary below the green crown so this method was extended to the whole stem. Sampling positions were defined at intervals along the stem of 4% of total tree height, from ground level to a point where the stem tapered to 10cm d.o.b. A disc was also taken from the 0.3m level in each tree. The number of positions varied from 23 for the largest trees to 20 for the smallest. The north datum mark was extended from B.H. to each sampling point so transverse disc sections (5cm thick) could be oriented correctly after cutting from the bole. An adjustment was made if a disc fell within 15cm of a whorl, branch, or evident branch scar (Shelbourne and Ritchie, 1968). In addition, a 5cm thick disc at breast height and a 1m log (from 3 to 4m above ground) were removed from each tree for the Division of Wood Technology, N.S.W. Forestry Commission. This affected the position of some discs.

All discs were placed in plastic bags and transported to the laboratory within three days of cutting. A radial bark-to-pith section of wood 1.2cm wide was cut from the north face of each disc for wood density studies and the rest of the disc was treated with P.C.N.B. (pentachloronitrobenzene) to prevent fungal attack during storage. Radial shrinkage of radiata pine grown in New South

Wales is about 2% from the green to the dry state (Booth, 1964): removal of the radial section gave the additional advantage that no checking resulted from loss of moisture during storage.

2.3.2 Crown Sampling.

Published data on sampling tree crowns indicate a minimum of about 60 branches is required to adequately describe the size and weight characteristics of tree crowns in a forest stand. In a study of Pinus echinata Mill., Loomis, Phares and Crosby (1966) sampled one branch from every fourth whorl in six trees growing in five different stand densities, which on average gave 60 branches per treatment. They achieved an error for predicted values of foliage weight of 5.1% at $p < .05$. Forrest and Ovington (1971) observed differences in weight and chemical content between radiata pine branch populations using only 40 branches, but in their study each population comprised genetically uniform cuttings so phenotypic variation was less than in the present study material. Hutnik and Hickok (1967) reported large sampling errors with a sample size of 20 branches per spacing treatment of Pinus resinosa.

In consequence, it was thought about 60 branches per treatment would be sufficient in this study to give an acceptable level of accuracy (about ±5%). Some stem foliage was present but its occurrence was relatively sparse. Because of the difficulties involved in sampling this foliage and applying regression methods, it was excluded from consideration.

The number of branch samples required per tree ranged from four to eight, depending on the number of trees sampled per treatment. The green crown was divided into an appropriate number of strata, containing equal numbers of whorls, and one branch was selected at random from each stratum. A two-dimensional matrix of branch diameter (1cm classes) against height sampled in tree (3m classes) was compiled for each treatment to ensure the selected branches adequately represented the range of branch sizes and positions within the canopy. A second or third choice was used if a matrix cell was already occupied. This procedure is valid for regression analysis since all branches were selected by size and position but without reference to foliage weight or the nature of the canopy at that position. Selected branches were cut flush with the stem, placed in heavy duty paper bags, then transported to the laboratory and stored at 2°C pending processing.

2.3.3 Processing Sample Material

Details of the methods used in processing and measuring the sampled material are described within the relevant chapters. Briefly, in addition to the field data described previously, various measurements were made in the laboratory on the sample branches and wood discs, namely:-

(i) branch samples - oven-dry weight of foliage by age classes

(ii) wood discs - stem analysis and six wood density parameters of each growth ring.

2.4 Data Analysis

The amount of field and laboratory data collected was voluminous. Computer facilities of both the A.N.U. Computer Centre (IBM 360/50 and UNIVAC 1108) and the Division of Computing Research, CSIRO, were used extensively to analyse them. Prepared programs, some of which required modification, were used for the more standard operations:-

(i) BASTATS (Sokal and Rohlf, 1969) was used to screen data before carrying out further statistical tests. The basic statistics used from the computer output were the coefficient of variation, and the Kolmogorov-Smirnov statistic, D_{max}, which compares the observed data with a normal distribution based on the sample mean and variance.

(ii) FACTO (Davidson, pers.comm.) performs principal component analysis and factor analysis.

(iii) A program described by Pluth (1971) was used to compute tree growth parameters from stem analysis.

(iv) LINREGR (McIntyre and Ward, 1970) is a linear regression program. Features include the testing of heterogeneity of slopes and intercept values of sets of regression lines.

(v) NO2FCT (McIntyre, 1970) computes a two-way factorial analysis of variance for non-orthogonal data.

CHAPTER 3

EFFECT OF THINNING ON CROWN STRUCTURE

The management of forests according to silvicultural principles requires a thorough understanding of the effects of thinning on crown morphology and crown-stem relationships. Tree growth, whether measured as dry matter production or crop volume increment, depends on the amount, distribution and relative efficiency of the foliage.

The crown characteristics of radiata pine in the study area are examined in this chapter and some interrelationships between stand density and parameters of the crown and stem are described.

3.1 Materials and Methods

3.1.1 Preparation of Foliage Material

The field collection of foliage was described in Chapter 2. The branchlets were stored at 2°C for about six weeks, then separated into three age classes - current or one-year, two-year, and three-year and over - and dried to constant weight at 85°C. The separation was according to the method described by Jacobs (1936). Some four-year and five-year-old needles occurred in the lower crown, particularly of trees in the more heavily thinned treatments, but their numbers were few and their weights were highly variable.

All dry weight data were adjusted by +8% to correct for losses due to respiration during storage. This adjustment was based on losses in dry weight of 7.6% recorded for radiata pine by Forrest (1968) and 10% suggested as an average weight loss for several conifers by Bray and Gorham (1964). Young foliage of radiata pine tends to have a higher moisture content and respire less than older foliage (Wood, 1969), therefore different dry weight adjustments might be valid for each age class. However, the available data are insufficient to justify such adjustment. Errors resulting from the use of a single correction factor will probably be small.

3.1.2 Forest Biomass Studies

Various methods employed in forest biomass studies have been described by Ovington and Madgwick (1959), Baskerville (1965) and Art and Marks (1971), among others.

Regression methods are commonly used in estimating biomass of foliage and other components; for this the choice of the most suitable model is important. Of the simple regression models (linear, exponential, allometric and hyperbolic) the allometric growth equation is the most widely accepted curve form for estimation of biomass. Huxley (1932) recognized the value of the function for describing the constant proportionality between the relative growth rates of two organs, or between the organ and the entire organism. The equation has the form:

$$\log_e Y = \log_e A + B \log_e X$$

where A denotes the initial size of the component, and the coefficient B is the ratio of the relative growth rates. Kittredge (1944) apparently was the first researcher to use the allometric equation in forestry. Since then foliage biomass and stem D.B.H. have been related by allometric regression in many studies.

Difficulties can occur in the use of the allometric equation e.g. Zar (1968) and Baskerville (1972) considered that use of the function commonly results in a systematic underestimate of biomass and they suggested methods to overcome the problem. Satoo (1966) overestimated foliage biomass by between 1% and 9% in stands of two different conifers using the allometric equation.

In the present study, the coefficient of determination was used to evaluate the most suitable mathematical model.

3.1.3 Data Analysis

The measured tree, crown and branch parameters were first screened using the BASTATS program (Chapter 2). This demonstrated the desirability of logarithmically transforming most data to fulfil the requirements for analysis of variance (Sokal and Rohlf, 1969). However, one parameter (the number of green whorls per tree) required a square root transformation, another (crown length ratio) an arcsin transformation, and two others (crown length and the number of green branches per tree) were left untransformed for optimum statistical presentation.

Separate analyses using Bartlett's test and the F-max test (Sokal and Rohlf, op.cit.) demonstrated homegeneity of variances, so the <u>a priori</u> test described by Sokal and Rohlf (p238) was used to test differences between treatment means of the individual crown and branch variables. Treatment combinations tested involved groups of two, three and four consecutive treatments respectively. The hypothesis was that for most variables the treatment means would grade from the most heavily thinned treatment to the "unthinned" control.

The weight of needles of each age class and the total weight of needles on each sample branch were related each in turn to branch cross-sectional area, using regression analysis techniques with both variables logarithmically transformed. Preliminary testing had indicated the allometric model was more suitable than the simple linear and exponential models.

The regression equations calculated to relate needle weights and branch sectional area were examined for trends between treatments in slope and intercept values. In some cases (e.g. 1-year-old foliage, Table 3.4) tests for homogeneity indicated that slopes did not differ significantly but significant differences between intercept values did occur. Data were pooled for those treatments which did not differ significantly and regression equations were recalculated.

The use of linear regressions with logarithmic terms follows the extensive experience in biomass studies, both for comparison between treatments and for summation of component weights. The problems associated with linear regression of logarithmically transformed variables have been discussed by Baskerville (1972). In this study the foliage weight per tree was estimated by summation of weights estimated for each branch. The lack of reliability of confidence limits calculated for such data (Keay and Turton, 1970; W. Müller, pers.comm.) remains unresolved.

Principal component analysis (Cooley and Lohnes, 1962; Seal, 1964) was used to test the overall relationship between various crown and stem parameters and to find the most useful variables for understanding intra-crown relationships. A matrix of correlation coefficients was generated for each pair of variables, and principal components were derived from this matrix so that each successive component accounted for the maximum amount of residual variance. The basic data, transformed to standard deviates from the mean because of the different units of measurement used for individual variables, and the eigenvectors from the first two principal components were combined to calculate two values for each tree (Norris, 1971). These values indicate the location of each tree in the optimum two-dimensional representation of the multidimensional space described by principal components. They are used to indicate differences between different thinning treatments and this might subsequently be confirmed by t-tests.

3.2 Results

The basic data for the results presented in the following sub-sections are summarized in Appendix 1.

3.2.1 Crown Parameters and Branch Characteristics

Analysis of variance indicates that three of the eleven crown variables are not affected by thinning, viz. total height, number of green whorls per metre of crown length and mean number of branches per whorl. Significant differences ($p < 0.01$) are evident between the number of green whorls per tree and mean branch diameter. The remaining six variables differ significantly at $p < 0.001$ (Table 3.1).

The regressions of crown length on stem D.B.H.O.B. indicate overall differences in slope and intercept ($p < 0.05$) between thinning treatments (Figure 3.1 and Table 3.2) but this results mainly from unusually short crowns in the smallest sample trees of Treatment 5. The regressions for Treatments 1, 3 and 4 are similar in both slope and intercept, while Treatment 6 has a significantly

TABLE 3.1

Effect of thinning on crown and branch variables[1]

	Trans-	Thinning Treatment					
Variable	form'n	1	3	4	5	6	Signif.
Total height (m)	$\log_e$	28.2	28.0	28.5	28.6	28.0	N.S.
Height to lowest green whorl (m)	$\log_e$	6.7	7.3	8.3	9.9	13.5	***
Crown length (m)	-	21.5	20.7	20.2	18.5	14.5	***
Crown length ratio	arcsin	.76	.74	.71	.64	.52	***
No. green whorls per tree	square root	41.9	46.2	44.3	36.3	32.9	**
No. green whorls per metre crown length	$\log_e$	2.0	2.2	2.2	2.0	2.3	N.S.
No. green branches per tree	-	205	231	220	184	164	***
No. green branches per whorl	$\log_e$	4.9	5.1	5.0	5.0	5.0	N.S.
Mean branch diameter (cm)	$\log_e$	2.2	1.9	1.9	1.7	1.6	**
Branch sectional area per tree (cm^2)	$\log_e$	1110	950	885	590	430	***
Mean branch sectional area (cm^2)	$\log_e$	5.5	3.9	4.0	3.3	2.7	***

---

[1] Figures given are the arithmetic equivalents of the means of the transformed variables.

Underlined values indicate non-significant differences at $p < .05$.

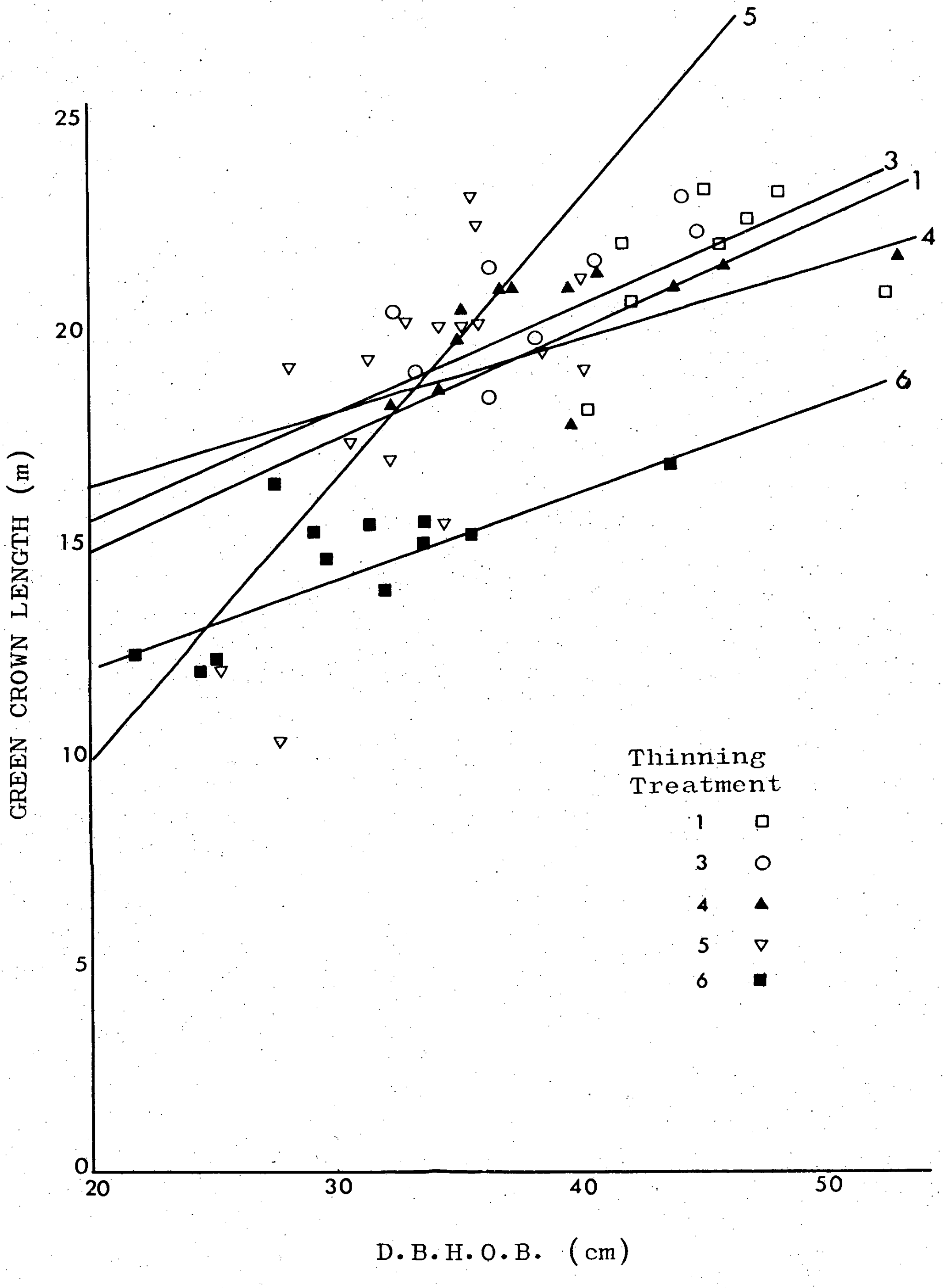


FIGURE 3.1 Relationship between green crown length and stem D.B.H.O.B.

smaller intercept.

The pattern of branch development within the green crown is shown in Figure 3.2. Branch diameter increases down the stem from the apex to approximately 60% of total tree height and then tends to stabilize. The large mean diameter of branches low in the crown of trees from Treatment 6 is due to one sample tree which was a "wolf" tree. The effect of thinning on branch diameter is most marked in the middle upper crown, corresponding to 50 - 80% of total tree height, where diameter decreases significantly with increasing stand density.

The distribution of branches by diameter class differs between thinning treatments (Figure 3.3). The proportion of branches in the $<$ 1cm diameter class increases with increasing stand density whereas in the 4cm class it decreases. The intermediate 1cm to 3cm classes are little affected by thinning treatment.

However, there is a strong relationship between branch size and tree bole size both within and between treatments. The relationship between total cross-sectional area of branches in the crown and cross-sectional area of the bole at the base of the crown is linear and is independent of stand density (Figure 3.4).

3.2.2 Foliage Distribution and Biomass

The foliage weight data, already separated into needle age classes for each tree, were further stratified into height classes based on percentile height (class intervals of 10% of total height).

Regression equations of the form:

Log_e needle weight = a + b $\log_e$ branch sectional area, were calculated for each height stratum, leaf age class and

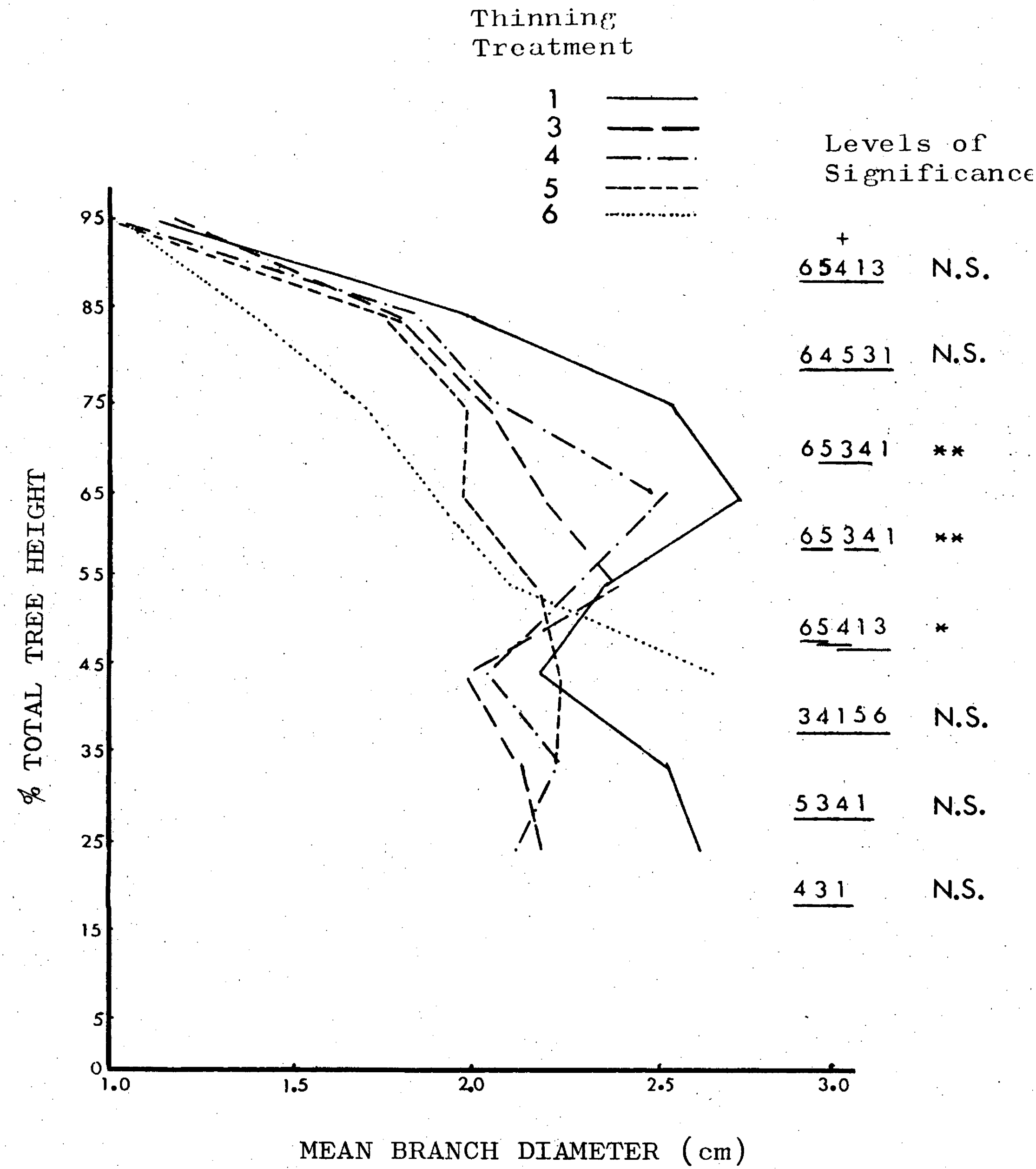
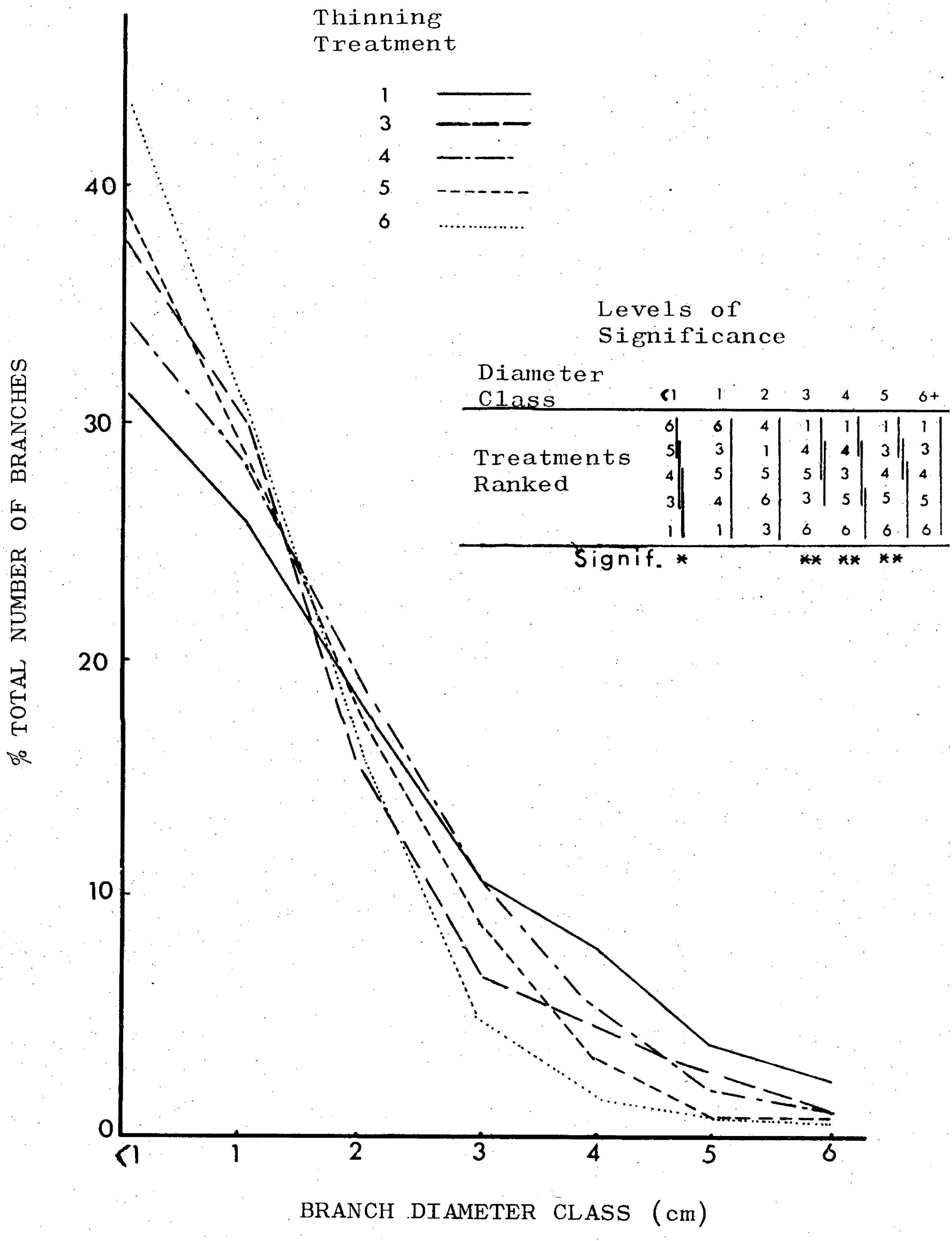


FIGURE 3.2 Variations in branch diameter within the green crown of 23-year-old radiata pine

\+ Underlined thinning treatments indicate no significant difference at $p < 0.05$



Diameter Class	<1	1	2	3	4	5	6+
Treatments Ranked	6	6	4	1	1	1	1
	5	3	1	4	4	3	3
	4	5	5	5	3	4	4
	3	4	6	3	5	5	5
	1	1	3	6	6	6	6
Signif.	*			**	**	**	

FIGURE 3.3 Distribution of branches by diameter class within the crown of 23-year-old radiata pine

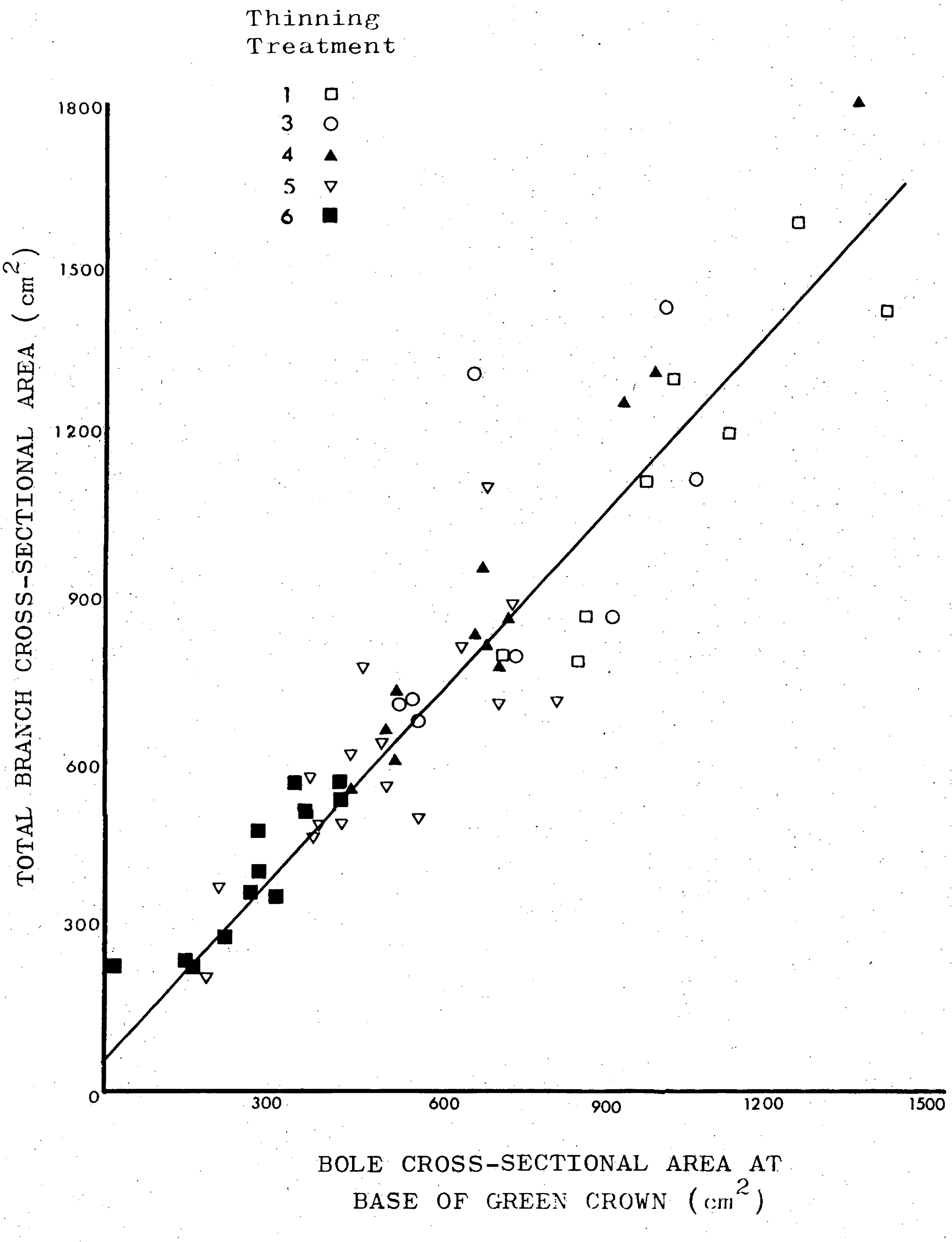


FIGURE 3.4 Relationship between total branch cross-sectional area in the crown and bole cross-sectional area at the base of the crown

TABLE 3.2

Linear regression coefficients of the relationship between green crown length and D.B.H.O.B. in 23-year-old radiata pine subjected to different thinning treatments

Thinning Treatment	b	$S.E._b$	a	r	Signif.
1	.440	.348	1.385	.46	N.S.
3	.462	.181	1.345	.72	*
4	.300	.123	1.903	.61	*
6	.479	.121	1.032	.78	**
5	1.164	.314	-1.187	.70	**
Combined	.786	.090	0.095	.77	***

thinning treatment. All regressions for each height stratum were independent of thinning treatment, so data were pooled by strata and common regression lines fitted for each foliage age class (Table 3.3). In some instances the regressions for adjacent strata were not significantly different so these were also combined. Generally the regression slope "b" is greatest at mid-crown level, least at the crown base, and decreases with increasing needle age.

Foliage weight by age classes within height strata was calculated by solution of the appropriate regression equation for each branch, and summing. The pattern of foliage distribution within the tree crown is presented in Table 3.4. Full data are given in Appendix 2.

The percentage of one-year-old foliage within a height stratum decreases from approximately 80% in the upper stratum to 35-40% in the mid and lower strata, whereas the percentage of two-year-old foliage tends to increase from approximately 20 to 35% with increasing depth in the crown. Three-year and older foliage is concentrated in the mid and

TABLE 3.3

Linear regression coefficients and constants for estimation of needle weight based on branch cross-sectional area as the independent variable. All treatments combined. Data stratified into 10% levels of total height (log:log transformation).

% Total Height	Foliage Age 1-yr b	 $S.E._b$	 a	 2-yr b	 $S.E._b$	 a	 3-yr and older b	 $S.E._b$	 a	 All ages combined b	 $S.E._b$	 a
90-100	1.017	.073	3.093	0.786	.175	1.954	-	+		1.075	.030	3.244
		(r = .90 ***)										
80-90	1.050	.042	2.803	1.066	.077	1.751	0.722	.128	1.260		(r = .91 ***)	
		(r = .92 ***)			(r = .87 ***)			(r = .65 ***)				
70-80				0.950	.074	2.372	0.665	.179	2.311	0.929	.075	3.685
					(r = .83 ***)			(r = .47 ***)			(r= .87 ***)	
60-70	1.167	.063	2.218	1.162	.059	1.904	1.192	.111	1.764			
		(r = .89 ***)			(r = .90 ***)			(r = .78 ***)				
50-60							1.051	.145	2.181			
								(r = .74 ***)				
40-50	1.099	.150	1.964	1.312	.144	1.405	1.192	.111	1.764	1.075	.030	3.244
		(r = .79 ***)			(r = .85)			(r = .78 ***)			(r = .91 ***)	
30-40	0.977	.170	2.247	0.992	.074	2.271	1.399	.360	1.126			
		(r = .73 ***)			(r = .77 ***)			(r = .71 ***)				
20-30	0.746	.238	3.127	0.502	.121	3.456	0.662	.417	2.927			
		(r = .79 **)			(r = .86 **)			(4 = .54 ***)				

lower strata where it comprises approximately 30% of the foliage weight.

TABLE 3.4

Percentage distribution of needles within height strata in the crown of 23-year-old radiata pine. All treatments combined.

% Total Height	Foliage Age 1-year Mean	S.D.	2-year Mean	S.D.	3-year & older Mean	S.D.
90-100	77.6	2.2	22.4	2.2	-	-
80-90	67.3	0.8	24.3	0.5	8.4	1.3
70-80	56.6	3.1	26.7	0.3	16.7	2.8
60-70	41.7	0.1	30.2	0.2	28.1	0.6
50-60	40.2	0.8	29.1	0.5	30.7	1.3
40-50	35.5	1.4	30.1	1.5	34.4	0.0
30-40	37.1	1.6	35.8	2.1	27.1	3.6
20-30	38.0	2.3	35.1	2.7	26.9	0.4

Trees in the most heavily thinned treatments carry a greater weight of their foliage high in the crown than do trees in lightly thinned stands (Figure 3.5). The estimated percentage of needles above 70% of total tree height in the five thinning treatments ranged from 34% in Treatment 1 to 55% in Treatment 6 (Appendix 3). On the other hand, no foliage occurred below 40% of total tree height in the "unthinned" control: corresponding values in the thinned treatments ranged from 7% in Treatment 5 to 13% in Treatment 1. These trends are further illustrated in Figure 3.6 which shows the distribution in 1970 of needles on trees belonging to the same stem diameter class in 1962 before thinning treatment was applied. The combined weight of one and two-year-old foliage in the crown appears to be unaffected by thinning treatment and ranges from 77% to 80% (Appendix 3).

The crown biomass was estimated by summing the foliage weights in each height stratum to give the weight of foliage in each age class and the combined weight for

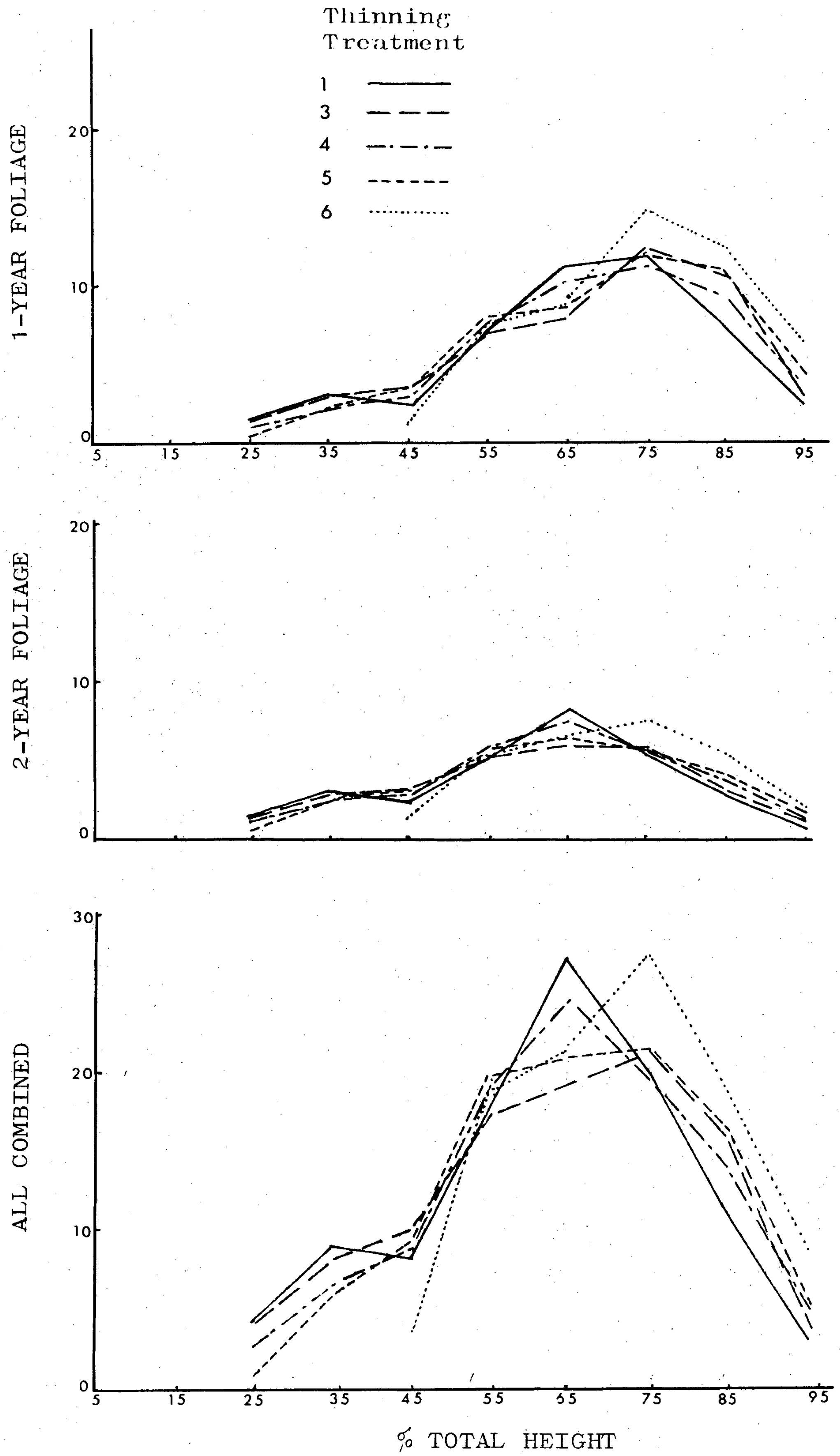


FIGURE 3.5 Distribution of needles in the crown of 23-year-old radiata pine

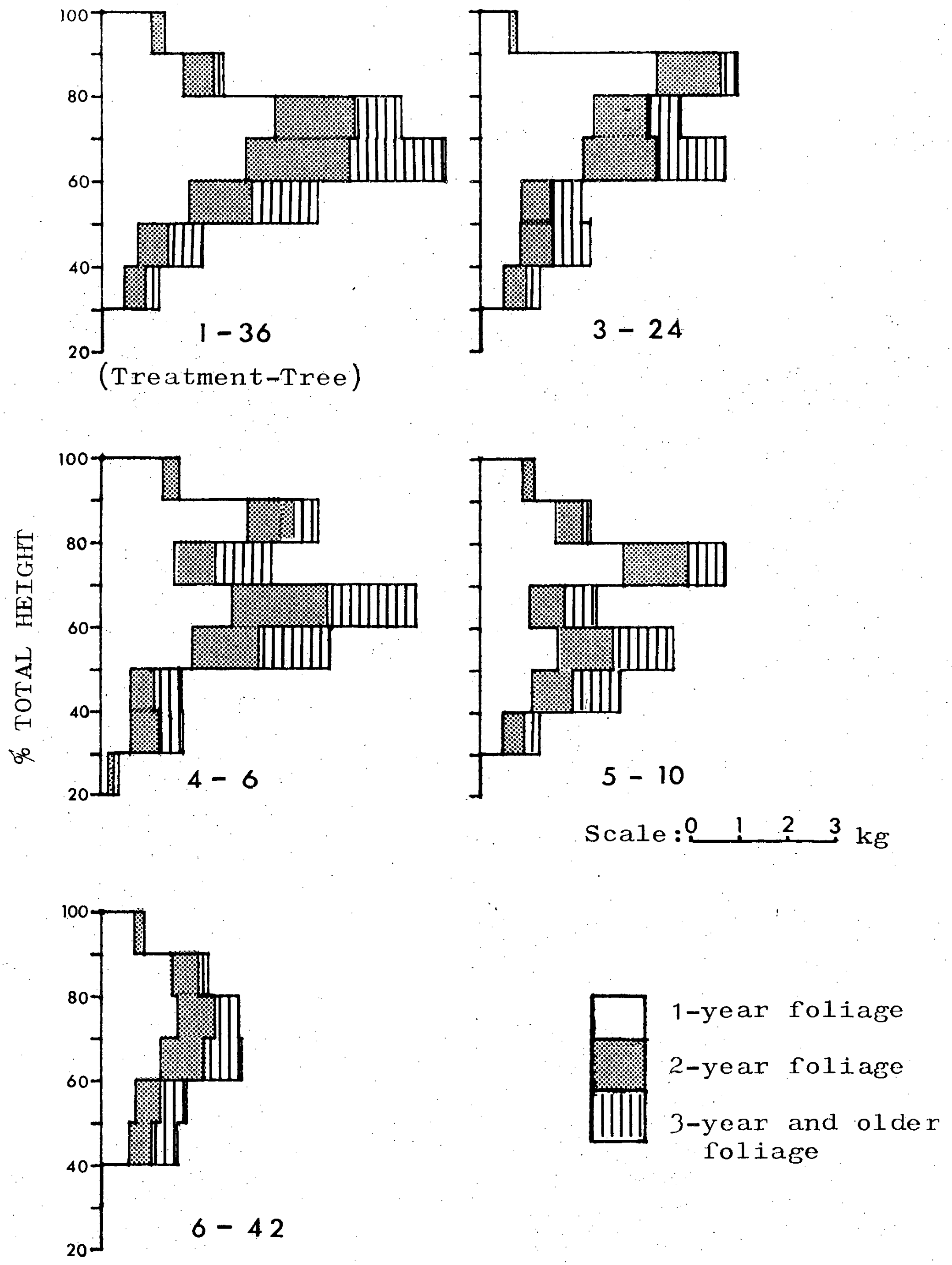


FIGURE 3.6 Distribution in 1970 of foliage in the crown of trees in the 22.0-23.9 cm stem diameter class in 1962

the individual tree (Appendix 4). These estimates were then related to various stem parameters as independent variables to find the most suitable variable for predicting foliage biomass per hectare e.g. D.B.H.O.B., D_B, D.B.H.O.B. x HEIGHT and B.A. x HEIGHT. Each was related to total crown foliage weight using the allometric growth equation. The coefficients of determination indicate that, overall, D.B.H.O.B. is the best predictor of foliage weight, followed by B.A. x HEIGHT (Table 3.5). The former variable was selected to estimate foliage biomass because its value was known for all trees in the study area, having been measured by the N.S.W. Forestry Commission in 1970.

TABLE 3.5

Coefficients of determination (r^2) relating total weight of foliage to various stem parameters

	Thinning Treatment					
Variable	1	3	4	5	6	Combined
D.B.H.O.B.	.83	.78	.90	.51	.93	.88
D_B	.83	.75	.93	.49	.94	.86
D.B.H.O.B. x HT	.88	.74	.83	.54	.92	.85
B.A. x HT	.87	.76	.86	.53	.93	.87

The regression lines for each foliage age class in the various thinning treatments had homogeneous slopes and intercepts so the data for each foliage age class were pooled (Table 3.6).

TABLE 3.6

Linear regression coefficients and constants for estimating foliage biomass at different stand densities, based on D.B.H.O.B. as the independent variable (log:log transformation)

Foliage Age	b	$S.E._b$	a	r	Signif.
1	2.286	0.107	-5.859	.95	***
2	2.593	0.123	-7.525	.95	***
3+	2.698	0.142	-8.162	.94	***
Total	2.459	0.114	-5.780	.95	***

The D.B.H.O.B. of each tree in the study area was substituted into the relevant equations to derive tree foliage weight.

The data were then summed to give foliage biomass by age classes within each treatment (Table 3.7).

TABLE 3.7

Estimates of foliage biomass (tonnes ha^{-1}) for radiata pine growing under a range of stand densities

Thinning Treatment	Stand Density ($m^2 ha^{-1}$)	Foliage Age 1-yr	2-yr	3-yr	All foliage[1]
1	11.5-18.4	1.88	1.15	0.91	3.95
3	18.4-25.3	2.64	1.54	1.19	5.38
4	23.0-29.8	3.21	1.86	1.45	6.54
5	27.5-34.4	3.52	1.97	1.51	7.02
6	Control	4.55	2.45	1.86	8.89
	L.S.D.	0.09	0.06	0.05	0.21

[1] The figures for all foliage differ slightly from the sum of those of the individual age classes because logarithmic transformations were used in the predicting regression equations (Kozak, 1970)

An analysis of variance on the estimates of foliage biomass of each age class and total weight, combined with L.S.D. tests (Sokal and Rohlf, 1969), showed that each successive pair of thinning treatments are significantly different at $p < 0.05$.

3.2.3 Interrelationships

The interrelationships between various stem, branch and foliage variables for all treatments combined were investigated by principal component analysis. This form of analysis has the advantage that the complex relationships between the many variables describing crown structure can be viewed in perspective. The correlation matrix based on all data, logarithmically transformed, was constructed using every possible combination of two variables (Table 3.8).

TABLE 3.8

Matrix of correlation coefficients between crown, branch, foliage and stem variables.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Total height	1	1.00	-.05	.46	.24	.30	-.06	.16	-.28	.43	.47	.50	.50	.49	.50	.50	.52	.47
Ht lowest whorl	2		1.00	-.88	-.95	-.52	.24	-.54	-.04	-.50	-.71	-.52	-.65	-.69	-.69	-.67	-.63	-.78
Crownllength	3			1.00	.97	.62	-.22	.58	-.09	.59	.82	.63	.77	.81	.82	.80	.77	.88
Crown length ratio	4				1.00	.60	-.22	.59	-.03	.53	.78	.56	.71	.76	.77	.74	.70	.84
Green whorls /tree	5					1.00	.62	.84	-.32	.04	.50	.09	.47	.47	.48	.47	.45	.53
Whorls/metre crown length	6						1.00	.46	-.32	-.53	-.19	-.50	-.18	-.22	-.21	-.20	-.19	-.21
Green branches/ tree	7							1.00	.22	-.03	.53	.04	.51	.50	.51	.51	.42	.52
Mean branches/ whorl	8								1.00	-.08	.07	-.07	.04	.01	.00	.02	-.07	-.04
Mean branch diam.	9									1.00	.82	.98	.80	.81	.80	.81	.81	.77
Total branch sect. area	10										1.00	.86	.97	.80	.97	.98	.93	.95
Mean branch sect. area	11											1.00	.86	.97	.86	.87	.86	.82
Wt 1-yr foliage	12												1.00	.98	.98	.99	.95	.94
Wt 2-yr foliage	13													1.00	.99	1.00	.94	.95
Wt 3-yr + foliage	14														1.00	.99	.93	.94
Total wt foliage	15															1.00	.95	.94
D.B.H.O.B.	16																1.00	.96
D_B	17																	1.00

Levels of significance
$p = 0.05$ .27
$p = 0.01$ .35 (d.f. = 54)
$p = 0.001$ .44

TABLE 3.9

Eigenvalues and associated eigenvectors derived from correlation coefficients between crown, branch, foliage and stem variables

Principal Components	I	II	III	IV	V
Eigenvalues	10.98	2.61	1.53	0.99	0.59
Cumulative % eigenvalues	64.6	80.0	88.9	94.8	98.1
% eigenvalue in each component	64.6	15.4	8.9	5.9	3.3
Total height	-.15	-.03	-.49	.19	-.75
Height lowest whorl	.24	-.11	-.33	.24	-.03
Crown length	-.27	.11	.09	-.30	-.32
Crown length ratio	-.26	.13	.23	-.37	-.15
Green whorls per tree	-.16	.15	-.13	-.06	.02
Whorls per metre of crown length	.07	.52	-.27	.22	.35
Green branches per tree	-.16	.47	.22	..26	-.11
Mean branches per Whorl	.01	-.11	.64	.56	-.21
Mean branch diameter	-.24	-.32	-.12	.04	.19
Total branch sectional area	-.30	-.02	.02	.14	.01
Mean branch sectional area	-.26	-.30	-.12	.01	.18
Wt. 1-yr foliage	-.29	-.03	.03	.20	.12
Wt. 2-yr foliage	-.30	-.03	-.02	.13	.09
Wt. 3-yr + foliage	-.29	-.02	.02	.12	.07
Total wt. foliage	-.29	-.03	-.03	.16	.10
D.B.H.O.B.	-.29	-.05	-.11	.11	.12
D_B	-.30	.01	.01	-.03	-.02

Five principal components were derived from the matrix, accounting for 98.1% of the total variation (Table 3. 9). The eigenvectors with the largest values in each component indicate which variables contribute most to that component. In Component I, total branch cross-sectional area, foliage weights, D_B and D.B.H.O.B. are the major contributors. The number of green whorls per metre of crown length, the number of whorls and number of branches per tree have most effect on Component II. Overall, the weight of foliage of each age class and total foliage weight per tree together with total branch sectional area and D_B are more strongly interrelated than are crown length, height to the lowest green whorl and crown length ratio.

The effect of thinning on the interrelationship of variables was assessed by combining eigenvectors and the basic data to calculate standard deviates from zero mean (Norris, 1971). The location of each tree in the best two-dimensional representation of the space described by the principal components, together with the mean position for each thinning treatment, are plotted in Figure 3.7. Most variation occurs in Component I, with differences obvious between each successive pair of thinning treatments with the exception of Treatments 3 and 4 (18.4-25.3 and 23.0-29.8 m^2ha^{-1} respectively). T-tests confirm that Treatments 3 and 4 are similar but all other pairs of treatments differ at $p < 0.05$. There are no significant differences between successive pairs of treatments with Component II (Table 3.10).

The conclusion reached is that thinning treatment affects the interrelationship of variables such as total branch cross-sectional area, foliage weight, D.B.H.O.B. and D_B.

3.3 Discussion

The observed negligible effect of thinning on tree height growth is well known (e.g. Dell and Collicott, 1968;

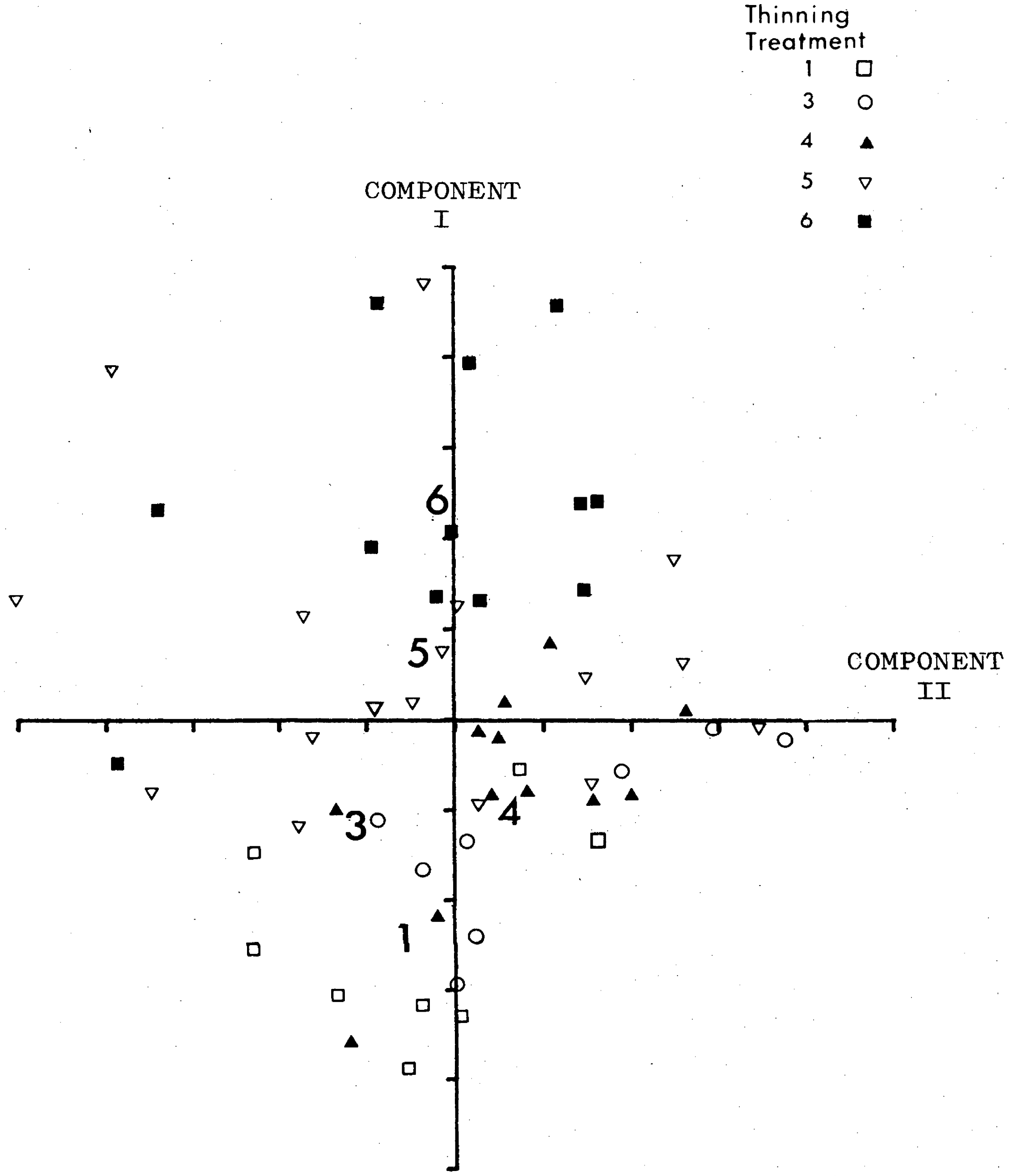


FIGURE 3.7 Relationship between the first and second principal components of crown, branch and stem variables

TABLE 3.10

T - tests between thinning treatments of coefficients derived from principal component analysis

Thinning Treatment	Component I	Component II
1, 3	-2.21 *	-1.94 N.S.
3, 4	-0.27 N.S.	0.58 N.S.
4, 5	-3.11 *	1.33 N.S.
5, 6	-2.63 *	-0.31 N.S.

Van Laar, 1969). Analysis of the variables height to the lowest green whorl, green crown length, and crown length ratio indicates that crown development is similar at stand basal areas ranging from 11.0 to 29.9 m^2ha^{-1} (Treatments 1, 3 and 4), whereas significant differences exist between thinning treatments with basal area ranges of 23.0-29.9 m^2ha^{-1}, 27.6-34.5 m^2ha^{-1} and the control (Treatments 4, 5 and 6). The basal area limits given are nominal. The actual upper limits for Treatments 4, 5 and 6 were 31.7, 35.6 and 46.0 m^2ha^{-1} respectively.

Beekhuis (1965) developed regression equations for predicting crown length from stocking data (stems per acre) in New Zealand-grown radiata pine. Substituting the stockings of each thinning treatment in the Green Hills trial into Beekhuis's equation (crown depth = 358.83 / N + 24.0 feet, where N is the stocking in stems per acre) gave fair predictions of crown length (Table 3.11) considering that the equation is general for New Zealand and that factors such as age, site quality, total height and ground slope affect crown length (Beekhuis, 1965; Kramer, 1966).

Crown length ratio (syn. crown percent) has received considerable attention in the literature. Loomis _et al._ (1966) found the ratio in _P. echinata_ varied from .55 to .35 in stands covering a range of stand densities comparable to the range covered in this study. However, the ratio for radiata pine at Green Hills varied from .76 in Treatment 1 to .52 in the control. Presumably species differences and the factors mentioned by Beekhuis (1965) and Kramer (1966) account for the absolute difference in the ratio.

TABLE 3.11

Comparison of observed and predicted crown lengths

	Thinning Treatment				
	1	3	4	5	6
Stocking (trees ha^{-1})	108	215	270	390	665
Measured crown length (m)	21.5	20.7	20.2	18.4	14.5
Predicted crown length (m)	23.9	19.1	17.8	16.1	14.0
Difference (%)	11.2	7.7	11.9	12.5	3.4

The number of green whorls produced per metre of green crown length and the number of green branches per whorl appear to be independent of thinning treatment (Table 3.1) as might be expected because both parameters are under strong genetic control (Fielding, 1960; Forrest and Ovington, 1971). The number of whorls on the annual shoot apparently is not influenced greatly by site differences (Fielding, 1960).

The influence of thinning on branch size is confined mainly to the 50-80% zone of total tree height. Branches in this zone in the most open stands receive full sunlight in contrast to the branches in the densest stands which are shaded. In the lower crown the branches would have developed under uniform conditions, that is, the conditions prevailing before the first thinning treatment was applied. The branches above the 80% level of total height are free of competition for light irrespective of treatment.

The highly significant relationship between cross-sectional area of all branches in the tree and the cross-sectional area of the bole at the base of the green crown, independent of thinning treatment, supports the findings of Jacobs (1938) for radiata pine. Similar results have been observed for trees with markedly different growth habit e.g. in Eucalyptus obliqua L'Hérit. (Curtin, 1970).

Needle weight and branch cross-sectional area were significantly related, irrespective of thinning treatment, at similar levels of the green crown. A single regression equation described the relationship between total foliage weight and branch sectional area in seven of the eight strata containing green branches.

Hall (1966) found that branches low in the crown of P. resinosa carry less weight of foliage than similar-sized branches higher in the crown because of needle shed. This is not the case for radiata pine. A primary branch low in the crown is older and has more orders of branchlets than a similar-sized branch in the upper crown. In the present study, the older branches have greater numbers of branchlets, which appears to compensate for the lesser weight of foliage on each branchlet. Consequently, position in the crown does not affect the weight of foliage carried by a branch of given size (Table 3.4). Although the "b" values for one-year and two-year-old needles decrease in the lower crown, which would support Hall's conclusions, as mentioned previously the intercept values must be considered as well when foliage weights are calculated.

Differences in weight of foliage both between height strata within trees and between trees growing at various stand densities apparently result from variation in branch diameter, as the number of branches within each stratum is independent of thinning. The amount of foliage produced on a branch in one season is influenced by branch age and the amount of light received. Branch size reflects the history of foliage growth. The concentration of foliage in the upper mid-crown of trees in this study (Figure 3.6) appears related primarily to a continuing full sunlight condition over several years, particularly in the more heavily thinned treatments.

Madgwick (1968) proposed a model to explain foliage distribution in P. resinosa crowns, viz., under conditions of free growth, the weight of needles in a whorl increases exponentially with time. However, with shading, as occurs in forest stands, branch apical growth is restricted, and individual needle development is less. The weight of a one-year-old needle at the canopy base is commonly only 40-45% of the weight of a needle near the crown apex. Wood (1969) found the length, width, surface area and weight of radiata pine needles of one age increased up the stem, and at any level in the crown these same parameters increased with needle age. In the present study the weight of individual needles might vary considerably between height strata, but no empirical data on needle morphology were collected.

There are few published data on the relative contribution of needles of different age classes to the total weight of foliage in tree crowns of Pinus species. In the present study, one and two-year-old foliage comprised 78% of the total foliage overall. Wood (1969) found in a total sample that these two age classes comprised 82% of the foliage in a six-year-old tree of radiata pine. Studying P. resinosa, Madgwick (1962) and White (1964) estimated that the two age groups comprised approximately 80% of total foliage, whereas Hall (1966) reported 63% for the same species. Hall found needles up to eight years of age in the three trees he studied. In radiata pine needles older than five years do not occur. This species difference could account for the different results.

In forest biomass studies, weight of the various tree components is commonly related to an easily-measured stem variable for predicting biomass. The best predictor of foliage weight in the crown in the present study was D.B.H.O.B. (cf. Weetman and Harland, 1964; Baskerville, 1965), which was superior to D_B, B.A. x HEIGHT and D.B.H.O.B. x HEIGHT (Table 3.4).

Loomis et al. (1966) found the stem diameter at the base of the green crown, D_B, was the best predictor of foliage biomass, but D_B is difficult to measure compared to D.B.H.O.B.. The parameters B.A. x HEIGHT and D.B.H.O.B. x HEIGHT were considered most suitable by Forrest and Ovington (1970) and Young, Strand and Altenberger (1964) respectively.

The relationships between either total foliage biomass and tree D.B.H.O.B. and foliage weight by age classes and D.B.H.O.B. in this study were both unaffected by thinning treatment. The "b" value of 2.46 for the total foliage equation is consistent with values reported in the literature. Forrest (1969) estimated "b" values of 1.70 and 3.32 for a five-year and a 12-year-old stand respectively of radiata pine, while Ovington and Madgwick (1959) reported a value of 3.60 for a 33-year-old P. sylvestris stand.

The increase in foliage biomass with increase in stand density suggests that the heavily thinned stands are not fully utilizing the site. This is substantiated by the observation at the time of sampling that undergrowth was absent only from the plots of the control treatment.

Möller (1947) proposed the classic theory that within a wide range of stand densities the amount of foliage of a given species remains constant with age and differs little with site. This proposal has been substantiated by many researchers working in diverse forest types, including Senda and Satoo (1956), Ovington (1957) and Hutnik and Hickok (1967).

Möller (1947) showed constant foliage biomass of *Picea abies* (L.) Karst. and *Fagus sylvatica* L., the latter in 50-year-old stands at basal areas ranging from 18 to 35 $m^2 ha^{-1}$. This range corresponds with that of Treatments 3 to 5 in the present study, where foliage biomass increased significantly with increase in stand density. Baskerville (1965) found with *Abies balsamea* and other species that foliage biomass increased with increasing stand density.

Madgwick (1970) found in *P. resinosa* that very heavy stocking (more than 5000 s.p.ha) significantly decreased stand biomass of one-year-old and total needles. This stocking is considerably greater than any in the present study.

The foliage biomass and annual foliage production estimated in this study are compared with selected results from other studies of *Pinus* species (Table 3.12). The maximum estimate for foliage biomass of 8.9 tonnes ha^{-1} is slightly less than the weights estimated by Will (1964) and Forrest and Ovington (1970) of 9.0 and 9.2 tonnes ha^{-1} respectively for 12-year-old stands of radiata pine. Will (1964) gave no estimate of stand basal area. The stand studied by Forrest and Ovington (1970) had a basal area of 32.9 m^2ha^{-1}, equivalent to Treatment 5 in this study, though 11 years younger. Forrest and Ovington considered that after the 10th year foliage biomass was fairly constant from year to year at just less than 10 tonnes ha^{-1}, with possibly a very gradual decrease with time.

TABLE 3.12

Foliage biomass and annual foliage production in plantations of *Pinus* species (tonnes ha^{-1} and tonnes $ha^{-1}yr^{-1}$ respectively)

Species	Biomass	Annual Production	Reference
P. sylvestris L.	-	2.9	Ovington (1957)
"	5.0	-	Möller (1947)
"	7.3	-	Ovington and Madgwick (1959)
P. densiflora Sieb. & Zucc.	-	1.7	Maruyama and Satoo (1953)
"	5.4	-	Satoo *et al.* (1955)
P. radiata (7yr)	11.2	4.8	Forrest and Ovington (1970)
" (9yr)	8.4	1.5	"
" (12yr)	9.2	3.0	"
" "	9.0	-	Will (1964)
" (23yr)	8.9	3.5[1]	Present study-control

[1] Assumes the mean weight of one- and two-year-old foliage is equivalent to annual production

The estimated annual foliage production was based on the mean values of one and two-year foliage to overcome the problems involved in sampling foliage produced in a single year (Madgwick, 1970). This estimate may differ from the actual annual production because it does not take into account factors such as any decline in the weight of individual needles at the end of the growing season, losses due to insects or physical damage, as well as the year to year variation in foliage production referred to earlier

(Bray and Gorham, 1964).

The relative efficiency of foliage in the different thinning treatments was briefly examined by relating foliage biomass of each sample tree both by age class of foliage and all age classes combined to total stem volume increment from 1968 to 1970 (Table 3.13); the estimation of the latter is being described in Chapter 4. Tests of homogeneity of slope and intercept indicated that thinning had no effect on the relationship between either the foliage of each age class or the total foliage with the total stem volume increment for 1968 to 1970.

TABLE 3.13

Linear regression relationships between stem volume increment (1968-1970) and foliage weight per tree. All thinning treatments combined and log:log transformation.

Foliage Age	b	$S.E._b$	a	r	Signif.
1	1.151	.074	-4.020	.90	***
2	1.018	.065	-3.144	.91	***
3	0.964	.062	-2.793	.90	***
Comb.	1.079	.067	-4.611	.91	***

Assessment of the interrelationships between crown, branch, foliage and stem variables by using principal component analysis confirms different relationships previously recorded in the literature. For instance, Fielding (1960) and Bannister (1962) noted a significant relationship between total number of green whorls and stem D.B.H.O.B. for Australian and New Zealand-grown radiata pine respectively. In this study green crown length is correlated to total foliage weight at $p < 0.001$ (cf. Senda and Satoo, 1956; Curtin, 1968), but D.B.H.O.B. and D_B have larger correlation coefficients when related to foliage weight.

In general, the principal component analysis indicates that thinning of radiata pine has a significant effect not only on individual variables, but also on the manner in which they are interrelated. The foliage biomass of the individual tree is closely related to the cross-sectional area of the branches and measures of stem dimensions, indicating the importance of the crown-stem relationship.

CHAPTER 4

EFFECT OF THINNING ON STEM FORM

The terms form and taper have been used frequently to describe the same concept (e.g. Larson, 1963a) and this has lead to confusion. Form refers to the shape of the tree stem and taper to the rate of decrease in diameter with increase in height up the stem (Gray, 1956; Ford-Robertson, 1971).

Knowledge of the stem form of forest trees and of the manner in which stems taper is important in many branches of forestry including mensuration, utilization, tree breeding and silviculture. Larson (1963a), in his review of stem form development, commented that the most controversial aspect from the forest management viewpoint is the degree to which silvicultural operations can alter stem form.

Any effect of thinning on the form and taper of radiata pine stems might have considerable significance for mensuration and utilization. Although Gray (1956) studied the relationship between height within the tree and stem cross-sectional area of more than three hundred stems of the species, he did not compare the form and taper of stems growing under different stand densities.

4.1 Stem Form Theories

Larson (1963a) discussed in detail the four general stem form theories - nutritional, water conduction, mechanistic and hormonal. He considered the hormonal theory of spatial and temporal variation in auxin gradients up the stem offers the most promising approach to the stem form problem, whereas Hall (1965) suggested the hormonal and nutritional theories in combination provide a satisfactory explanation. Duffield (1968), on the other hand, favoured a combination of the hormonal and mechanistic theories (which he termed a "dynamic hypothesis") as being more realistic than any single theory. He pointed out that researchers only recently have come to appreciate the relationship between stem form and wood structure.

Assmann (1970) made a basic division of the stem form theories into "physiological" theories based on the function of water and sap conduction processes, and "mechanical" theories. He considered that no individual theory can provide a satisfactory explanation for stem shape because each is based on only one stem function and, under constantly changing environmental conditions, stem form must fulfil all functions. Assmann suggested that reactions to mechanical stresses have the major influence.

The nutritional and water conduction theories do not lead to any assumptions regarding the specific shape of the stem (Carron, 1968). Similarly, the hormonal theory provides a physiological explanation of tree growth and differences in taper, but does not specify the particular shapes trees might have under varying circumstances. The mechanistic theory does suggest a specific stem shape. This theory, proposed by Metzger and described in Büsgen and Münch (1929) considers the stem as a cantilever beam of uniform resistance against bending forces caused by wind, and requiring the dimensions of a cubic paraboloid. Gray (1956) maintained this shape is required only if the tree is imbedded in material sufficiently strong to ensure that attachment at the stem base will resist forces greater than those necessary to break the stem. As roots are usually imbedded in relatively weak material, Gray suggested the quadratic paraboloid is more realistic.

While the stem form theories were being proposed to explain how a tree grows and the cause of variations in tree shape, empirical evidence on shape was gathered by researchers such as Jonson (1910-1912), Wright (1927) and Behre (1927). These workers sought to describe the profiles of conifers by formulae termed stem profile equations. One major problem was that the formulae derived only applied above buttswell. Their application was difficult if buttswell extended above breast height. Petrini (1921), recognizing that two major points of inflection occur in the conifer stem (one in the crown and one in the butt region), has emphasized that the compound nature of tree profiles can only be described accurately by developing separate expressions for the upper crown section, the main bole and the buttswell region.

4.2 Materials and Methods

The selection of sample trees and the method of collecting wood discs were described in Chapter 2.

Methods of stem analysis are described in the literature (e.g. Jerram, 1939; Chapman and Meyer, 1949; Husch, 1963). The technique described by Jerram (1939) to reconstruct the growth history of sample trees has the disadvantage that estimating mean diameter of a disc from two measurements taken at right angles to each other assumes a centrally located pith. Eccentric discs and circular discs with off-centre pith are not uncommon and, for these, the intersection of the maximum and minimum diameters may not coincide with the pith. To overcome this problem, Chapman and Meyer (1949) estimated the mean radius of the disc from the maximum and minimum diameters then, measuring from the pith, they located the two points on the circumference at a distance from the pith equivalent to the mean radius. The lines joining these points to the pith are used as the axes for ring measurements. This method was used in the present study.

The discs were air-dried before stem analysis. Some radial shrinkage, less than 2% (Booth, 1964), would have occurred but no correction was made as comparative measurements are more important than absolute figures in this instance.

A general equation for the profiles of the set of solid bodies approximated by tree stems is:

$$y^2 = k\,x^b \qquad \text{(Whyte, 1971)}$$

where k = a constant

y = radius of cross-section at x

x = distance from apex.

The exponent "b", the stem form index, determines the way the solid tapers i.e. its shape, and "k" determines the rate of taper within this shape. For a cylinder, $b = 0$; for a quadratic paraboloid, $b = 1$; for a cone, $b = 2$; and for a neiloid, $b = 3$.

Logarithmic transformation of the general equation gives $\log_{10}(y^2) = \log_{10}k + b \log_{10} x$. The exponent "b" is now given by the slope of the linear regression line and "k" is derivable from the regression constant.

However, as "k" determines the rate of taper within a given shape, it is invalid to use it as a measure of taper in comparing the effects of thinning if shape has also changed in the period under study. As results indicate that stem shape was a second degree paraboloid in more than

80% of the stem profiles examined (Appendix 5), that is, sectional area plotted against height up the stem is linear, an alternative method of assessing change in taper with time is to assume that the boles of all trees are second degree paraboloids and use the slope "b" of the linear regression line as the index of taper, namely:

Height in tree = a + b (Diameter^2).

Although by definition taper is the rate of decrease of diameter per unit increase in height, height is used as the dependent variable in this study to allow visualization of the standing tree (Appendix 6).

Preliminary plotting indicated that buttswell effects in most trees extended to a height of approximately 2.5 m from ground level, therefore data from the lowest three discs were excluded from analysis.

The indices calculated for stem form and taper were screened and found to be homogeneous and normally distributed. A two-way factorial analysis of covariance was made using the program NO2FCT (McIntyre, 1970) to test the effect of thinning and of stem diameter class on the indices of form and taper, and to find if any interaction occurred between treatment and size class.

The *a priori* tests for comparisons among means (Sokal and Rohlf, 1969, p228) were used to detect significant changes in stem taper with time from before treatment (average of 1961 and 1962 values) to 1970 inclusive.

The stem analysis data for each tree were processed using a modified version of the program described by Pluth (1971). A second degree parabolic model was substituted into the program for computing tree volumes, as this model was suggested by the results presented in Appendix 5.

4.2 Results

Average stem form index was similar in all stands prior to thinning in 1962 at the end of the 1961-62 growing season (Table 4.1, Appendix 5), more than 70% of the trees sampled having a shape best described by a second degree paraboloid; the remainder were closer to conoidal. By 1966, significant changes in stem form had developed between thinning treatments and the differences tended to increase with time (Table 4.1, Figure 4.1).

Form did not vary significantly with stem diameter class either before or after thinning (Table 4.1) although data suggest a slightly decreasing stem form index with decreasing stem size (Figure 4.2). No interaction between thinning treatment and diameter class occurred.

Thirty of the sample trees retained their original shape throughout the 10-year period (Appendix 5). The remaining trees except one changed from a conoidal to a second degree paraboloidal shape. Tree 31 changed from a second degree to a third degree paraboloid. In assessing these changes, a stem form index 1.5 was arbitarily selected as the boundary between the conoidal and second degree paraboloidal shapes, and 0.83 as the boundary between second degree and third degree paraboloids. A small variation in the index value could therefore affect the classification of shape and this has to be kept in mind when interpreting the data.

Average stem form index decreased with time in the least heavily thinned treatments and the control, shape approaching closer to a second degree paraboloid as the stands aged. In the more heavily thinned treatments, average stem form index remained more or less constant with time after treatment (Figure 4.1), the average stem

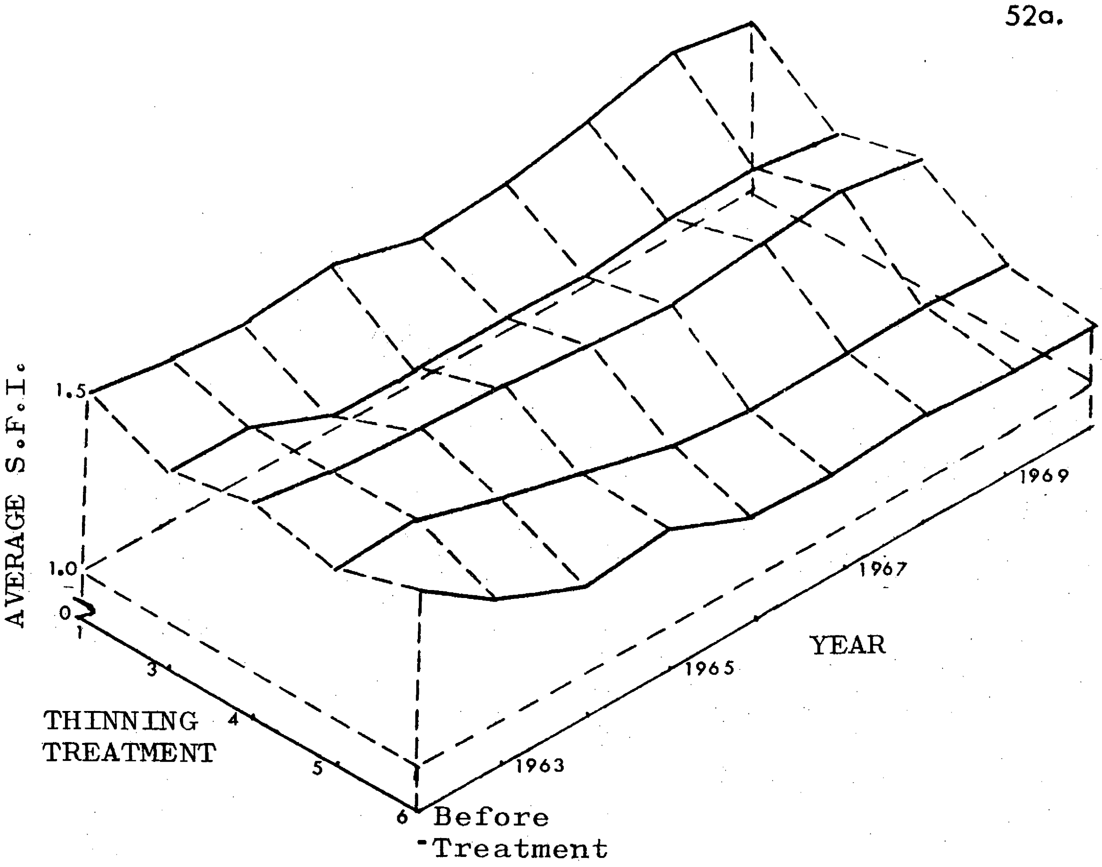


FIGURE 4.1 Time course of the effect of thinning on average stem form index (S.F.I.)

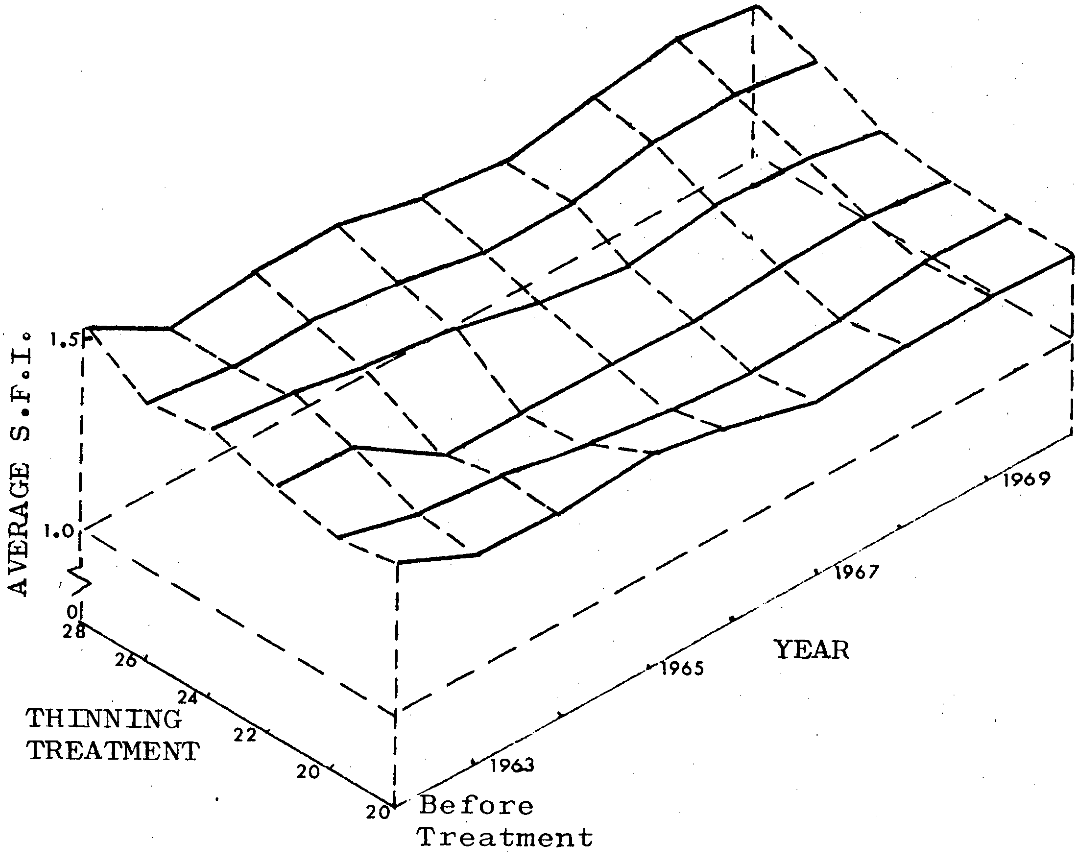


FIGURE 4.2 Variation of average stem form index (S.F.I.) with time within diameter classes. All treatments combined.

TABLE 4.1

Variation in stem form with thinning and tree diameter class

	Variance ratios[1]		
Year	Thinning Treatment	Diameter Class	Interaction
Before treatment	-	-	-
1963	1.77 N.S.	0.71 N.S.	1.09 N.S.
1964	3.24 *	1.50 N.S.	1.43 N.S.
1965	1.49 N.S.	0.89 N.S.	0.99 N.S.
1966	3.65 *	0.49 N.S.	0.94 N.S.
1967	4.77 **	0.59 N.S.	0.52 N.S.
1968	4.64 **	0.60 N.S.	0.42 N.S.
1969	6.14 ***	0.66 N.S.	0.33 N.S.
1970	4.92 **	0.79 N.S.	0.24 N.S.
Combined 1963-1970	4.25 **	0.65 N.S.	0.61 N.S.

[1]

Source of Variation	d.f.
Thinning treatment	4,44
Diameter class	5,44
Interaction	17,44

retaining a shape intermediate between a conoid and a second degree paraboloid.

While thinning, or a lack of thinning, clearly affects stem form, the effect of thinning on stem taper is more marked. From 1961/2 (before treatment) to 1970, the percentage increase in mean taper ranged from 55% in Treatment 1 to 6% in Treatment 6 (Table 4.2). This increase of 6% for trees in the control plots is not statistically significant, but it may be a real effect associated with mortality losses in 1966 and the subsequent light thinning in 1967 to maintain stand hygiene. Taper was not affected by tree diameter class nor was there any interaction between thinning treatment and diameter class

TABLE 4.2

Time course of the effect of thinning on stem taper[1] (m/m^2)

Thinning Treatment		Before Treat.	1963	1964	1965	1966	1967	1968	1969	1970	Percentage change 1962-1970	Signif.
1	Mean	368	328	291	261	235	213	198	177	166	55	***
	S.E.	17.2	15.8	14.6	13.3	12.6	12.6	12.1	11.3	11.1		
3	Mean	427	403	375	341	320	293	277	251	233	46	***
	S.E.	34.8	30.6	38.0	23.6	24.1	21.2	20.0	18.3	16.6		
4	Mean	424	399	369	338	312	289	273	249	235	45	***
	S.E.	33.2	32.2	29.7	26.5	23.9	21.9	20.5	19.2	18.7		
5	Mean	435	424	408	394	382	368	358	339	326	25	***
	S.E.	19.8	20.7	19.9	19.0	18.9	19.2	19.3	18.8	19.1		
6	Mean	449	452	451	451	451	446	442	430	420	6	N.S.
	S.E.	42.5	43.6	44.3	45.4	46.0	46.5	46.1	45.6	45.3		

---

[1] Stem taper represented by the linear regression coefficient of the H/D^2 relationship. Common lines indicate that results are not significantly different at $p = 0.05$.

The effect of thinning on the stem taper of trees of similar D.B.H.O.B. in 1962 is illustrated in Figure 4.3.

Stem profile diagrams (height in tree plotted against stem diameter) were drawn for one tree per thinning treatment selected at random from the 23 cm D.B.H.O.B. class in 1962 (Figure 4.4). This class was selected because it includes trees closest to average size in most thinning treatments. The profile diagrams indicate the effect of thinning on diameter increments at different heights in the stem, namely, diameter increment remains more or less constant down the stem in the more heavily thinned treatments, and decreases down the stem in the control and lightly thinned treatments. This finding assists in interpreting the observed variation in both stem shape and taper following thinning, as differences in ring width at the top and base of the bole obviously bring about changes in stem shape and taper with time.

4.3 Discussion

This study of stem form and taper in radiata pine suggests that stem form changes most in unthinned or lightly thinned stands whereas stem taper changes most in the more heavily thinned stands. However, the effect of thinning on form may be indirect because of the effect of the green crown. Most data from the most heavily thinned Treatments 1 and 3 were derived from discs located within the green crown because of the depth of crown (approximately 75% of total height - Table 3.1) and because the lowest three discs (to 2.5 m above ground) of each sample tree were discarded due to buttswell. This may partly explain why stem form index was virtually constant under heavy thinning in Treatment 1, whereas in the less

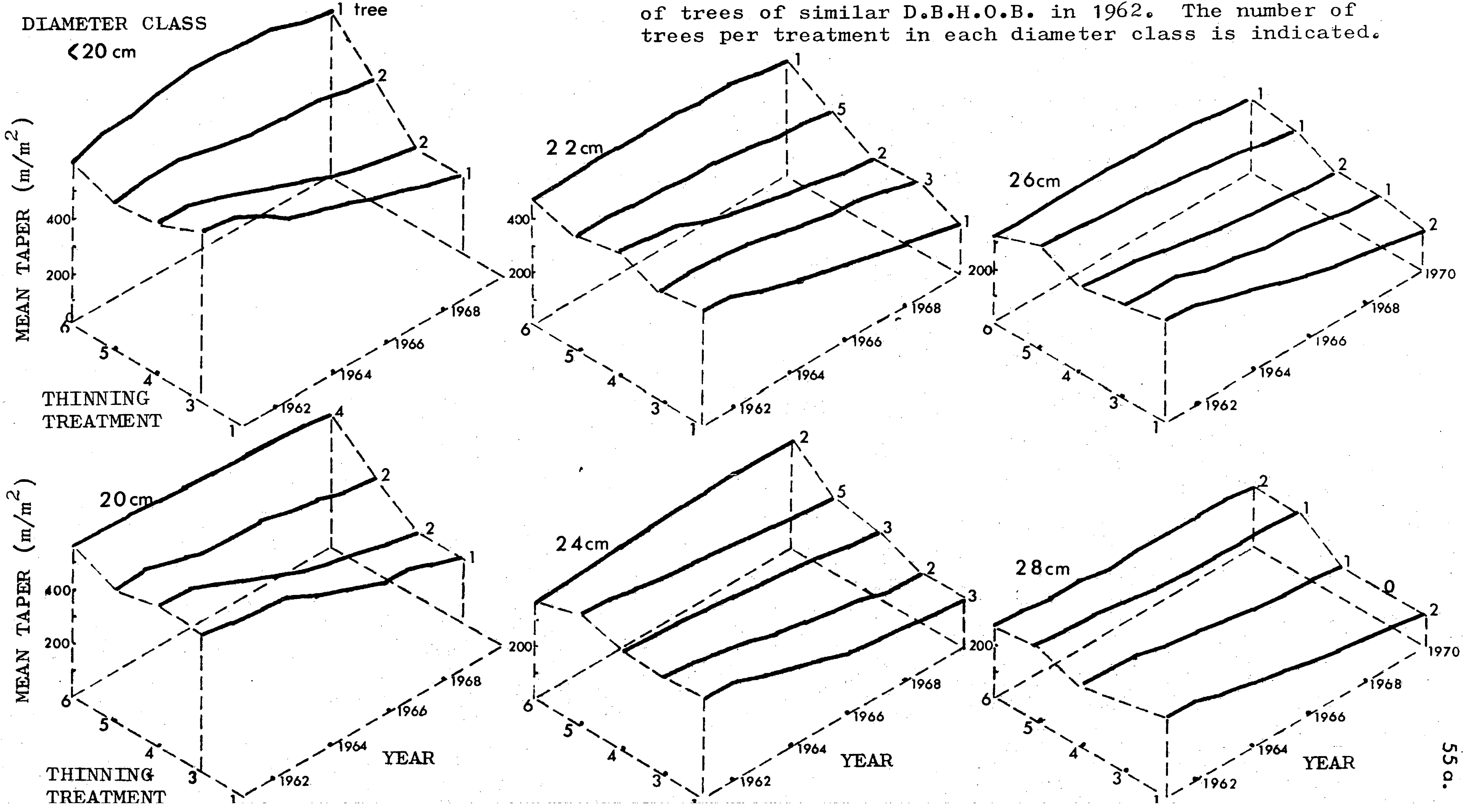


FIGURE 4.3 Time course of the effect of thinning on the stem taper of trees of similar D.B.H.O.B. in 1962. The number of trees per treatment in each diameter class is indicated.

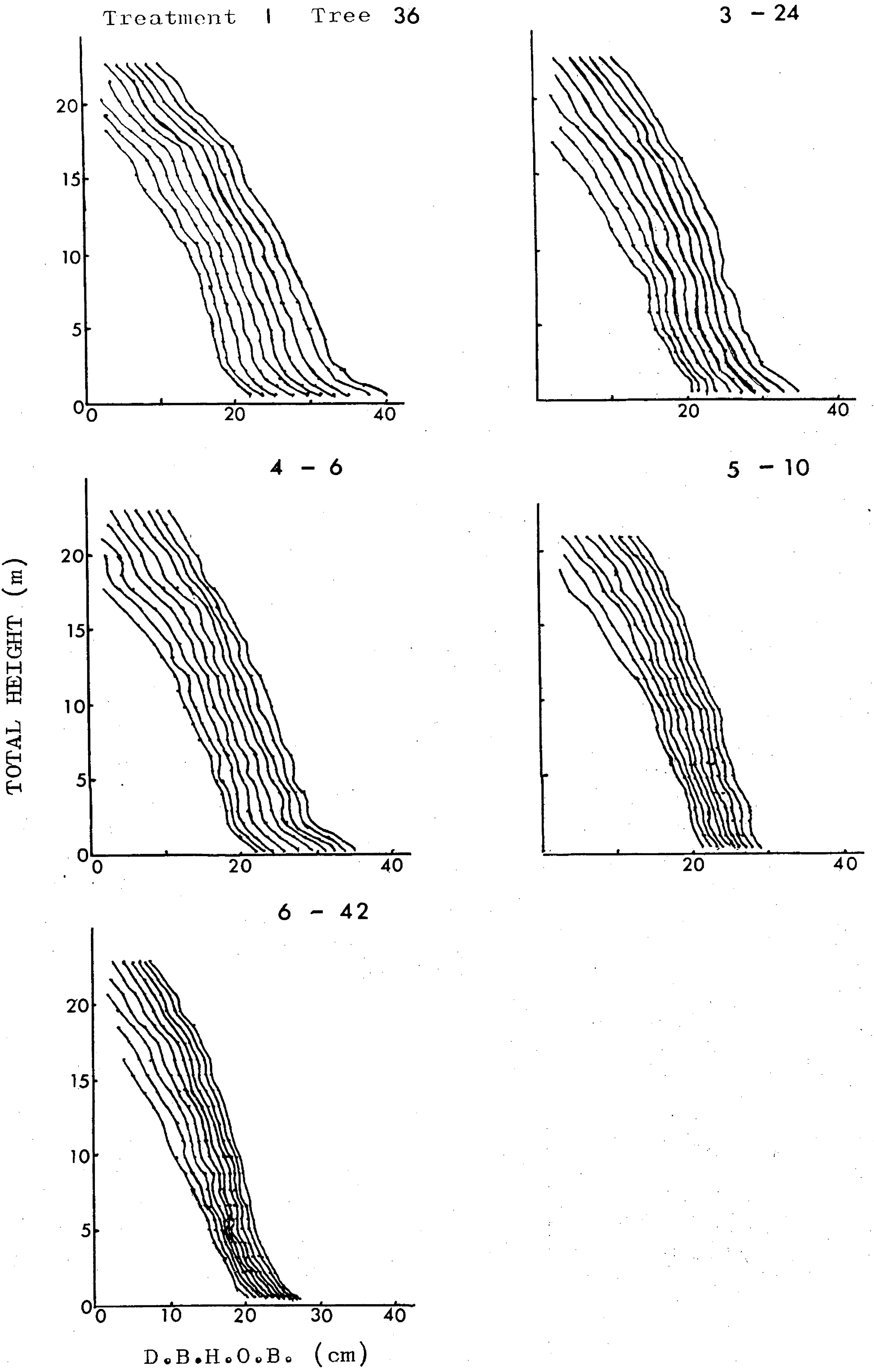


FIGURE 4.4 Time course of the effect of thinning on the profile of stems of similar D.B.H.O.B. (22.0-23.9 cm class) in 1962.

heavily thinned stands (Treatments 5 and 6) it decreased with time.

Differences in the average stem form index between treatments would be partly due to the combination of some crown thinning with low thinning in the more heavily thinned treatments. In the lightly thinned treatments, low thinning only was applied. Stem form varies with dominance class (Larson, 1963a) so removal of dominants in one stand and suppressed trees in another will affect the average stem form of the stand. Although considerable variation could be encountered in the growing conditions available to individual trees at each nominal stand density, trees of different size classes in 1962 responded to thinning in a similar manner, generally tending towards the second degree paraboloidal shape.

Larson (1963a) pointed out that most differences in the results of studies of the effect of thinning on stem form may be accounted for by differences in the type of thinning applied as well as in thinning grade and stem form prior to thinning. As mentioned, crown and low thinning have quite different effects on average stem form of the stand. Dominant trees are more likely to have deeper crowns and a stem shape tending towards a conoid. Removal of some of these trees in crown thinning could result in a change of average stem shape towards the second degree paraboloid.

The findings of this study tend to support Larson (1963a) who considered that any change in crown development resulting from thinning will be reflected by a change in stem form. Stiell (1964) and Bassett (1969), studying two different coniferous species, found thinning had no effect on stem form. The increased diameter growth after thinning may not change the stem profile, depending on stem shape before thinning and the regularity of changes of diameter up the stem.

From 1961-62 to 1970 the percentage of stems approximating a conoidal shape fell from 30% to 9%. The great majority of stems approximated second degree paraboloids (Appendix 5) which is consistent with the findings of Gray (1956) and Newnham (1965).

Newnham (1958) in a study of fir, hemlock and cedar trees, found stem form in stand-grown trees approximated a second degree paraboloid. In contrast, stem form of open-grown trees of the same species approximated a conoid or occasionally a neiloid. Newnham considered these differences resulted from the greater crown lengths in trees of open-grown stands than in trees of the same height in forest stands. With larger crowns, wind pressure effects and stresses at the stem base are greater, and the larger cross-sectional area at the stem base (Larson, 1969) increases the tendency to the conoidal shape. Jacobs (1954), Myers (1963) and Larson (1965) also accredited increased increment at the stem base after thinning, and the possible effect on stem form, to the influence of wind.

Möller (1947) proposed frequent light thinnings to alleviate the problem of increased taper due to greater diameter growth at the stem base than higher up the stem. This proposal is reasonable as heavy thinning does produce more diameter growth at the stem base because of closer proximity to the green crown and greater availability of photosynthates (Larson, 1969).

The observed increase of average stem taper with severity of thinning (Table 4.2) is consistent with the findings of Newnham (1965) for <u>P</u>. <u>sylvestris</u> stands thinned using light low (Grade A) to heavy low (Grade D) schedules (Hummel, 1953). Lohrey (1961) found with <u>P. resinosa</u> that an increase in stem taper occurs only in heavy thinning treatments with stand density less than 14 m^2ha^{-1}. This suggests a difference in response between species.

In contrast to Larson (1963a), the response in stem taper after thinning in the radiata pine stands studied occurred equally in all diameter classes. Larson suggested the variation in stem taper of trees in different dominance classes could explain why thinning was considered by some authors to have no effect on mean taper of the stand. Mackenzie (1950) considered the effect of thinning on average stem taper of a stand is often regarded as negligible, because even though trees of the smaller diameter classes may respond more to treatment than those in larger diameter classes, they make the least contribution to stand volume.

The range of stem taper values of trees in the thinned treatments decreased after thinning, because stem taper and D.B.H.O.B. are closely related (Cromer and Pawsey, 1957) and thinning almost inevitably reduces the diameter distribution of residual trees in the stand.

The stem profile diagrams (Figure 4.4) also indicate that thinning affects stem form. Under light or no thinning the annual diameter increment up the stem increases, and stem diameter at different heights in the stem is changing differentially each year. A change in stem shape with time therefore occurs. In the more heavily thinned treatments diameter increment remains more constant up the stem, and stem shape is relatively unchanged after thinning. A longer period than eight years is probably necessary for more conclusive results, particularly as the time between each successive thinning of this trial has been only two or three years. The variation of ring width at different heights in the stem will be discussed in more detail in Chapter 5.

CHAPTER 5

EFFECT OF THINNING ON WOOD DENSITY

The effect of silvicultural techniques such as thinning on basic wood density, which is an important component in overall wood quality, has been reviewed by a number of workers, e.g. Paul (1963), Boyd (1967) and Fielding (1967b). Current research in this field mostly concerns the effects of mineral fertilizing and variation of available growing space through initial spacing and thinning (Elliott, 1970a).

The distribution of basic density within the stem of coniferous stems has been discussed by Spurr and Hsiung (1954) and Goggans (1961). In general, basic density decreases with increasing height up the stem, and, at any level, increases with increasing age and distance from pith. Ring width and percent latewood also influence wood density. The diversity of findings in the literature can be attributed to the large number of factors affecting basic density.

In this study, the effects of thinning on wood density in radiata pine are examined. The results of the study have practical application because wood density is correlated with other wood properties such as strength, machinability, weight, and pulp quality and yield.

5.1 Measurement of Wood Density

The study of wood properties within the individual ring has increased during the last decade with the development of radiation techniques. Before this, the conventional gravimetric methods for determining specific gravity and basic density were widely applied (Phillips, 1960; Elliott, 1960a).

Rudman (1968) referred to techniques using visible light (e.g. Green and Worrall, 1964) and X-rays and visible light (e.g. Polge, 1963) as microspectrophotometric. Green and Worrall (1964) developed a technique in which a computer tape record is produced of the area and distribution of cell walls from measurements of relative transmission of light through a stained microtome wood section. Specific gravity and percent latewood are estimated from these measurements. Besley (1969) modified the technique by using reflected light which allows direct scanning of smoothed increment cores or discs.

Three radiation techniques have been evolved for measurement of wood density: (i) beta-ray e.g. Cameron, Berry and Phillips (1959), Phillips (1960). (ii) gamma-ray e.g. Loos (1961), Jurasek and Zokel (1963). (iii) X-ray e.g. Polge (1963, 1965, 1966), Rudman *et al*. (1969).

Each of these techniques assumes that in a sample of uniform thickness and moisture content the amount of radiation absorbed is directly proportional to wood density. The thickness of samples using the beta-ray technique ranges from microtome sections (^{14}C source) to sections approximately 12 mm thick (^{90}Sr source). The ^{14}C isotope has relatively low penetration, and the sample is passed between the source and a scintillation probe to obtain particle counts whose variations are converted to a continuous record of wood density variation.

Gamma-rays penetrate better than beta-rays so wood sections as thick as 6 cm may be used (Loos, 1961).

The X-ray technique is based on radiographs of the wood samples. Variation in optical density of the sample images on the X-ray negative is converted to a continuous recording of wood density by a double-beam recording microdensitometer. The relationship between wood density and optical density is approximately linear when using low energy or "soft" X-rays over a range of approximately 0.2 to 0.9 g cm^{-3}. Polge (1965) has described the theoretical background to the technique. The samples can be either increment cores or machined specimens of standard thickness cut from larger blocks.

Rudman _et_ _al_. (1969) described a practical method of X-ray densitometry developed at the Australian National University. Other variations of the technique have been used, for instance at the University of Toronto (Annual Report, 1970-71), where a moving stage was constructed to pass the film and wood sample at a constant rate past a stationary X-ray source.

Harris and Polge (1967), Phillips (1968) and Polge (1969) compared the beta-ray (^{90}Sr) and X-ray techniques and concluded that the beta-ray method could not resolve within-ring patterns as effectively as the X-ray method, but results of the two methods generally agreed. Phillips (1968) obtained reasonably accurate results, using microtome sections and the ^{14}C isotope, comparable to results using the X-ray technique.

Polge and Nicholls (1972) discussed choice of parameters using these new radiation methods, and concluded that maximum and minimum density and ring width are useful characteristics easily read from the recording charts. Where charts only are available, mean ring density must be estimated by measuring the area under the curve using a dot grid, planimeter, or by positioning a horizontal line to divide the space under the density curve and above the minimum density level into two equal areas. Nicholls and Brown (1971) described an alternative method in which a triangle is constructed equal in area to the area under the density curve.

The most controversial of the parameters measured using radiation techniques is percent latewood. Green and Worrall (1964) and Elliott and Brook (1967) suggested the earlywood-latewood boundary should be halfway between the first-formed earlywood and the last-formed latewood. Similar suggestions were made by Harris (1969) with his "latewood ratio" and by Nicholls and Brown (1971).

Phillips (1960) suggested that percent latewood should be the proportion of the ring having density greater than a specified figure, and Rudman (1968) and Brazier (1969) also considered that division of the ring should be on the basis of an arbitary density level.

5.2 Materials and Methods

The selection of sample trees from each thinning treatment and the subsequent removal of bark-to-pith samples from each disc of wood taken at 4% levels of total height were described in Chapter 2.

Wood density was assessed using the X-ray densitometry technique developed by Rudman _et_ _al_. (1969).

Each radial bark-to-pith segment was reduced to a 1 cm square cross-section ensuring that the radial axis was aligned at right angles to the direction of the grain. The sample was then extracted for eight hours in a Soxhlet apparatus containing a 2:1 benzene-alcohol mixture to remove the extractive contents.

Samples were vacuum-dried for approximately 24 hours and then placed in a desiccator over a saturated solution of sodium dichromate for conditioning to 8 ± 0.5 per cent moisture content. Finally, the samples were machined to a thickness of 6.9 ± 0.5 mm in the radial longitudinal direction and returned to the desiccator until removed for X-raying.

The procedures recommended by Rudman et al. (1969) to minimize errors were adhered to. Two cellulose acetate working standards ("step wedges") were placed with the wood samples on each X-ray film. Samples were kept at least 4 cm from the edge of the film.

The manual techniques used for developing the X-ray films occasionally resulted in variation in the amount of blackening on the plates and therefore variation in optical density. Where the variation of the baseline (i.e. the amount of blackening on the background of the film) exceeded ± 3 mm, the samples were X-rayed again. A proportional correction was made in measuring height above the baseline whenever a variation less than 3 mm was encountered.

The optical contrast of the X-ray plates was transferred to continuous recordings, using a Joyce-Loebl microdensitometer, and the optical density measured by the linear displacement from the arbitary baseline.

The values for maximum and minimum density read from the tracings may not be true values because of machine response characteristics. A constant scanning beam of 0.18 x 1.0 mm and a constant scanning speed were used to ensure that any error incurred was constant.

The technique of measuring the wood density parameters involved: (i) measuring the height above baseline of each step of the step wedges and plotting these values against the known density values - 0.229, 0.344, 0.468, 0.592, 0.717 and 0.867 g cm^{-3} for steps 2-7 respectively.

(ii) recording the height above the baseline of the maximum and minimum optical densities for each ring and reading the absolute density value from the graph

(iii) constructing a triangle to represent the area under the curve of the density tracing, based on the level of minimum density (Nicholls and Brown, 1971; Figure 5.1).

(iv) calculating mean density using the equation of Nicholls and Brown (loc.cit.), viz.

$$\text{Mean density} = \frac{w}{r}(M - m) + m$$

where w = mid-height width of the triangle constructed

r = ring width

M = maximum ring density

m = minimum ring density

Nicholls and Brown (1971) claimed their method was "precise". The precision was checked by measuring both a narrow and a wide ring several times, mean density being calculated on each occasion. The coefficient of variation was calculated and substituted into the equation -

$$n = \left(\frac{c\ t}{e}\right)^2$$

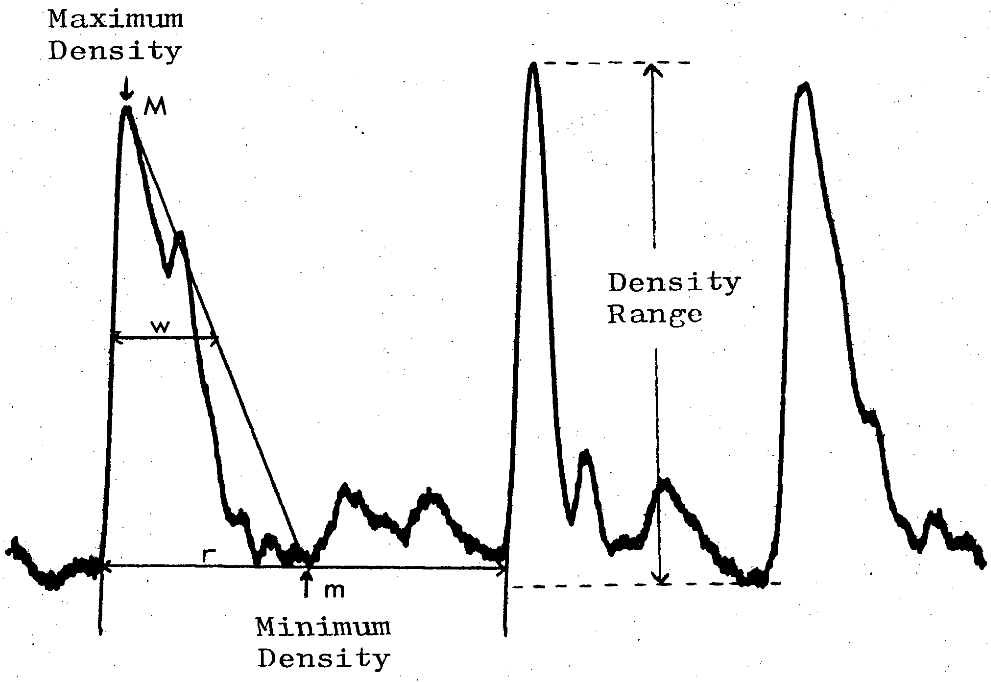
where n = number of measurements

c = coefficient of variation of measurements

t = Student's "t" value for small samples

e = error per cent of the mean.

The error for a single measurement of mean density was 2.1% for the narrow ring and 2.5% for the wide ring. These errors were considered acceptable considering the many factors which influence wood density.



$$\text{Mean density} = \frac{w}{r}\,(M-m) + m$$

$$\text{Percent latewood} = \frac{w}{r} \times 100\%$$

FIGURE 5.1 Method of calculating mean wood density and percent latewood (after Nicholls and Brown, 1971)

Percent latewood, equivalent to the "late wood ratio" of Nicholls and Brown (1971), was calculated from the equation: Percent latewood = $\frac{w}{r}$ x 100%.
This method is independent of variation in density at different heights in the tree.

Determinations were not carried out on material from the growth ring adjacent to the pith because this ring is invariably incomplete and non-representative (Nicholls and Brown, 1971).

In summary, the parameters measured or derived for each sample tree were minimum, maximum and mean ring density, density range, ring width and percent latewood. Samples were taken from the outer 10 or, where less than 10, from all rings (except the innermost) of discs collected at each 4% of total height.

Data Analysis

The effect of thinning on the properties of wood formed in a given year at different heights in the stem was investigated by an analysis of covariance using NO2FCT (McIntyre, 1970). The data were grouped in decile levels from 10% to 80% of total tree height, with data from the first and second discs at the stem base (0.3 m and 4% of total height respectively) combined to give values representative of breast height. The samples in a growth sheath are equivalent to those in Duff and Nolan's (1953) "oblique" sequence.

The mean value of each wood density parameter in each growth sheath was calculated (Append.7-12). The data enable an examination of the effect of thinning and size of tree (based on the 1962 D.B.H.O.B. classes) on the average value of properties of wood laid down in each successive year after treatment, again using analysis of covariance. The analysis compares the average of each parameter for each growth sheath, from 1963 to 1970, to the mean of values from the pre-thinning 1961 and 1962 growth sheaths.

5.3 Results

Both thinning and position in the tree (using the word "position" because both height in the tree and distance from pith are involved) significantly affect ($p < .001$) each of the six wood density parameters studied. In addition, the interaction of these two factors is significant (Table 5.1).

All parameters except ring width exhibit a similar trend of increasing values with increasing stand density (Figures 5.2 to 5.7). The effect of thinning on maximum ring density may be overridden by environmental effects such as the 1967 drought (Figure 5.2), while minimum density was not affected (Figure 5.3). The notable feature is the marked drop in maximum density in 1968 following peak values at all levels in the stem during 1967. The increase in minimum density becomes less pronounced with increasing height in the stem, and at lower levels, becomes more pronounced with time. Density range exhibits a poorly defined trend, even though tending to increase with stand density (Figure 5.4). The density range was reduced by the 1967 drought, particularly in the lower bole. The increase in mean ring density with stand density is less marked at higher levels of the bole (Figure 5.5). Percent latewood increases with decreasing severity of thinning, mainly in the lower bole at less than 40% of total height (Figure 5.7). Ring width, in contrast to the other parameters, decreases with increasing stand density with the most marked effects at the lower levels in the tree (Figure 5.6).

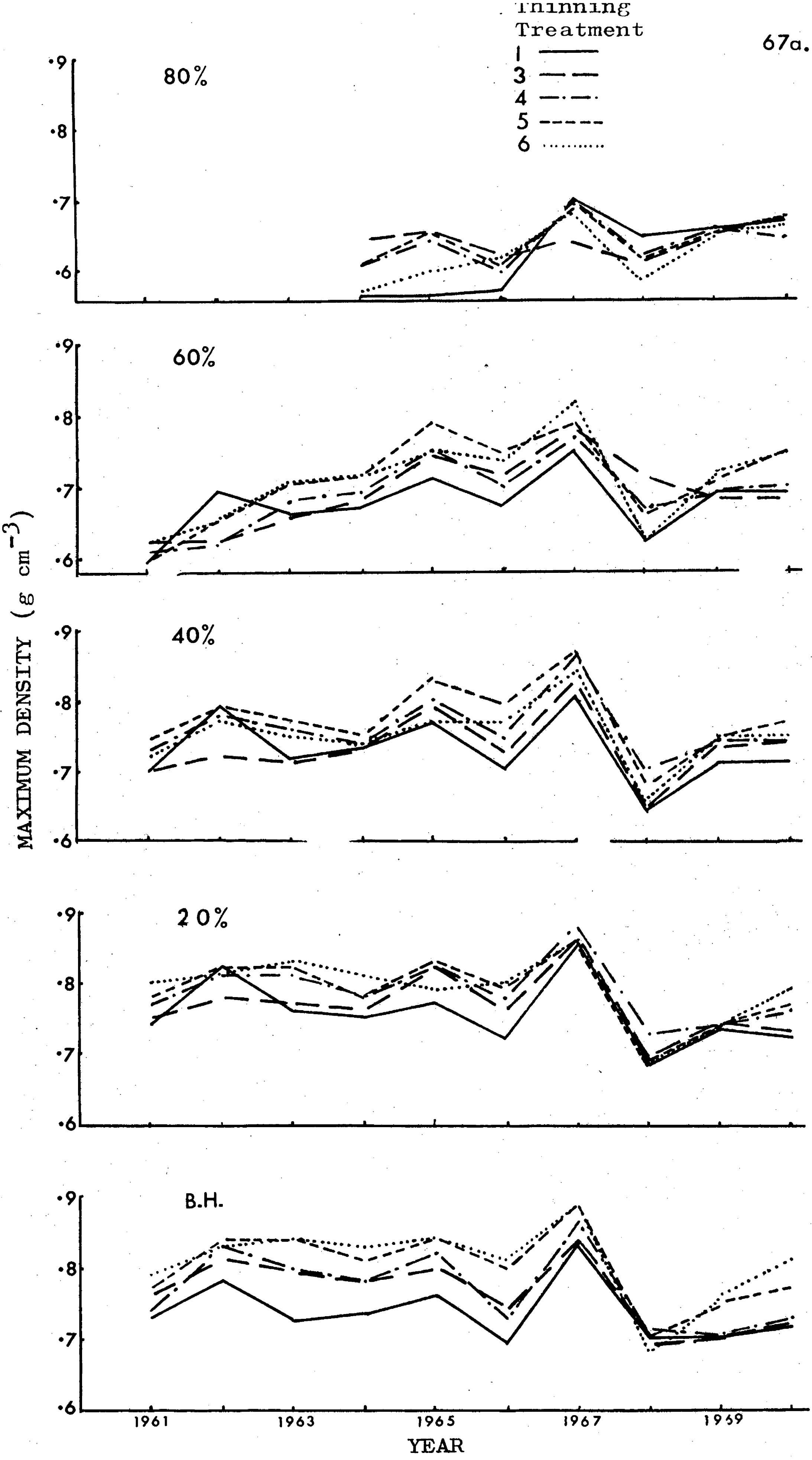


FIGURE 5.2 Maximum density within annual growth sheaths at selected percentile heights in the stem.

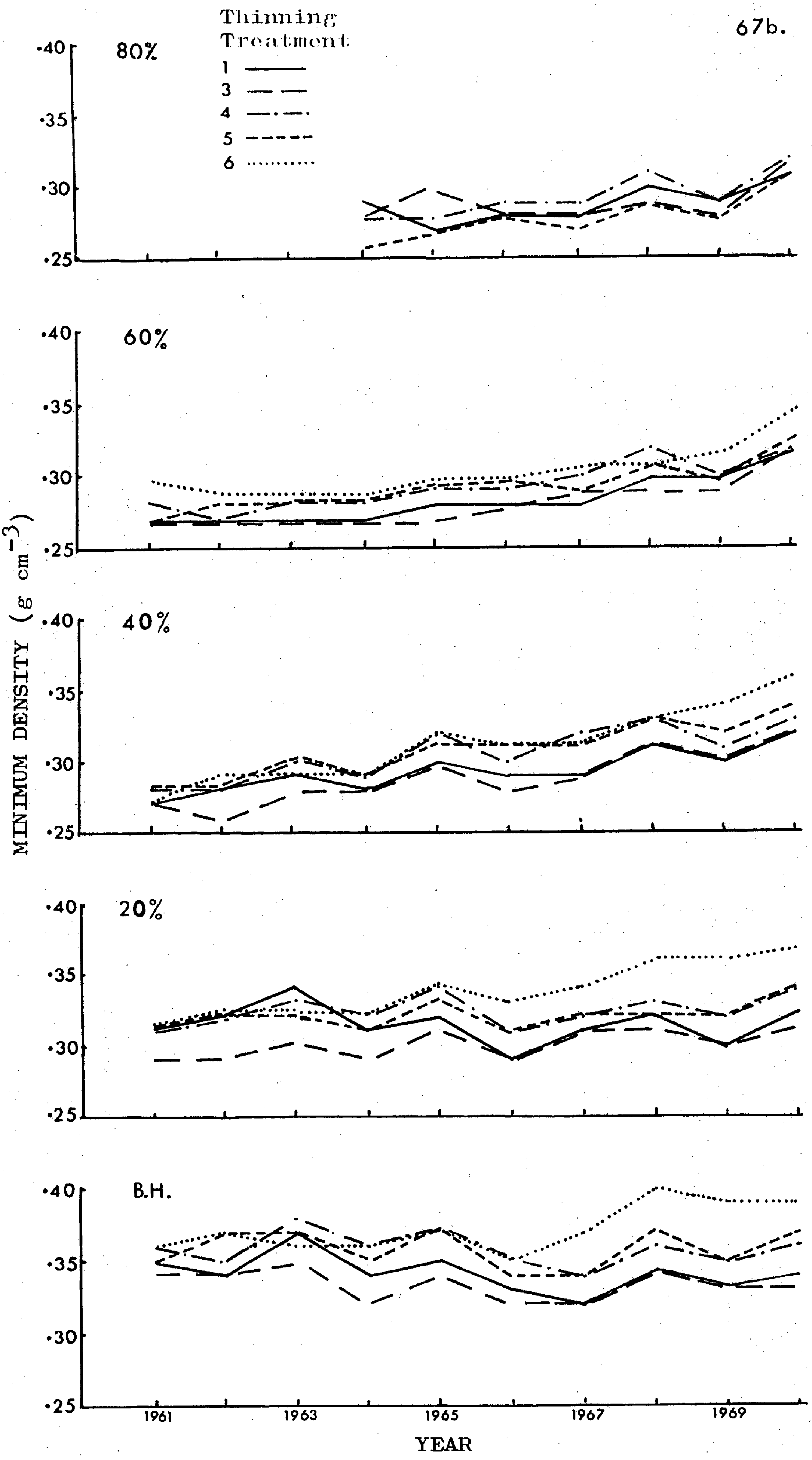


FIGURE 5.3 Minimum density within annual growth sheaths at selected percentile heights in the stem.

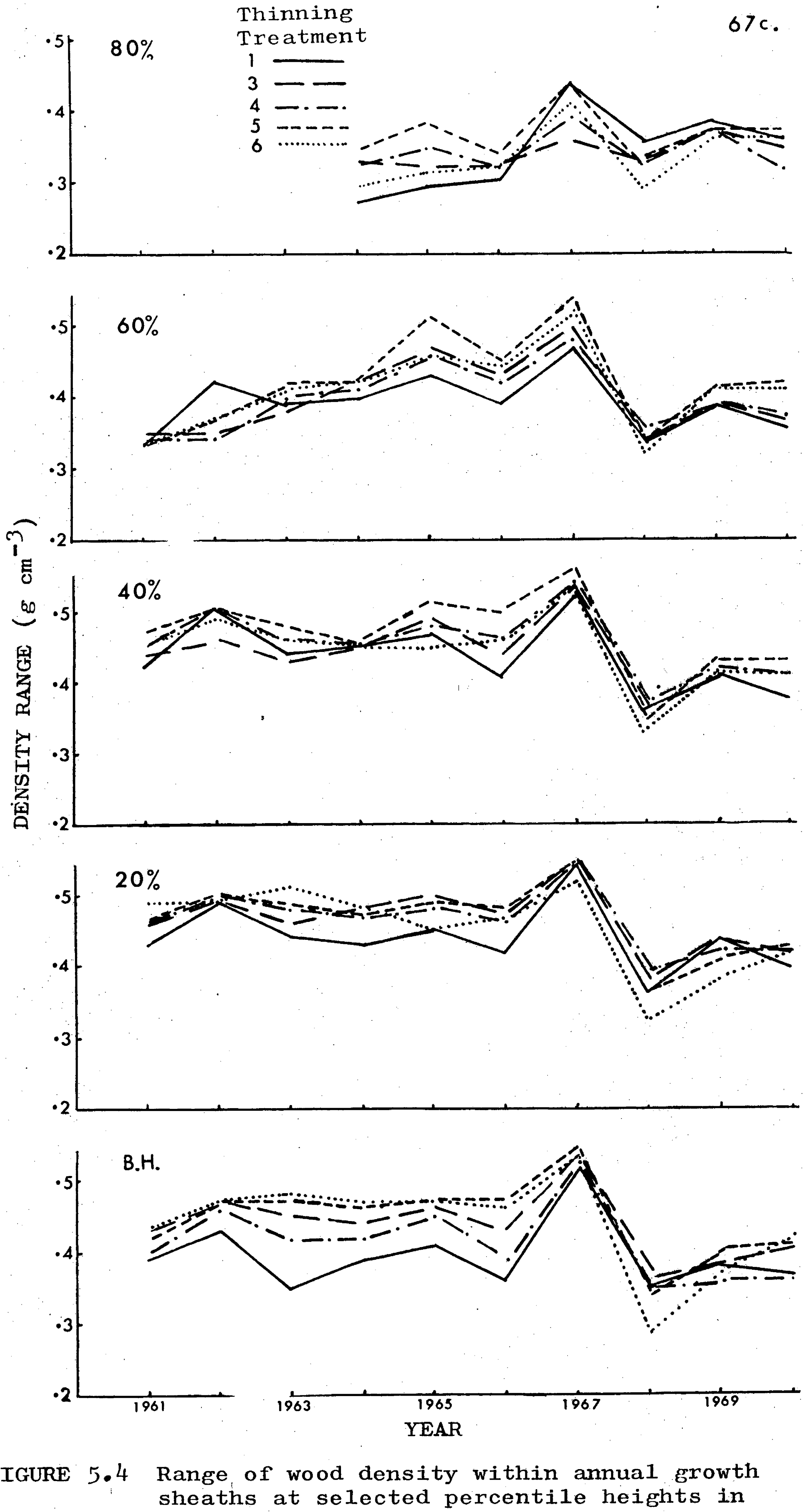


FIGURE 5.4 Range of wood density within annual growth sheaths at selected percentile heights in the stem.

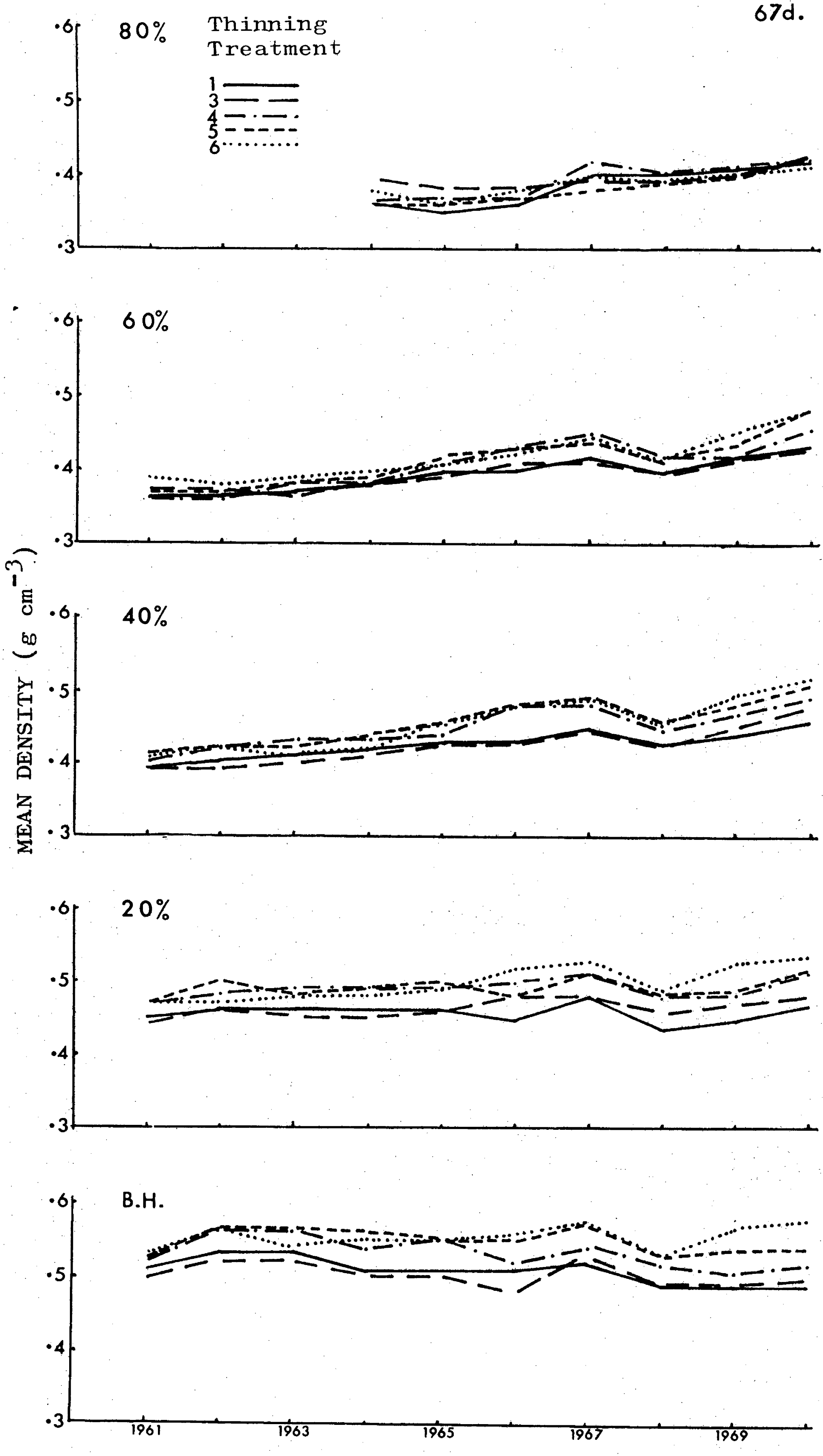


FIGURE 5.5 Mean density within annual growth sheaths at selected percentile heights in the stem

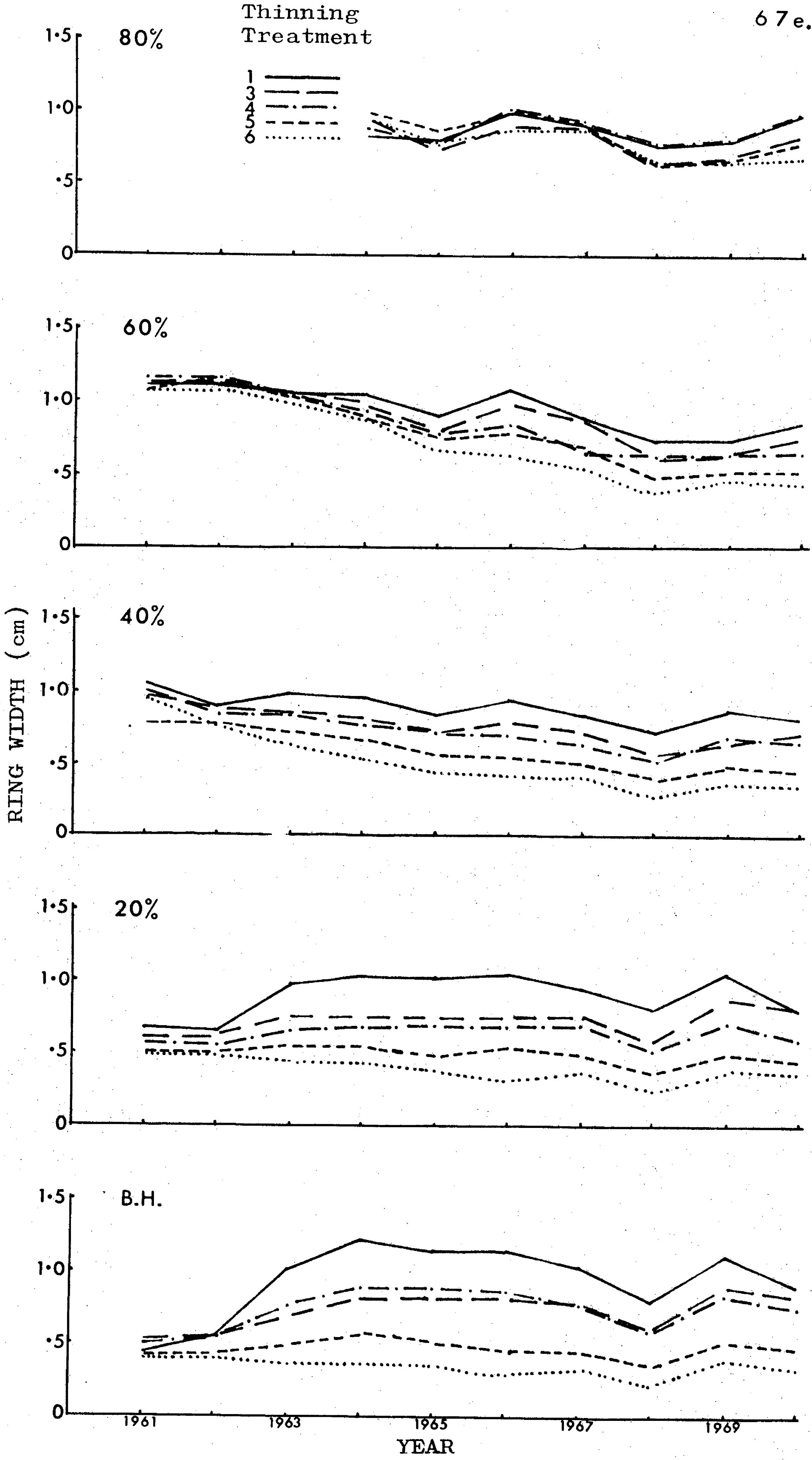


FIGURE 5.6 Ring width at selected percentile heights in the stem.

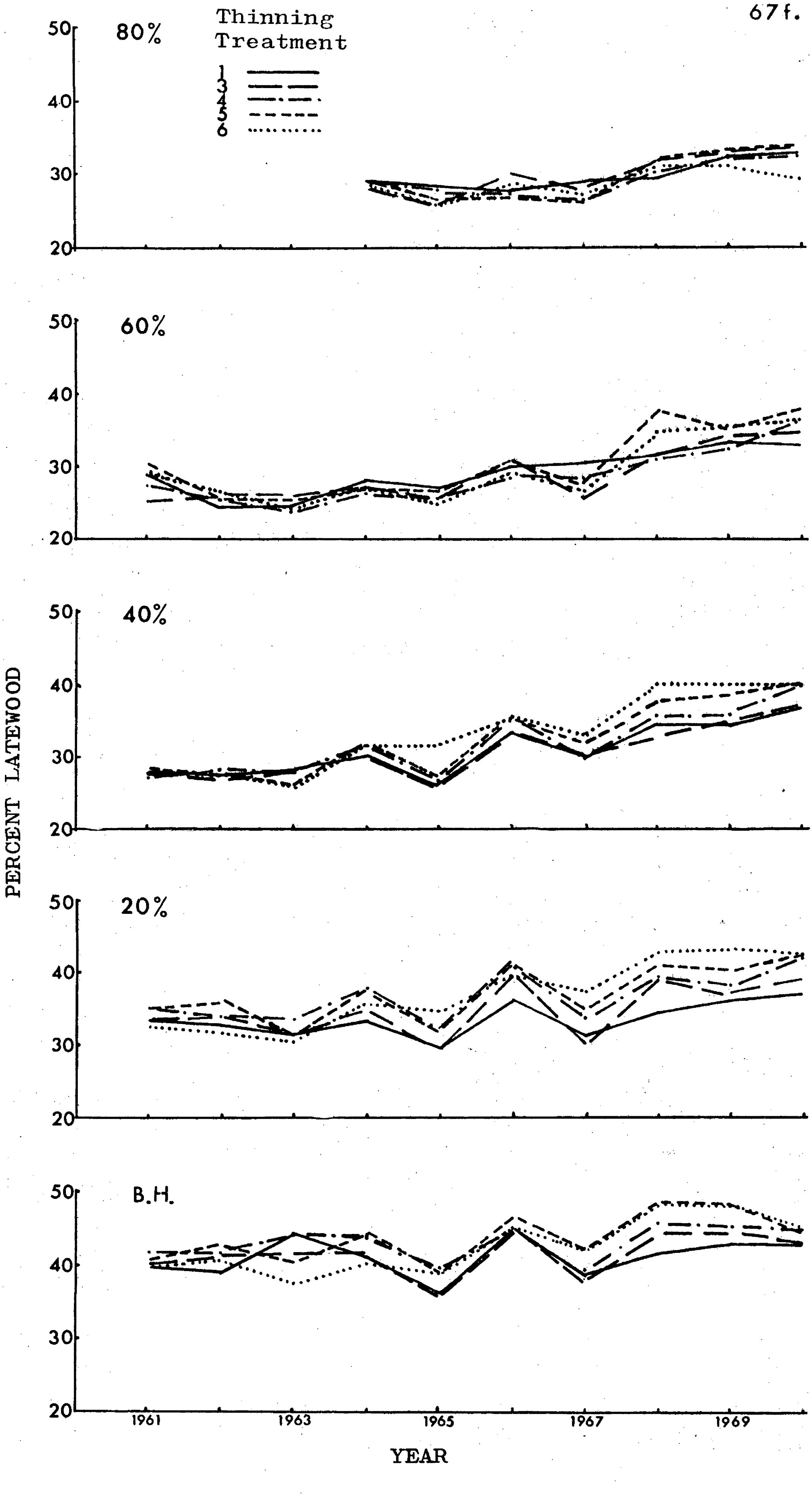


FIGURE 5.7 Percent latewood at selected percentile heights in the stem.

TABLE 5.1

Variation in wood density parameters with height in stem and thinning. Data grouped by 10% levels of total height.

				Variance ratios[1]					
Year	1963	1964	1965	1966	1967	1968	1969	1970	Comb.
MAXIMUM DENSITY									
Thinning	11.8	10.8	26.4	29.1	10.2	6.0	11.6	59.7	36.7
Height	9.6	14.8	25.0	14.2	8.0	1.6	5.7	5.3	25.1
Interaction	1.8	4.3	3.0	1.1	2.8	1.0	1.8	1.4	1.7
MINIMUM DENSITY									
Thinning	3.6	3.7	11.2	16.5	17.7	23.2	37.6	39.0	38.2
Height	11.6	4.5	40.8	7.6	16.8	13.3	8.8	5.8	25.4
Interaction	1.2	1.3	0.7	1.1	1.4	2.7	3.4	3.2	2.1
DENSITY RANGE									
Thinning	13.1	4.4	18.2	32.6	4.6	26.4	1.9	14.1	14.7
Height	9.2	12.3	23.1	11.2	4.3	3.6	5.3	2.4	15.2
Interaction	1.8	1.4	2.6	1.0	2.6	1.4	2.4	1.9	1.8
MEAN DENSITY									
Thinning	4.3	9.6	18.0	41.8	22.7	10.0	47.6	62.2	53.5
Height	3.2	7.8	15.9	17.8	10.2	3.9	9.5	15.8	23.2
Interaction	1.5	2.1	0.8	1.6	3.1	1.4	3.9	2.8	2.3
RING WIDTH									
Thinning	30.2	45.3	47.2	83.5	65.5	170	76.1	221	96.1
Height	3.8	5.6	4.9	13.8	10.4	9.0	1.0	21.7	8.2
Interaction	11.7	14.0	19.4	13.3	19.1	6.2	13.8	2.2	24.2
PERCENT LATEWOOD									
Thinning	9.1	1.8	8.2	3.8	10.8	38.3	19.7	9.1	13.0
Height	8.5	10.8	1.9	17.2	3.4	12.6	5.4	11.3	11.8
Interaction	2.4	2.3	2.9	2.0	4.6	2.0	3.6	2.6	5.2

[1]

Source of variation	d.f.	p= .05	.01	.001
Thinning treatment	4,44	2.58	3.78	5.62
Height in tree	5,44	2.43	3.46	5.06
Interaction	17,44	1.86	2.42	3.28

Thinning has no significant effect on maximum ring density and density range. However, differences in minimum density are significant between treatments at $p < .05$ (due to the 1968 and 1969 figures), as are differences in percent latewood (due primarily to the 1968 figure).

With increasing height in the stem, the values of all parameters except ring width decrease. Maximum density decreases above 40% of total height. The density range tends to decrease slightly in the upper bole, at 80% of total height. Percent latewood decreases to the 60% level.

The effect of distance from the pith at different heights in the stem differs with different variables. Maximum and minimum density increase with increasing distance from the pith in the upper levels, from 60% of total height upwards. Mean density increases with increasing distance from the pith at 40% of total height and above. Density range exhibits no clear trend, and is largely unaffected by increasing age at any given height. Percent latewood increases with distance from the pith. Again, ring width differs from the trend exhibited by the other variables. With increasing distance from the pith, ring width decreases at the higher levels in the stem, with the effect most marked in the control and lightly thinned stands. The average ring width in the 1970 growth sheath at different percentile heights, for each thinning treatment, is plotted in Figure 5.8.

Even though minimum density values tend to increase with distance from pith, the comparatively larger values from 1968 to 1970 of the control and lightly thinned stands could partly result from machine response characteristics of the microdensitometer because the growth rings were very narrow.

The overall effect of thinning on each wood density parameter was studied using the average value for each individual growth sheath. Results of the two-way factorial analysis of covariance of the basic data, using thinning treatment and stem size class as factors, are given in Table 5.2. Trends are illustrated in Figures 5.9 to 5.11.

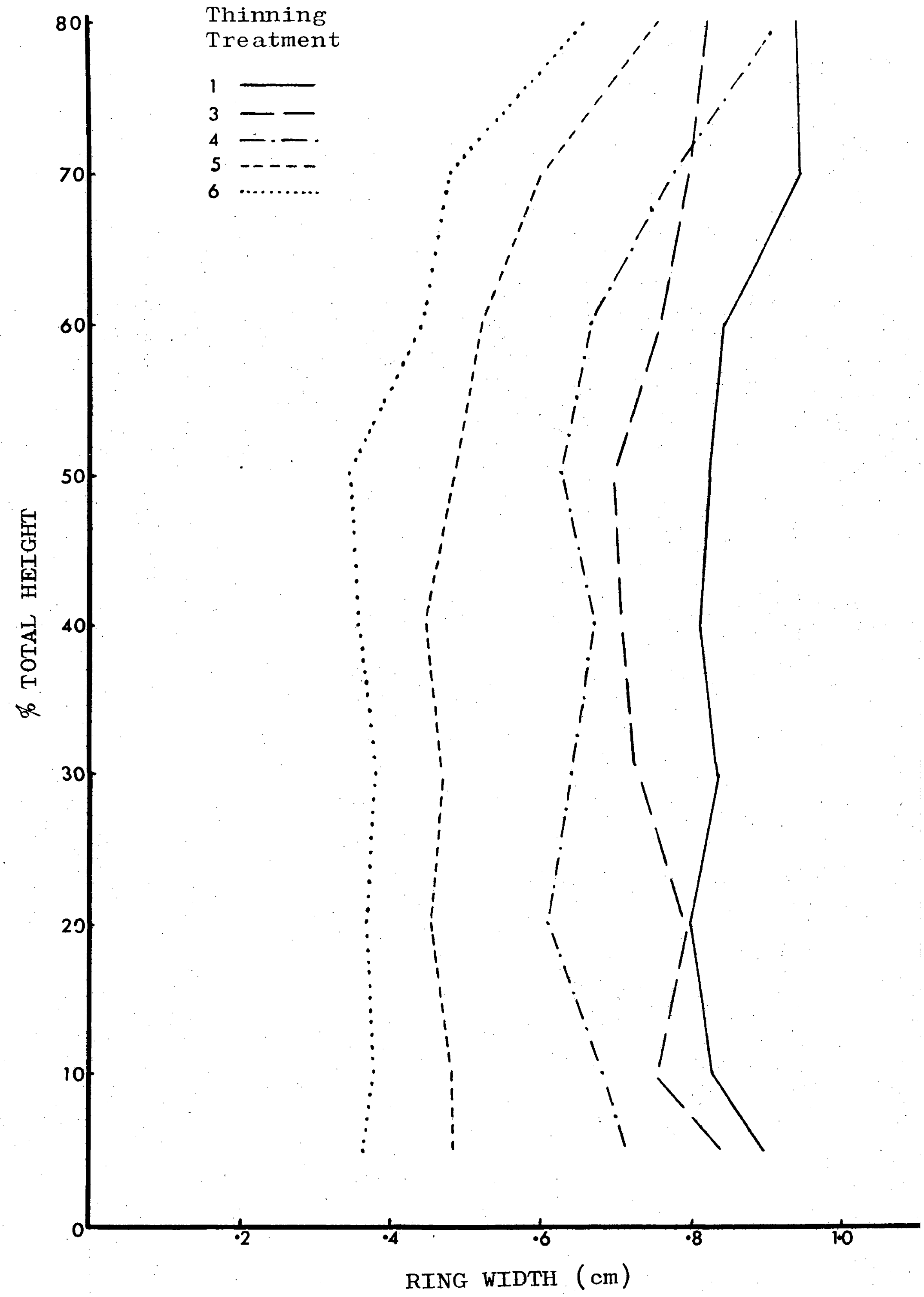


FIGURE 5.8 Average ring width per treatment of the 1970 growth sheath at different heights in the stem.

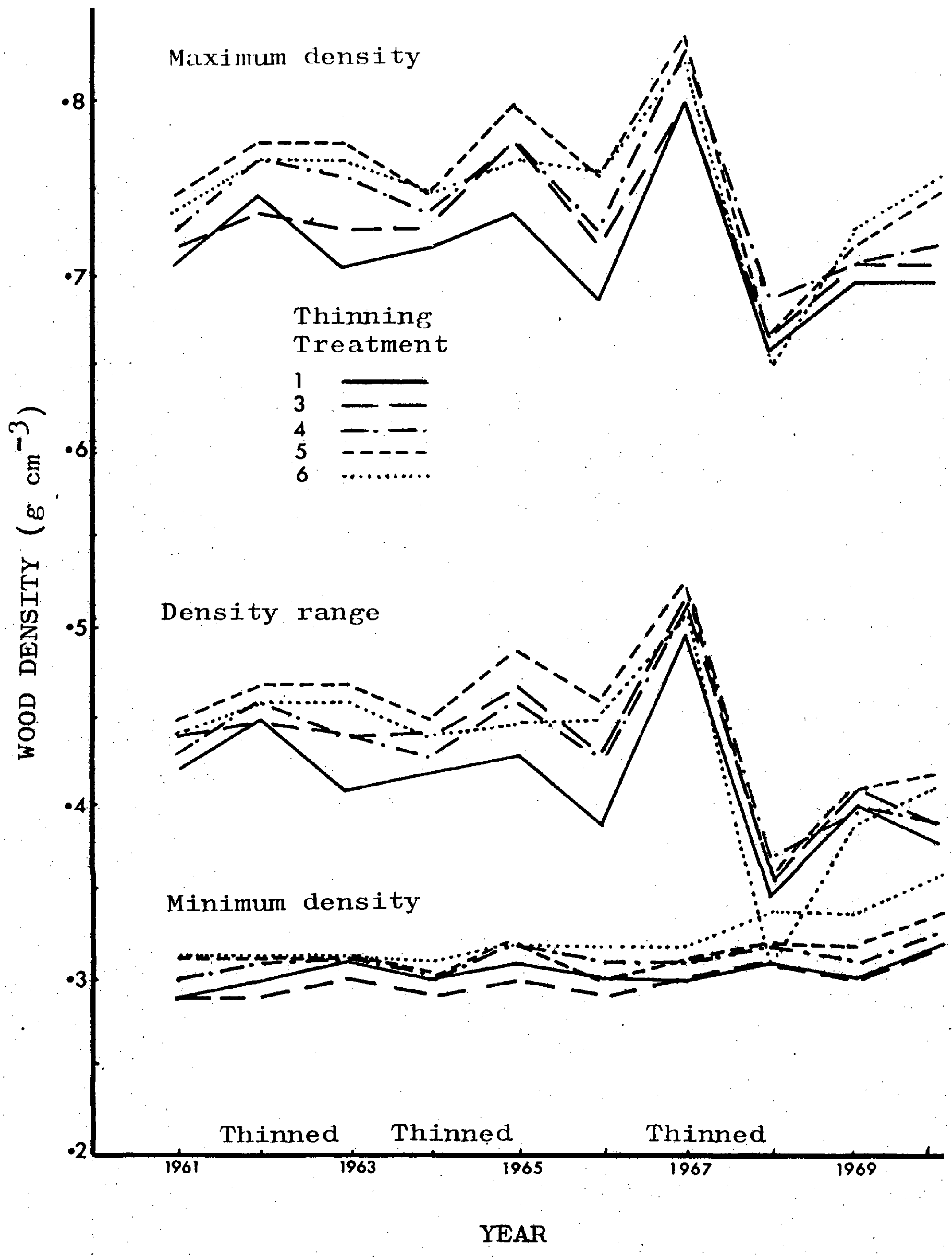


FIGURE 5.9 Maximum and minimum wood density and density range within each annual growth sheath from 1961 to 1970. Data are means by treatments for all trees and heights sampled.

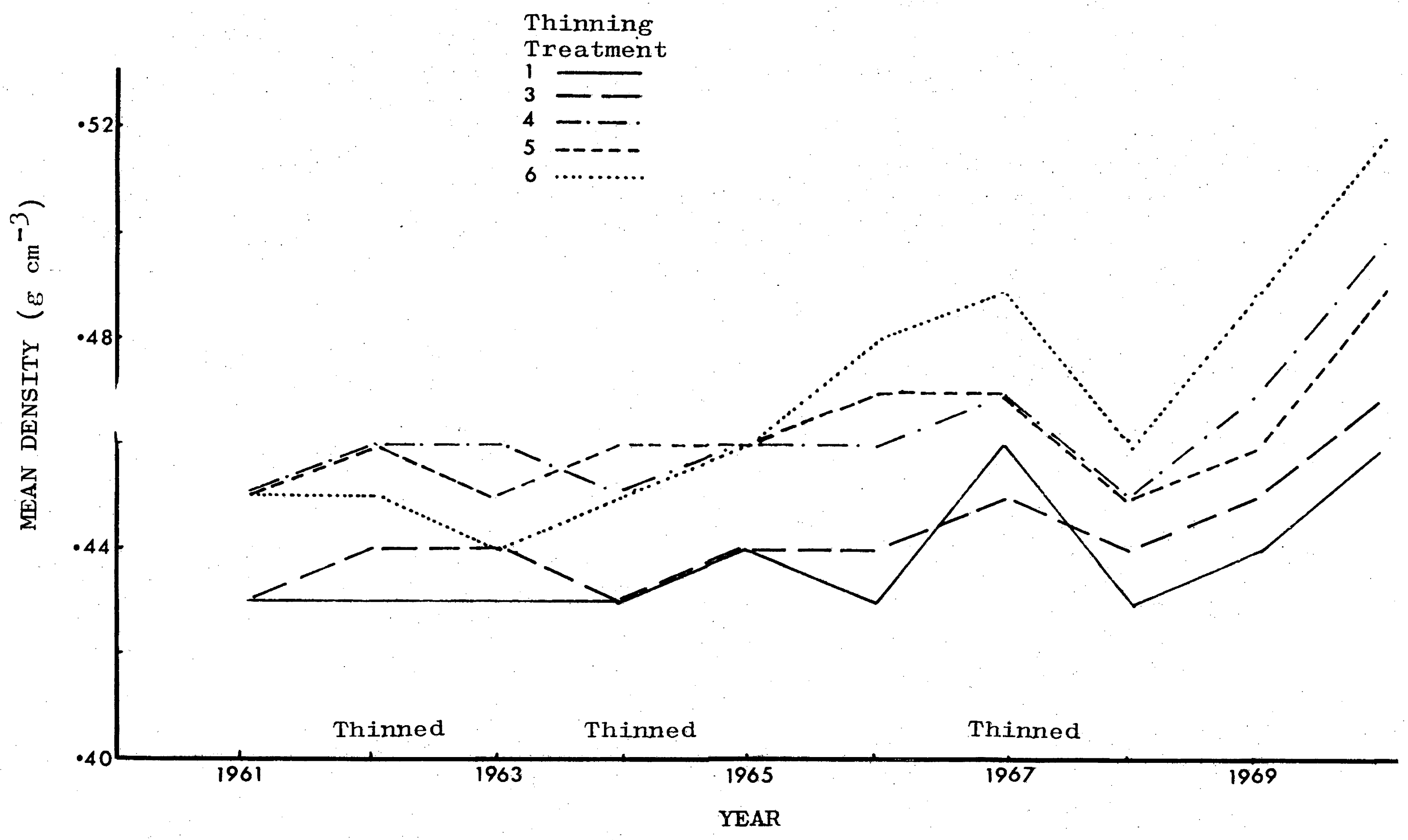


FIGURE 5.10 Mean ring density within each annual growth sheath from 1961 to 1970. Data are means by treatments for all trees and heights sampled.

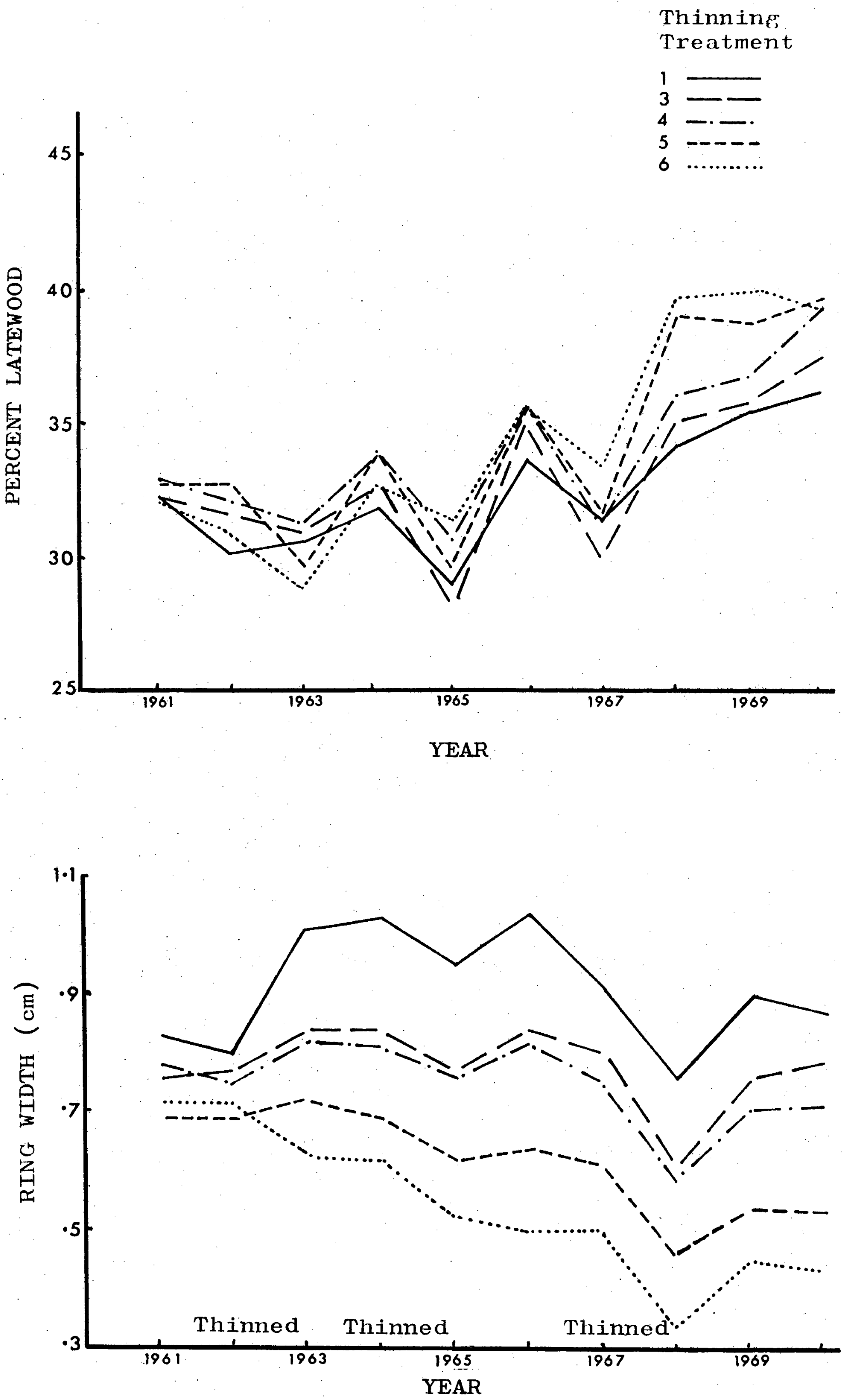


FIGURE 5.11 Mean percent latewood and ring width within each annual growth sheath from 1961 to 1970.

TABLE 5.2

Variation in wood density parameters with thinning and stem size class. Average for each growth sheath.

	Variance ratios[1]								
Year	1963	1964	1965	1966	1967	1968	1969	1970	Comb.
MAXIMUM DENSITY									
Thinning	2.08	0.37	1.27	6.40	0.21	1.54	0.74	1.73	1.05
Size class	1.23	0.25	0.61	0.46	0.58	0.25	1.83	0.51	0.28
Intreaction	0.46	0.63	0.67	2.03	0.83	0.26	1.01	0.93	1.20
MINIMUM DENSITY									
Thinning	0.86	1.33	0.22	2.23	2.11	2.74	3.86	2.33	2.78
Size class	0.44	2.43	1.95	1.01	0.51	0.97	0.62	0.53	0.97
Interaction	1.03	0.61	0.68	1.37	1.12	0.61	0.40	0.30	0.70
DENSITY RANGE									
Thinning	2.44	0.18	1.55	4.32	0.46	2.72	0.53	0.20	0.71
Size class	0.79	0.35	0.99	0.49	0.39	0.51	0.56	0.23	0.12
Interaction	0.38	0.80	0.67	1.73	0.87	0.23	0.52	0.60	1.00
MEAN DENSITY									
Thinning	0.87	0.85	0.79	5.74	3.25	1.42	6.31	5.63	4.16
Size class	1.45	1.47	0.72	1.37	0.35	0.19	0.80	0.82	0.89
Interaction	0.40	1.03	0.90	1.76	2.01	0.68	1.11	0.51	1.18
RING WIDTH									
Thinning	17.8	16.5	21.7	28.1	14.7	19.3	10.2	9.8	20.4
Size class	1.14	0.99	0.92	1.37	0.66	0.88	0.59	0.50	0.87
Interaction	0.75	0.83	1.08	0.96	0.91	0.52	0.64	0.93	0.77
PERCENT LATEWOOD									
Thinning	3.16	0.36	3.76	1.91	3.62	7.68	2.47	0.81	3.70
Size Class	1.05	1.01	0.04	2.58	0.30	1.82	1.38	0.29	1.38
Interaction	0.55	1.19	0.52	0.57	1.08	0.88	0.47	0.71	0.57

---

[1]

Source of variation	d.f.	p= .05	.01	.001
Thinning treatment	4,44	2.58	3.78	5.62
Size class	4,44	2.43	3.46	5.06
Interaction	17,44	1.86	2.42	3.28

Mean ring density differs significantly overall at $p < .01$, with treatment having no effect until 1966. (Figure 5.10). Though differences are not significant in 1968, the same trend is evident. The most marked response is in average ring width, highly significant differences ($p < .001$) occurring immediately after the application of treatment (Figure 5.11).

Of the six parameters studied, the trend with five is for the parameter to increase with increase in stand density, whereas with ring width the trend is the exact opposite. The effect of thinning on maximum density and density range was overridden by the adverse environmental effects of the 1967 drought, in which both variables increased in all treatments and differences between treatments were almost eliminated. In contrast minimum density was not affected by the drought.

The average parameter values of each growth sheath exhibit varying trends with increasing time after treatment. Minimum and mean density increase with time, while there is no clear trend in maximum density or density range. Average ring width increases initially, with the absolute change depending on the grade of thinning, then decreases with time. Percent latewood decreased initially in 1963, then increases with time.

The effect of thinning on wood density does not vary with tree size class (Table 5.2) which suggests that trees in different diameter classes react similarly to changes in stand density. The interaction between thinning and size class in all instances is insignificant (Table 5.2).

5.4 Discussion

There is little available literature on wood studies of Australian-grown trees of <u>Pinus</u> spp. using radiation methods because such methods are a recent innovation. Any studies using radiation have been by the X-ray densitometric method, either at the Forest Products Laboratory of CSIRO or at the Australian National University: the Forestry and Timber Bureau has recently acquired a beta-ray apparatus.

Maximum ring density increased with increasing distance from the pith in the upper levels in the tree, from 60% of total height and above (Figure 5.2). This increase corresponds to the findings of Harris (1969) and Nicholls and Brown (1971) that in radiata pine maximum density increased through successive growth rings in at least 12 rings from the pith. Even though samples were taken at different heights in the separate studies, comparisons are possible.

Nicholls (unpub. data, quoted by Nicholls and Brown, 1971) found in both a 27- and 29-year-old radiata pine tree that maximum density towards the top of the stem was 10% less than that recorded at breast height. In this study, the maximum density at breast height in the 1970 sheath (averaged over all treatments) was .75 g cm^{-3} and at the 80% level was .67 g cm^{-3}, a decrease of 11%. However, most of the decrease occurred in the upper half of the stem above the 40% level of total height. Part of the decrease with increasing height up the stem would be due to differences of physiological age in the cambium.

Thinning had a significant effect on maximum, minimum and mean density (Table 5.2, Figures 5.2, 5.3 and 5.5) in contrast to the findings of Nicholls (1971) who showed that maximum and minimum density were unaffected by treatment in mature P. pinaster. Presumably some of the variation may be accounted for by differences in species and climatic conditions. For radiata pine, Harris (1969) and Nicholls and Brown (1971) showed that values of the last two parameters increased with increasing distance from the pith, and results of this study agree. However, the rate of increase of maximum density in the rings near the pith may be very small e.g. the 60% level in Figure 5.3, from 1961 to 1967. The slight decrease of maximum density at breast height (Figure 5.2) agreed with the findings of Harris (1969).

As a more uniform raw material is easier to process, density range is economically important. The finding that, overall, thinning had no effect on density range is significant. The differences in this parameter at different heights in the stem exhibited an ill-defined trend (Figure 5.4).

There was no evidence of reduction in mean density after thinning, even though percent latewood decreased in Treatments 6 and 6. Larson (1963a) suggested basic density decreased initially after thinning because of increasing earlywood production (i.e. a reduced percent latewood results). The increasing mean density with increasing age at a given height in the tree (Figure 5.5) corresponded with an increase in percent latewood (Figure 5.7). A similar pattern has been observed in other <u>Pinus</u> species e.g. Larson (1963a), Paul (1963). At 80% of total height (Figure 5.5), where the data are from rings near the pith, mean density decreased slightly from the second to the fourth growth ring from the pith (1964-1966) and then increased with age. Nicholls and Dadswell (1965) reported a similar trend.

Within each growth sheath, the cambia decrease in physiological age with increasing height in the stem. A valid comparison between thinning treatments of the average values of the six wood density parameters is possible, because the growth sheath formed in a given year in trees growing under different stand densities includes a similar range of physiological ages. The increase in average parameter value with time is due to data coming from fewer rings of crown-formed wood and more rings of mature wood below the green crown and outside the juvenile core. Larson (1963a) pointed out there are subtle differences between crown-formed and juvenile wood, although they are often considered similar. Both terms describe the wood formed in the young tree, while a similar type of wood is produced in the rings near the pith at all heights in the stems of older trees.

Percent latewood differed between thinning treatments, increasing with stand density except at the 80% level of total height (Figure 5.7). The decrease in percent latewood from 43% at breast height (all treatments combined) to 32% at 80% of total height agrees with Larson (1969), who also states that near the stem apex latewood formation ceases. Zahner (1963) proposed that differences in percent latewood can result from variations in basic density. The large amount of variation in percent latewood in the 1968 growth sheath could be accounted for by this explanation. Edlin (1965) commented that the reasons for variation in latewood between species, within species and at different heights in the stem are either unknown or else are imperfectly understood.

Ring width was more affected by thinning than was any other variable tested. It responded to all thinning grades, particularly the more heavy, soon after treatment (Figure 5.9). Jacobs (1962) reported a similar finding. Turnbull (1947) and Larson (1957) concluded that rate of growth, based on ring width measurements, did not determine the basic density of wood formed in any particular year. Fielding and Brown (1960) found rate of growth has either little or no effect on specific gravity, or else has a small but significant effect because of the great variation in the genus Pinus and the diverse environmental conditions encountered. According to Turnbull (1947), age is the most important factor affecting basic density. The results of this study indicate that wood of higher density is formed below the region of the crown, and outside the rings formed close to the pith. This suggests that the increased density is a function of age and position in the stem.

The patterns of variation in average ring width at different heights in the stem, for the 1970 growth sheath, indicated that maximum ring width occurs in the mid-upper crown (Figure 5.8), where the maximum concentration of foliage is found (Figure 3.5).

CHAPTER 6

INTERRELATIONSHIPS AND GENERAL DISCUSSION

The concept of a close relationship between crown and stem parameters has been frequently overlooked in forestry practice (Larson, 1969) even though it is important in the development of suitable silvicultural techniques.

Larson (1962) has emphasized the role of the green crown in the physiology of wood formation. Generally, environmental factors have a direct effect on cambial activity only under extreme conditions such as drought and abnormal heat or cold. The green crown responds to variation in environmental factors through photosynthesis, respiration and growth-regulator production, and hence wood formation is influenced indirectly.

Silvicultural treatment directly affects crown characteristics and, through modification of the tree's growth environment, indirectly affects the processes of wood formation. Ring width and percent latewood in particular are affected, changes in ring width influencing stem form and taper.

Thinning to manipulate stand density is a most effective method available to the silviculturist to regulate the quantity and quality of wood yield (Larson, 1969). Thinning reduces competition in the root zone for moisture and nutrients, and in the crown zone for light and CO_2. It may result in optimal metabolic activity. However, the actual response generated, for both total wood production on the bole and wood quality, depends on the intensity and type of thinning, and on the responsiveness of the individual tree.

The previous three chapters dealt with the effects of thinning on crown structure, stem form and wood density respectively. In this chapter the interrelationships between crown, stem and wood parameters are examined using principal component analysis, and the overall findings of the study are discussed.

6.1 Interrelationships between Crown, Stem and Wood Density Variables

The crown variables selected for the principal component analysis were those significantly affected by thinning, namely, height to the lowest green whorl, crown length, total number of branches, total cross-sectional area of branches, and total foliage weight of each tree (Appendix 1, Table 3.1). Variables unaffected by treatment were ignored as they would contribute little to the analysis.

Stem form and taper indices of the 1970 stem profiles were used in the analysis (Appendices 5 and 6 respectively). Taper increases with decreasing index value. The wood density parameters included mean density of the ring, ring width and percent latewood, the data being means of all heights sampled in the 1970 growth sheath of each tree (derived from Appendices 10-12).

The matrix of correlation coefficients for the different combinations of variables (all treatments combined) highlights the interrelationship of crown, stem and wood density parameters (Table 6.1). The highly significant correlation of total branch cross-sectional area and total foliage weight with mean ring width, stem taper, D.B.H.O.B. and D_B indicate that these are the most influential of the crown variables. The other crown variables are also correlated with the stem and wood density variables, but

TABLE 6.1

Matrix of correlation coefficients between selected crown, stem and wood density variables

		1	2	3	4	5	6	7	8	9	10	11	12
Mean ring density	1	1.00	-.50	.57	.26	-.33	-.16	-.46	-.47	-.51	-.47	.54	-.22
Ring width	2		1.00	-.51	-.66	.77	.47	.89	.90	.92	.92	-.92	.34
Percent latewood	3			1.00	.24	-.31	-.09	-.36	-.38	-.47	-.44	.46	-.01
Height to lowest green whorl	4				1.00	-.88	-.54	-.71	-.74	-.63	-.78	.66	-.37
Crown length	5					1.00	.58	.82	.82	.77	.88	-.76	.34
Total number of branches	6						1.00	.53	.54	.42	.52	-.46	.17
Total sectional area branches	7							1.00	.99	.93	.95	-.93	.40
Total foliage weight	8								1.00	.95	.96	-.95	.43
D.B.H.O.B.	9									1.00	.96	-.98	.39
D_B	10										1.00	-.96	.39
Stem taper index	11											1.00	-.48
Stem form index	12												1.00

<u>Levels of significance</u>	(54 d.f.)
p = 0.05	.27
p = 0.01	.35
p = 0.001	.44

to a lesser extent. Ring width is highly correlated with D.B.H.O.B., D_B, and stem taper, as well as with the two crown variables mentioned above.

There is no reasonable explanation for the strong correlation between stem form index and stem taper index, because a stem with a particular shape can have a wide range of taper valves.

The eigenvectors derived from the matrix of correlation coefficients indicate which variables contribute most to each component (Table 6.2). These are total cross-sectional area of the branches, total foliage weight, and crown length among the crown variables, and D.B.H.O.B., D_B, stem taper and mean ring width among the remainder. Percent latewood and mean ring density of the outer growth sheath contribute most to the second component, and stem form index contributes most to the third component. Together, these three components account for 85% of the total variation.

T-tests were used to determine the effect of thinning on the interrelationship between crown, stem and wood density variables (Norris, 1971), results of which are given in Table 6.3. The tests were based on values describing the position of each sample tree in the multidimensional space defined by the principal components, and calculated from eigenvectors and basic data to give standard deviates from zero mean (Figures 6.1, 6.2).

Differences between treatments, taking successive pairs, are significant for the first principal component, excepting Treatments 3 and 4; the greatest difference occurring between Treatments 4 and 5 (23.0 - 29.9 m^2ha^{-1} and 27.6 - 34.5 m^2ha^{-1} respectively). Differences between successive treatments are not significant for Component II and are only significant for Component III ($p < .05$)

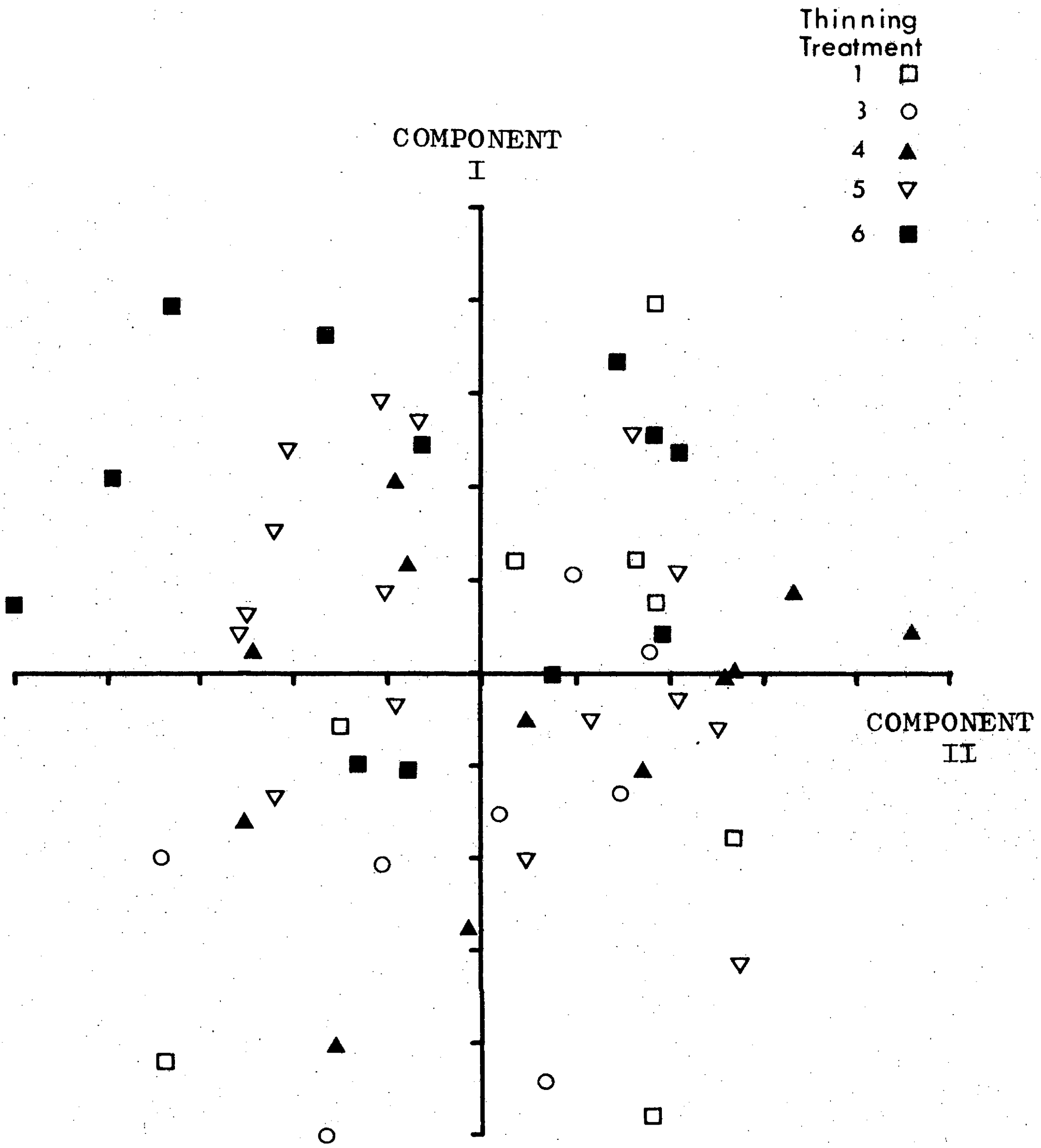


FIGURE 6.1 Relationship between the first and second principal components of crown, stem and wood density variable

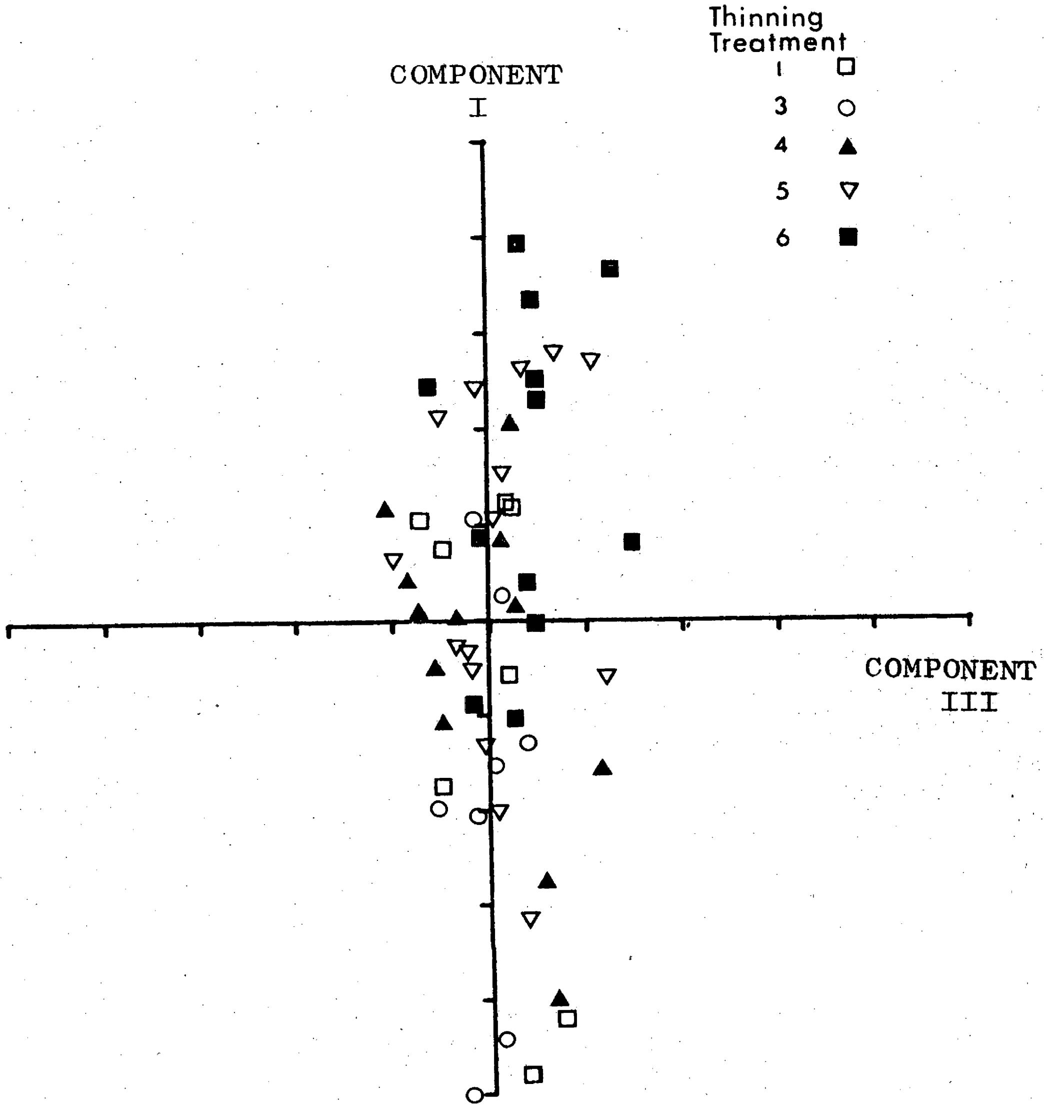


FIGURE 6.2 Relationship between the first and third principal components of crown, stem and wood density variables.

TABLE 6.2

Eigenvalues and associated eigenvectors derived from correlation coefficients between selected crown, stem and wood density variables

Principal Component	I	II	III	IV	V	VI
Eigenvalues	7.99	1.34	0.91	0.60	0.49	0.37
Cumulative % of eigenvalues	66.5	77.7	85.3	90.3	94.3	97.4
% eigenvalue in each component	66.5	11.2	7.6	5.0	4.0	3.1

Variables	Eigenvectors					
Mean ring density	-.19	.53	-.12	-.53	-.16	.60
Ring width	.33	-.09	-.04	-.18	.10	.11
Percent latewood	-.17	.63	.20	-.14	.37	-.58
Height to lowest whorl	-.28	-.28	.13	-.15	.61	.22
Crown length	.31	.21	-.17	.04	-.38	-.18
Total number of branches	.20	.36	-.42	.61	.41	.32
Total branch cross-sectional area	.34	.05	.01	-.17	.18	-.08
Total foliage weight	.34	.05	.02	-.14	.16	-.04
D.B.H.O.B.	.34	-.09	.06	-.27	.18	.05
D_B	.35	.02	-.03	-.15	-.02	-.03
Stem taper index	-.34	.07	-.13	.14	-.17	-.06
Stem form index	.16	.20	.84	.32	-.12	.30

TABLE 6.3

T-tests between thinning treatments of coefficients derived from principal components analysis.

Thinning Treatments	Component t-values I	II	III
1,3	2.49 *	-0.46 N.S.	3.20 *
3,4	0.64 N.S.	-0.96 N.S.	-1.33 N.S.
4,5	3.44 **	0.96 N.S.	0.48 N.S.
5,6	2.42 *	1.28 N.S.	-0.86 N.S.

between Treatments 1 and 3 due to differences in the stem form index.

Over a wide range of basal areas (from approximately 11.0 to 30.0 m^2ha^{-1}) growth of the crown and stem is such that parameters are related in a similar manner. Thinning affects the interrelationships between branch cross-sectional area, foliage weight, and measures of stem size and taper at basal area levels above 30 m^2ha^{-1}.

6.2 General Discussion

The 23-year-old radiata pine stand studied, in the Green Hills State Forest near Tumut, has stand density as the only variable. The site and general environmental conditions are uniform. The trees include a wide range of genetic variability because their origin was seed from silvicultural thinnings. Each of the six thinning treatments has four replications, which is uncommon in experiments in stands of this age. A large stratified random sample (a minimum 10% of standing trees) was taken from each treatment. Thus the source of material is most suitable considering the objectives of this study.

The data, which include parameters of crown structure, stem form and taper, and wood density, were used to study tree growth following thinning in this stand. The results generally should not be extrapolated to stands on different site qualities.

In deciding which crown parameters to measure, crown width was excluded because observations indicated that large errors were likely in estimating this parameter in the control and lightly thinned treatments. The crown parameters included in the study (Table 3.1) allowed precise measurement.

The strong relationship between foliage weight and branch cross-sectional area was based on large numbers of sample branches in each decile height stratum of the different treatments. Considerable variation was expected in this relationship in individual branches, because of the nature of the green crown. The association of a branch with other branches in the same crown and neighbouring crowns results in differences in the amount of light received, while branch and foliage age are also involved. Consequently, the contribution of an individual branch to stem growth is difficult to assess, and estimates of foliage weight in the crown must include some errors.

The stem analysis data used to study stem form and taper were precisely measured to an accuracy of 0.5 mm. The analysis was based on the main stem above the region of buttswell (2.5 m) even though the latter contained 25% of stem volume.

The wood density data were measured using the very accurate X-ray densitometry technique, the major disadvantage of which is the time taken to obtain each measurement. The data, which came from wood samples taken from the north-point of the stem to the pith, would have errors of measurement less than the variation found around the stem at a given height (Taras, 1965). Fielding (1967b) commented that results of thinning studies are often confusing because of complications due to reaction wood formation. In this study, the problem was not encountered because any compression wood forms on the underside of the stem, away from the prevailing north-westerly winds in the Tumut area (Brown and Hall, 1968), to compensate for the general lean of the stand to the south-east. In addition, the presence of compression wood would be obvious using the X-ray densitometry technique because of distinctive density patterns.

In general, the sources of error in the data were relatively limited.

Certain crown and stem characteristics such as total tree height generally are independent of stand density (Dell and Collicott, 1968). In the 23-year-old radiata pine stands studied, thinning treatment had no effect on variables such as total height, the number of green whorls per metre of crown length and the number of green branches per whorl (Table 3.1). The last two parameters are under strong genetic control (Fielding, 1960; Forrest and Ovington, 1971). However, significant differences were obvious between thinning treatments for such characteristics as the total number of green whorls and branches per tree, the height to the lowest green whorl, crown length and crown length ratio, and total and mean branch cross-sectional area and mean branch diameter. The most marked differences occurred between the moderately thinned Treatment 4 (23.0 - 29.9 m^2ha^{-1}) and the lightly thinned Treatment 5 (27.6 - 34.5 m^2ha^{-1}) and also between Treatment 5 and the "unthinned" control at 46 m^2ha^{-1}. At lower stand densities these same variables were unaffected by treatment. Thus progressively intense thinning results in increasing effect on several crown characteristics, but only to a stand density of approximately 30 m^2ha^{-1}. Thinning beyond this density has little further influence on any crown parameter.

In the management of Australian radiata pine plantations, it is common for stands in the 15-to 25-year age class to be thinned to approximately 20 m^2ha^{-1} (Forrest, pers.comm.). Generally accepted lower limits of standing basal area range from 23 to 30 m^2ha^{-1}, depending on age and site quality (Shepherd, 1970). Trees grown at such stand densities would have crowns which differ markedly from the crowns of trees growing in unthinned stands. A more intense thinning to stand basal areas less than 23 m^2ha^{-1} presumably would have little effect on crown characteristics.

As a result of moderate or heavy thinning, crowns lengthen as the upward recession of the live branches decreases; the size of live branches increases and their distribution in the crown changes particularly in the mid-upper crown from 50% to 80% of total tree height (Figures 3.2 and 3.3). The uppermost branches of each tree (80% of total height and above) are in full sunlight irrespective of stand density. The lowest branches, below 50% of the total height of approximately 28 m, have presumably developed under full sunlight then tended to become moribund under low light conditions prior to thinning. These branches remain partly shaded because of higher branches in that crown and in neighbouring crowns, although shading is least in the open, most intensively thinned stands. The branches growing in the mid-upper zone may or may not receive full light depending on stand density.

The size increase in live branches after thinning is greater with increasing severity of treatment. The foliage weight per branch was closely correlated with branch cross-sectional area (Table 3.3) with the relationship being independent of thinning although variation was evident between different levels within the canopy at different stand densities In addition the cross-sectional area of all green branches per tree was closely correlated with the bole cross-sectional area at crown base, as suggested by Jacobs (1938), and this also was independent of thinning treatment (Figure 3.1).

The longevity of the lower branches was increased by thinning, as suggested by the presence of a higher proportion of three-year and older needles on branches from trees in the more heavily thinned treatments (Appendix 3). Crown length increased with intensity of thinning. The relationship between crown length and D.B.H.O.B. also differed between treatments mainly because of the effect of differences in the rate of crown recession after thinning.

The growth patterns of wood as interpreted from the basic data are similar to those described by Larson (1969). The major changes in wood formation occurred in the lower stem below the green crown. Some variation was observed in the base of the green crown, beneath the most active branches. The actual height of the most active zone varies little between thinning treatments. As branches in the upper crown carry a greater percentage of more efficient foliage than branches in the lower crown (Wood, 1969) and from 34% (Treatment 1) to 55% (Treatment 6) of the total foliage weight (Appendix 3), it is probable that leaves of those branches have a major effect on wood formation. Larson (1969) commented that "..... accumulated evidence strongly suggests that the foliar organs regulate wo formation during the entire seasonal course of development".

Thinning promotes an increase in both branch and crown size, which in turn increases the amount of wood formed in the bole. The increase in diameter growth is throughout the bole but dependent on stand density. At the base of the stem, the average ring width increases with thinning grade; at breast height the average ring widths for the 1970 sheath of trees in Treatments 1 and 6 are 0.90 and 0.36 cm respectively (cf. Jacobs, 1962). The maximum width of ring in the 1970 sheath occurred between 70% and 80% of total height in all treatments (Figure 5.8). These levels correspond to the greatest concentration of foliage in the crown (Appendix 3) in all treatments. This contrasts with the findings of Büsgen and Münch (1929) and Duff and Nolan (1953) that maximum ring width was immediately below the crown. Hall (1965) found maximum ring width at three-quarters of crown depth, which presumably was near the occurrence of maximum foliage concentration in the crowns of the P. resinosa trees of his study.

Thus ring width decreases with distance below the position of maximum ring width in all thinning treatments, the greatest decrease being found in the control and lightly thinned treatments (Figure 5.6). The variation in wood properties (Figures 5.2 to 5.5, 5.7) occurs below this level. Wood production is relatively uniform between treatments in the upper part of the stem, because at the 80% level of total height, in the region of the active crown, thinning has no effect as branches are in full sunlight.

The 23-year-old radiata pine trees exhibited the general tendency of the species for mean density to decrease with increasing height in the stem and to increase with increasing distance from the pith at any given height (e.g. Elliott, 1970a). The influence of increasing age and distance from the pith was therefore evident. Wood formed in the region of the crown was of lower density than wood formed below the crown and outside the juvenile core. Within the green crown, wood properties were relatively uniform over all stand densities (Figures 5.2 to 5.7).

Trees in the most heavily thinned stands have a larger amount of juvenile wood in the upper crown

(Figure 5.5) and a smaller percent latewood in the lower bole (Figure 5.7) than trees in the control or lightly thinned stands. Larson (1969) suggested a gradual latewood transition zone is found in the stem of more open-grown trees while in more closed stands the latewood transition is more abrupt, i.e. the type of latewood tracheid changes. Stand density affects wood quality by gradual changes in crown size, structure and efficiency. Larson (1962) thought that through these changes in the crown a large amount of the variability in wood quality can be interpreted. The intensity of thinning determines the degree of response to treatment.

Hence each of the six wood density parameters measured (maximum, minimum and mean density, density range, percent latewood and ring width) were influenced by thinning treatment when height within the stem was considered. Significant differences were found between thinning treatments and between different heights in the stem and there was significant interaction between the two factors (Table 5.1). Variation in wood properties at different levels within the crown is associated with corresponding variation in crown parameters as a response to thinning.

The relationship between the crown, the stem and bole wood is extremely complex and not amenable to simple description. For example, unless the state of health and relative efficiency of the individual branch are known, it is difficult to assess the contribution of that branch to stem growth - the fact that the needles are still green does not mean the branch is contributing. At any height specified in the tree branches of the same cross-sectional area may carry the same weight of foliage, but contribute quite differently to stem growth (cf. Labyak and Schumacher, 1954), depending on the amount of light received and needle age. Thus the influence of the individual branch on stem growth is determined by position of the branch in the crown, the efficiency of the foliage, and general environmental conditions.

The patterns of wood density distribution in one randomly selected tree of the 22.0 to 23.9 cm D.B.H.O.B. lass (1962) from each treatment were plotted on the stem profiles from 1961 to 1970, taking each second growth sheath (Figure 6.3). These five trees had a second degree paraboloidal shape before treatment and maintained the same shape afterwards. The data suggest that the tree meets its strength requirements by producing a smaller volume of high density wood (e.g. Treatment 6) or a larger volume of low density wood (e.g. Treatment 1), as postulated by Trendelenberg (1932, 1935), Schniewind (1962) and Doerner (1964). The wood density of the stem and strength properties are closely related (Fielding, 1967b).

The effect of thinning on stem form and taper is most interesting. The average stem form index decreased after treatment, and the shape tended towards the second degree paraboloidal shape postulated by Gray (1956). Over the 10-year study period, stem shape approximated a second degree paraboloid in 83% of the profiles examined. Prior to the first thinning at age 15 years, the shape of the larger trees in Treatment 1 was closer to a conoid, while the other trees tended towards the second degree paraboloid. Many researchers have found that stem shape within the green crown is approximately conoidal (Carron, 1968), and this is supported by the present study, because in Treatment 1 most sample discs came from the region of the crown. Trees in this treatment tended to retain a

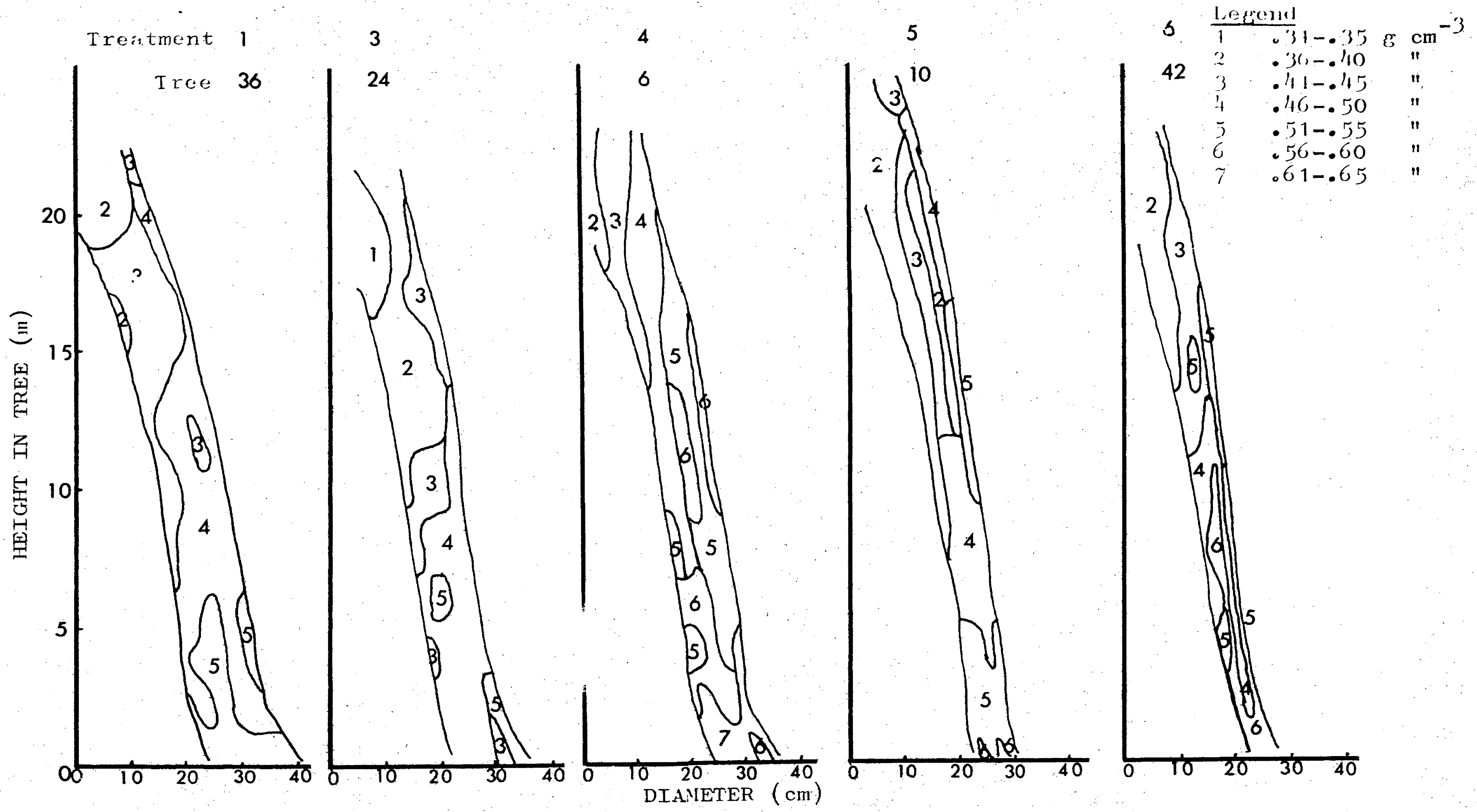


FIGURE 6.3 Patterns of wood density distribution from 1961 to 1970 in one tree per treatment from the 22.0-23.9 cm diameter class (1962).

uniform stem form index because thinning delayed the recession of the crown and the distribution of samples from within and below the green crown remained relatively constant.

The cubic paraboloidal shape proposed by Metzger (Büsgen and Münch, 1929)-the proposal has had considerable support in the literature (e.g. Assmann, 1970) - was found after thinning in a single tree (Tree 31) which came from Treatment 5.

Petrini (1921) had suggested a stem equation comparable to the one used in Chapter 4, viz.

$$y^2 = k\,x^b$$ (Whyte, 1971)

where y = radius of cross-section at x

x = distance from apex

k = a constant

b = the stem form index.

The results of this study agree with Petrini's suggestion that the power value "b" describing the stem shape was rarely a whole number (Appendix 5), in contrast to the opinion of Gray (1956).

The propositions advanced by Metzger and by Gray (1956) regarding the shape of the tree stem, together with those of Jonson (1910-12) describe the stem in part only, because the shape actually changes along the length of the stem. The base of a plantation-grown radiata pine is neiloidal in shape, being affected by buttswell. In this study buttswell effects were obvious to approximately 2.5 m above ground, over the range of treatments. Above the buttswell, the main part of the bole has generally been considered a second degree paraboloid, while the section of the stem in the upper crown is generally conoidal (Carron, 1968). The results presented in Chapter 4 confirm this.

Even though there are two major points of inflection in the stem, there may be several minor points. The shape of the stem is determined by the way in which each successive sheath is laid down along the length of the bole (Figure 4.4). Any variation in shape would result from differences in ring width at different heights in the tree.

The bending force of the wind and the weight of the crown and stem produce stresses which result in redistribution of growth along the bole. Although more than 80% of the stem profiles studied were second degree paraboloids, Gray's (1956) theory is based on the tree being anchored in a relatively weak substrate and so requiring less stem volume than the third degree paraboloid postulated by Metzger. However, the two control plots excluded from sampling because of severe wind damage were damaged soon after the light thinning in 1967 to maintain stand hygiene. Trees were broken rather than wind-thrown, suggesting that part of the response after thinning is adjustment of tree shape to counteract the general climatic conditions found in the area (e.g. Jacobs, 1954). Therefore, some trees were unable to withstand the stresses imposed by a severe storm after the structure of the canopy was changed by thinning. The mechanistic theory apparently does not explain all variation found in the stem shape of forest trees.

There is no evidence from the data that either nutritional gradients (e.g. Hall, 1965) or hormonal gradients (e.g. Larson, 1963a) regulate the distribution of radial growth along the stem and hence stem form and taper. However, these hypotheses would help to interpret the phenomenon of changes in stem shape and taper resulting from the bending stresses imposed by the wind and the weight of the tree. Duffields' (1968) "dynamic hypothesis" suggested the involvement of piezoelectric effects as an extension of the auxin hypothesis.

Thinning has a considerable effect on stem taper. The average stem taper of trees in both the thinned and the control stands was similar before treatment. Average taper increased in all treatments, the increase ranging from 55% in the most heavily thinned stand to 6% in the control. The latter required a light thinning in 1967. Although stem form remained constant in the most heavily thinned treatment, taper increased considerably.

At the standard rates of thinning employed in Australian radiata pine plantations, viz. thinning to a lower basal area limit of 23 to 30 m^2ha^{-1} depending on site and age (Shepherd, 1970), the effect of treatment on stem taper is limited (Table 4.2).

In the previous discussion, the importance of the association between crown, stem and wood density was discussed. The principal component analysis relating variables indicated strong correlations between the crown and stem (Tables 6.1, 6.2), bearing in mind that relationships between crown size and stem growth may or may not give a good statistical correlation because of the varying contributions of branches to stem growth. However, it is evident the processes of wood formation are directly affected by the size and efficiency of the green crown, hence the crown and stem shape and taper are closely related.

The effect of thinning on foliage biomass and stem volume production as elements of stand growth was considered.

In Australian-grown radiata pine, biomass and annual productivity have received little attention. Forrest and

Ovington (1970) studied an age sequence of stands in the Tumut area to estimate the biological production of the total plantation ecosystem. The stands, aged up to 12 years, were regarded as representing the development of an individual stand. Dargavel (1970) estimated the biomass of individual trees, but did not extrapolate his findings to an area basis. However, no assessments had been made of foliage biomass in stands over 20-year-old, or of the effect of thinning on foliage biomass in Australian pine plantations until this study.

The strong correlation between the weight of foliage in the individual tree and stem D.B.H.O.B. (Table 3.6) indicated these variables could be used to estimate stand foliage biomass. This was found to increase with increasing stand density (Table 3.7).

Generally, it is accepted that within certain basal area limits the weight of foliage per hectare of a forest stand is relatively constant (Möller, 1947; Satoo <u>et al</u>., 1955). Although the range of stand densities specified by Möller (1947) corresponds to the basal area range of Treatments 3 to 5 (18.4 to 34.5 m^2ha^{-1}) in the thinning trial reported here, the weight of foliage per hectare differs significantly between treatments. A possible explanation for the difference in foliage biomass at different stand densities is that the stands in the study were thinned every two or three years. This is a shorter period than the average life of the needles (three to five years) so new foliage produced after thinning is not fully developed. Consequently the more heavily thinned stands may carry less weight of foliage than usual for stands of their basal area. The maximum estimate for foliage biomass of 8.9 tonnes ha^{-1} in the control plots is slightly less than the weight estimated by Forrest and Ovington (1970) of 9.2 tonnes ha^{-1} for 12-year-old stands of radiata pine at a basal area of 32.9 m^2ha^{-1}. Forrest and Ovington suggested that after the 10th year foliage biomass remains relatively constant with perhaps a slight decrease with time.

The relationship between foliage weight per tree and total stem volume increment from 1968 to 1970 seemed to be independent of thinning (Table 3.13). However, foliage weight is not the only determinant of volume production. The age of needles and their relative efficiencies at different heights in the tree, and at different stand densities, also influence production. Volume increment was poorest in the most heavily thinned stands where foliage biomass was least, but increment in the unthinned stand with greatest foliage biomass was only slightly greater than in the moderately or lightly thinned stands.

Shepherd and Forrest (in press) estimated merchantable volume production to 10 cm d.u.b. in the study plots. The merchantable volume increment (1968 to 1970) in the control was less than increment in Treatment 5 and approximately equal to increment in Treatment 4. However, when these merchantable volume increments are related to foliage biomass estimates from this study, the quantity of foliage required to produce one cubic metre of merchantable wood in Treatments 1 to 6 is 0.23, 0.21, 0.22 and 0.29 tonnes ha^{-1} respectively. The unthinned control treatment is therefore relatively inefficient as far as merchantable volume production is concerned. Even a light thinning apparently allows the foliage to be more efficient.

Shepherd and Forrest (op.cit) found that, overall, light thinning in Treatment 4 (23.3 - 29.9 m^2ha^{-1}) produced the largest merchantable volume to 10 cm d.u.b.. After the initial thinning in 1962 and rethinning in 1964 and 1967 the merchantable volume increment produced in Treatments 4, 5 and 6 was similar. A light thinning therefore, rather than a heavy thinning, results in more volume production.

The silvicultural treatments applied to forest stands depend generally on current management objectives, which should allow a certain amount of flexibility because market requirements may change over a short time. The silvicultural requirements of the forest are in effect flexible, and decisions in forestry management now tend to depend on such criteria as the current market demand and forecasts of future demand, with the objective of maximizing profits from the forestry enterprise while ensuring an adequate supply of forest products.

Thinning as a cultural treatment has considerable importance in forestry, particularly with regard to utilization and mensuration. From the utilization viewpoint, the quality of the product for a particular end use depends on the manner in which the crown and stem have developed. The increased crown size following thinning is related to the intensity of treatment, and is the result of increasing diameter and length of green branches. In lightly thinned stands the lowest branches apparently do not respond to thinning by increased growth. These branches become moribund and die, and crown recession continues upward. In the most heavily thinned stands, the recession almost ceases. In the study stand the base of the green crown in every tree was above the upper limit of pruning, so some crown recession had occurred after treatment. With larger branches, wood quality suffers because of the large knots found over the major length of the bole after the continued development of the lower branches. These affect peeling quality, veneer appearance, pulp qualities and the strength properties of sawn timber (Wright, 1971).

In radiata pine, the number of whorls, the number of branches per whorl, branch diameter and angle, internode length and stem taper are characteristics associated with wood quality (Fielding, 1967b). The number of branches per whorl and internode length are under strong genetic co control. The other variables can be controlled by thinning.

The results of the study indicate that heavier thinning produces larger, more tapered logs. However, this is economically advantageous where sawlogs rather than pulp logs are required, because of the large price differential between royalties paid on sawlogs of different size classes. Shepherd and Forrest (in press) found in the same thinning trial that light thinning produces the maximum yield of pulp logs.

From the mensurational aspect, the findings on stem taper are important. The significant differences in average stem taper between trees of different size classes at a given stand density, and between trees of the same size class in stands of different densities, suggests a measure of stem taper is essential as an independent variable in the preparation of tree and stand volume tables. Estimates of stem volume from such tables would be considerably more precise than estimates from tables based on D.B.H.O.B. and total height only. The radiata pine general volume table prepared in 1955 includes stem taper.

Because stand density has such a great influence on the quality of wood formed, the silviculturist controls the initial stocking by spacing, and once canopy closure occurs, stand density can be regulated by thinning. Judicious thinning schedules are a valuable means of regulating both wood yield and quality, because in uncontrolled growth lack of uniformity in the wood is a major problem to the wood-using industries. Other silvicultural treatments such as fertilizing and pruning influence wood properties, but overall thinning is the most useful technique available. Thinning affects crown development, and through the crown influences the processes of wood formation and the size and shape of the stem.

APPENDIX 1

Crown and branch data for individual trees by thinning treatment

Thinning T'ment	Tree No.	Total height (m)	Crown length (m)	Height lowest Whorl (m)	Crown length ratio	No. green Whorls	Whorls/ Crown length	No. green branches	Mean branches /whorl	Mean branch diam (cm)	Total branches sec.area (cm^2)	Mean branch sec. area (cm^2)
1	3	28.5	23.2	5.3	.81	41	1.8	176	4.3	2.4	1212.1	6.9
	4	29.0	22.5	6.5	.78	48	2.1	196	4.1	2.5	1309.0	6.7
	19	29.6	23.1	6.4	.78	46	2.0	231	5.0	2.5	1591.6	6.9
	20	28.0	21.9	6.1	.78	50	2.3	226	4.6	1.7	798.1	3.5
	35	28.0	20.6	7.5	.73	32	1.6	168	5.3	2.2	874.5	5.2
	36	26.5	18.0	8.5	.68	39	2.2	243	6.2	1.6	808.8	3.3
	55	28.2	20.7	7.4	.74	47	2.3	223	4.7	2.3	1433.6	6.5
	56	27.9	21.9	6.0	.78	34	1.6	174	5.1	2.4	1122.8	6.4
3	1	28.2	21.3	6.8	.76	42	2.0	207	4.9	2.0	876.6	4.2
	2	26.8	20.4	6.4	.76	57	2.8	288	5.1	1.5	721.5	2.5
	21	29.6	23.1	6.5	.78	47	2.0	217	4.6	2.1	1130.2	5.2
	22	28.0	19.8	8.3	.70	46	2.3	278	6.0	1.6	801.6	2.9
	23	26.8	19.0	7.8	.71	52	2.7	280	5.4	1.6	727.4	2.6
	24	27.9	18.4	9.5	.66	36	2.0	163	4.6	1.9	687.1	4.2
	50	28.7	22.2	6.4	.78	47	2.1	222	4.7	2.3	1440.4	6.5
	51	28.0	21.4	6.9	.75	44	2.1	195	5.8	2.2	1316.8	5.2
4	5	28.2	17.7	10.5	.63	54	3.1	224	4.2	2.0	964.8	4.3
	6	27.1	20.8	6.3	.77	42	2.0	232	5.5	1.7	822.8	3.6
	7	27.7	20.8	6.9	.75	48	2.3	250	5.2	1.9	838.3	3.3
	16	31.1	21.6	9.5	.69	47	2.2	200	4.3	2.9	1809.6	9.0
	17	28.7	20.9	7.8	.73	44	2.1	222	5.1	2.2	1263.8	5.7
	18	29.0	20.8	8.1	.72	34	1.6	205	6.0	1.9	875.0	4.3
	37	29.0	20.4	8.6	.70	55	2.7	211	3.8	1.6	612.4	2.9
	38	29.3	21.2	8.0	.72	42	2.0	223	5.3	1.8	787.8	3.5
	39	27.7	19.7	8.0	.71	37	1.9	229	6.2	1.6	736.2	3.2
	52	28.7	21.4	7.2	.75	48	2.2	253	5.3	2.2	1316.8	5.2
	53	28.3	18.4	9.9	.65	41	2.2	210	5.1	1.8	668.2	3.2
	54	27.4	18.2	9.3	.66	42	2.3	184	4.4	1.5	557.8	3.0

Thinning T'ment	Tree No.	Total height (m)	Crown length (m)	Height lowest Whorl (m)	Crown length ratio	No. green Whorls	Whorls/ Crown length	No. green branches	Mean branches /whorl	Mean branch diam (cm)	Total branches sec.area (cm^2)	Mean branch sec. area (cm^2)
5	8	28.3	19.4	9.0	.68	34	1.8	149	4.4	2.0	716.8	4.8
	9	30.5	20.0	10.5	.65	39	2.0	169	4.3	1.9	644.7	3.8
	10	29.5	19.3	10.2	.65	49	2.5	261	5.3	1.4	626.3	2.4
	11	26.8	10.3	16.6	.38	18	1.8	123	6.8	1.7	378.7	3.1
	12	29.9	19.0	10.9	.64	36	1.9	177	4.9	2.3	1111.4	6.3
	13	30.5	20.0	10.5	.66	49	2.5	179	3.7	1.7	567.4	3.2
	14	29.3	20.1	9.1	.69	56	2.8	299	5.3	1.5	784.0	2.6
	15	27.7	15.4	12.3	.55	47	3.1	205	4.4	1.5	477.2	2.3
	31	30.2	21.1	9.1	.70	42	2.0	235	5.6	1.9	893.4	3.8
	32	29.9	22.4	7.5	.75	27	1.2	167	6.2	2.1	821.7	4.9
	33	27.4	16.9	10.5	.62	22	1.3	96	4.4	2.3	499.2	5.2
	34	26.8	12.0	14.8	.45	27	2.3	126	4.7	1.3	216.8	1.7
	46	29.6	23.1	6.5	.78	48	2.1	228	4.7	1.7	720.5	3.2
	47	29.9	20.0	9.9	.67	38	1.9	164	4.3	1.7	507.9	3.1
	48	25.6	17.3	8.3	.68	27	1.6	178	6.6	1.7	585.6	3.3
	49	26.5	19.1	7.4	.72	35	1.8	182	5.2	1.6	489.6	2.7
6	25	31.1	16.8	14.3	.54	28	1.7	130	4.6	2.3	948.5	7.3
	26	29.9	14.9	15.0	.50	40	2.7	227	5.7	1.4	573.1	2.5
	27	29.7	15.4	14.2	.52	35	2.5	167	4.8	1.7	574.3	3.4
	28	28.2	16.3	11.9	.58	41	2.5	177	4.3	1.4	371.2	2.1
	29	29.0	14.5	14.5	.50	34	2.3	182	5.4	1.6	485.5	2.7
	30	28.2	11.9	16.3	.42	27	2.3	120	4.4	1.4	231.0	1.9
	40	27.8	15.1	12.7	.54	36	2.4	193	5.4	1.6	560.5	2.9
	41	26.6	13.8	12.9	.52	29	2.1	179	6.2	1.6	520.8	2.9
	42	27.0	15.2	11.8	.56	23	1.5	122	5.3	1.8	410.8	3.4
	43	27.7	15.4	12.4	.55	40	2.6	178	4.5	1.5	368.1	2.1
	44	26.2	12.2	14.0	.46	31	2.5	141	4.6	1.4	287.5	2.0
	45	25.1	12.3	12.8	.49	33	2.7	146	4.4	1.3	239.2	1.6

APPENDIX 2

Weight distribution of foliage by age class in the crown of 23-year-old radiata pine (kg)

Thinning Treatment	Tree No.	Foliage Age	% Total Height							
			90 - 100	80 - 90	70 - 80	60 - 70	50 - 60	40 - 50	30 - 40	20 - 30
1	3	1	0.55	3.58	2.70	4.75	2.57	1.01	1.81	0.50
		2	0.14	1.31	1.22	3.42	1.85	0.94	1.69	0.36
		3+	-	0.31	.70	3.27	1.86	1.02	1.84	0.32
	4	1	1.07	2.51	5.73	3.46	3.22	1.44	1.34	0.70
		2	.25	0.91	2.47	2.49	2.32	1.33	1.28	0.62
		3+	-	0.25	1.21	2.36	2.31	1.45	1.10	0.49
	19	1	0.56	1.92	5.54	5.29	3.70	1.98	2.11	1.58
		2	0.16	0.70	2.44	3.81	2.67	1.97	1.99	1.41
		3+	-	0.20	1.25	3.62	2.57	2.05	1.96	1.10
	20	1	0.87	2.96	3.72	1.56	1.73	0.48	0.58	0.29
		2	0.26	1.08	1.74	1.10	1.25	0.41	0.60	0.29
		3+	-	0.31	1.06	1.01	1.33	0.47	0.40	0.21
	35	1	0.95	2.94	2.76	2.09	1.95	0.77	0.72	0.74
		2	0.24	1.07	1.22	1.51	1.41	0.63	0.68	0.62
		3+	-	0.31	0.62	1.41	1.45	0.74	0.63	0.51
	36	1	1.02	1.67	3.50	2.90	1.75	0.71	0.44	-
		2	0.27	0.60	1.61	2.09	1.27	0.62	0.43	-
		3+	-	0.20	0.95	1.96	1.33	0.70	0.28	-
	55	1	0.40	4.12	6.79	5.27	3.39	0.99	1.04	0.37
		2	0.15	1.52	2.89	3.79	2.45	0.88	0.99	0.35
		3+	-	0.34	1.35	3.61	2.49	0.98	0.80	0.26
	56	1	0.68	0.64	2.86	7.51	1.80	0.83	1.37	0.68
		2	0.18	0.23	1.21	5.39	1.30	0.68	1.31	0.59
		3+	-	0.01	0.57	5.19	1.38	0.80	1.06	0.47
3	1	1	0.82	2.51	3.10	2.02	2.55	0.93	0.71	0.27

Thinning Treatment	Tree No.	Foliage Age	% Total Height							
			90 - 100	80 - 90	70 - 80	60 - 70	50 - 60	40 - 50	30 - 40	20 - 30
3	1	2	0.23	0.90	1.46	1.46	1.84	0.81	0.68	0.27
		3+	-	0.31	0.91	1.36	1.79	0.91	0.47	0.20
	2	1	1.29	1.22	4.07	1.61	1.16	0.82	0.41	0.19
		2	0.39	0.43	1.82	1.16	0.84	0.68	0.41	0.20
		3+	-	0.19	1.00	1.07	0.91	0.79	0.20	0.14
	21	1	0.58	3.26	5.71	2.61	1.99	1.38	0.93	0.67
		2	0.21	1.20	2.46	1.88	1.44	1.20	0.89	0.59
		3+	-	0.28	1.20	1.77	1.41	1.36	0.69	0.47
	22	1	1.16	2.99	2.51	1.38	1.84	0.44	0.92	0.42
		2	0.36	1.08	1.19	1.00	1.33	0.35	0.88	0.41
		3+	-	0.37	0.75	0.91	1.45	0.41	0.80	0.30
	23	1	0.48	2.53	2.05	1.48	1.34	0.90	0.90	0.07
		2	0.17	0.90	0.99	1.07	0.97	0.69	0.87	0.08
		3+	-	0.35	0.66	0.97	1.06	0.84	0.60	0.05
	24	1	0.58	3.51	2.25	2.04	0.79	0.77	0.45	-
		2	0.15	1.28	1.07	1.47	0.57	0.66	0.44	-
		3+	-	0.34	0.67	1.37	0.62	0.75	0.27	-
	50	1	0.67	3.05	4.38	4.15	4.19	1.72	1.29	1.68
		2	0.23	1.11	1.93	2.99	3.02	1.78	1.21	1.31
		3+	-	0.30	1.01	2.85	2.85	1.82	1.20	1.13
	51	1	0.53	2.02	1.76	1.72	1.46	0.63	0.69	0.48
		2	0.15	0.73	0.87	1.24	1.06	0.50	0.68	0.46
		3+	-	0.24	0.60	1.15	1.14	0.60	0.39	0.34
4	5	1	1.73	3.27	2.97	3.57	1.87	1.02	0.27	-
		2	0.47	1.18	1.31	2.58	1.35	0.83	0.26	-
		3+	-	0.36	0.69	2.42	1.43	0.97	0.21	-
	6	1	1.25	2.96	2.30	2.65	1.84	0.59	0.61	0.15

Thinning Treatment	Tree No.	Foliage Age	% Total Height							
			90 - 100	80 - 90	70 - 80	60 - 70	50 - 60	40 - 50	30 - 40	20 - 30
4	6	2	0.33	1.08	1.12	1.91	1.33	0.48	0.59	0.11
		3+	-	0.33	0.76	1.80	1.41	0.56	0.47	0.10
	7	1	0.93	1.13	3.37	1.94	1.76	0.90	0.71	0.97
		2	0.27	0.40	1.58	1.40	1.28	0.69	0.69	0.97
		3+	-	0.15	0.96	1.29	1.40	0.83	0.41	0.71
	16	1	0.97	5.68	5.69	5.87	6.55	2.74	0.74	-
		2	0.26	2.08	2.48	4.22	4.72	2.44	0.70	-
		3+	-	0.53	1.24	4.04	4.48	2.56	0.65	-
	17	1	1.60	3.11	4.97	2.70	3.74	1.14	1.21	0.69
		2	0.38	1.13	2.20	1.95	2.70	1.06	1.15	0.55
		3+	-	0.34	1.15	1.83	2.59	1.15	0.99	0.47
	18	1	1.00	2.73	2.48	2.84	2.17	0.56	0.87	0.29
		2	0.27	0.99	1.13	2.05	1.57	0.48	0.83	0.28
		3+	-	0.34	0.63	1.92	1.61	0.55	0.69	0.21
	37	1	0.46	2.29	1.81	2.02	1.47	0.32	0.39	0.08
		2	0.16	0.82	0.89	1.46	1.06	0.26	0.37	0.07
		3+	-	0.29	0.60	1.35	1.17	0.30	0.24	0.05
	38	1	1.00	2.73	2.97	1.49	1.55	0.90	0.56	0.35
		2	0.25	0.99	1.38	1.08	1.12	0.71	0.55	0.35
		3+	-	0.32	0.84	0.99	1.21	0.85	0.33	0.25
	39	1	0.63	0.74	2.63	3.86	1.47	0.49	0.65	0.14
		2	0.22	0.26	1.20	2.78	1.07	0.37	0.64	0.17
		3+	-	0.12	0.69	2.63	1.19	0.45	0.39	0.11
	52	1	1.52	2.37	5.77	2.79	2.94	1.41	1.33	1.07
		2	0.36	0.86	2.56	2.01	2.13	1.19	1.27	1.00
		3+	-	0.27	1.34	1.88	2.19	1.36	1.05	0.76
	53	1	1.43	2.07	2.60	1.25	1.08	0.70	0.60	-

Thinning Treatment	Tree No.	Foliage Age	% Total Height							
			90 - 100	80 - 90	70 - 80	60 - 70	50 - 60	40 - 50	30 - 40	20 - 30
4	53	2	0.38	0.75	1.21	0.91	0.79	0.55	0.59	-
		3+	-	0.26	0.72	0.83	0.90	0.66	0.36	-
	54	1	0.33	1.96	1.10	2.75	1.20	0.61	0.20	--
		2	0.12	0.71	0.56	1.98	0.87	0.54	1.97	-
		3+	-	0.24	0.43	1.88	0.94	0.60	0.12	-
5	8	1	0.80	1.05	1.47	3.59	2.33	0.57	0.57	-
		2	0.25	0.38	0.72	2.58	1.69	0.59	0.53	-
		3+	-	0.13	0.49	2.45	1.74	0.60	0.70	-
	9	1	0.84	1.49	2.85	0.96	1.54	1.01	0.44	-
		2	0.24	0.54	1.29	0.70	1.11	0.81	0.42	-
		3+	-	0.17	0.71	0.64	1.20	0.96	0.30	-
	10	1	0.83	2.15	1.54	1.46	1.19	0.98	0.46	-
		2	0.26	0.78	0.76	1.05	0.86	0.78	0.44	-
		3+	-	0.26	0.54	0.97	0.93	0.42	0.30	-
	11	1	0.79	1.74	1.99	1.74	-	-	-	-
		2	0.21	0.62	0.97	1.26	-	-	-	-
		3+	-	0.23	0.66	1.16	-	-	-	-
	12	1	1.16	0.79	6.27	3.91	2.85	1.54	0.56	-
		2	0.31	0.28	2.64	2.81	2.06	1.47	0.54	-
		3+	-	0.11	1.23	2.68	2.04	1.57	0.46	-
	13	1	0.67	1.18	1.85	1.75	1.19	0.80	0.47	-
		2	0.16	0.42	0.87	1.27	0.86	0.67	0.45	-
		3+	-	0.17	0.54	1.18	0.91	0.77	0.31	-
	14	1	0.79	1.68	2.37	1.12	3.05	1.08	0.85	-
		2	0.25	0.60	1.19	0.81	2.20	0.88	0.81	-
		3+	-	0.27	0.87	0.74	2.08	1.04	0.60	-

Thinning Treatment	Tree No.	Foliage Age	% Total Height							
			90 - 100	80 - 90	70 - 80	60 - 70	50 - 60	40 - 50	30 - 40	20 - 30
5	15	1	0.44	2.05	2.16	1.16	0.85	0.37	-	-
		2	0.15	0.74	1.07	0.84	0.62	0.27	-	-
		3+	-	0.27	0.75	0.76	0.71	0.34	-	-
	31	1	0.97	3.03	3.11	2.77	1.76	1.06	0.41	-
		2	0.31	1.10	1.50	2.00	1.27	0.85	0.39	-
		3+	-	0.33	0.96	1.85	1.27	1.01	0.26	-
	32	1	0.36	3.40	1.02	1.95	2.16	0.74	1.24	0.64
		2	0.13	1.23	0.45	1.40	1.56	0.62	1.19	0.56
		3+	-	0.36	0.24	1.31	1.56	0.71	0.90	0.44
	33	1	0.69	1.92	1.28	1.02	1.57	0.67	0.21	-
		2	0.17	0.70	0.59	0.74	1.13	0.59	0.20	-
		3+	-	0.21	0.32	0.68	1.15	0.66	0.14	-
	34	1	0.47	1.44	0.72	0.58	0.25	-	-	-
		2	0.15	0.51	0.38	0.42	0.18	-	-	-
		3+	-	0.22	0.31	0.38	0.22	-	-	-
	46	1	0.52	2.74	2.06	1.56	1.64	0.78	0.68	0.08
		2	0.17	0.99	0.98	1.13	1.19	0.64	0.66	0.07
		3+	-	0.30	0.62	1.04	1.29	0.75	0.48	0.06
	47	1	0.63	1.17	2.33	1.03	1.78	0.24	0.33	-
		2	0.20	0.42	1.12	0.74	1.29	0.20	0.30	-
		3+	-	0.13	0.72	0.68	1.35	0.23	0.24	-
	48	1	0.73	1.87	2.01	0.76	1.96	0.44	0.76	-
		2	0.20	0.67	1.00	0.55	1.41	0.39	0.73	-
		3+	-	0.25	0.70	0.50	1.39	0.43	0.54	-
	49	1	1.18	1.27	2.01	1.03	0.95	0.32	0.20	0.30
		2	0.28	0.45	1.01	0.75	0.69	0.23	0.20	0.53
		3+	-	0.17	0.74	0.68	0.76	0.29	0.13	0.20

Thinning Treatment	Tree No.	Foliage Age	% Total Height							
			90 - 100	80 - 90	70 - 80	60 - 70	50 - 60	40 - 50	30 - 40	20 - 30
6	25	1	0.66	1.18	5.52	5.35	2.76	0.37	-	-
		2	0.21	0.43	2.26	3.85	1.99	0.35	-	-
		3+	-	0.16	0.98	3.69	1.92	0.38	-	-
	26	1	1.32	2.50	1.61	0.96	2.91	-	-	-
		2	0.34	0.90	0.81	0.70	2.10	-	-	-
		3+	-	0.33	0.60	0.63	2.03	-	-	-
	27	1	0.49	1.91	2.40	1.74	1.54	0.60	-	-
		2	0.16	0.69	1.11	1.26	1.11	0.60	-	-
		3+	-	0.27	0.70	1.17	1.17	0.63	-	-
	28	1	0.46	0.98	2.16	0.97	0.65	0.28	-	-
		2	0.15	0.35	1.06	0.71	0.47	0.24	-	-
		3+	-	0.16	0.76	0.64	0.52	0.27	-	-
	29	1	0.93	2.55	1.96	1.18	0.80	0.19	-	-
		2	0.25	0.92	0.99	0.86	0.58	0.15	-	-
		3+	-	0.30	0.71	0.78	0.67	0.18	-	-
	30	1	1.17	1.09	1.49	0.18	0.15	-	-	-
		2	0.31	0.39	0.78	0.13	0.11	-	-	-
		3+	-	0.17	0.63	0.19	0.13	-	-	-
	40	1	1.20	1.61	2.19	1.53	1.50	0.49	-	-
		2	0.29	0.58	1.06	1.11	1.08	0.40	-	-
		3+	-	0.23	0.72	1.02	1.14	0.47	-	-
	41	1	1.22	1.98	2.13	1.27	1.28	0.25	-	-
		2	0.30	0.71	1.05	0.92	0.93	0.22	-	-
		3+	-	0.25	0.73	0.84	1.01	0.25	-	-
	42	1	0.68	1.44	1.55	1.19	0.68	0.55	-	-
		2	0.19	0.52	0.75	0.86	0.49	0.45	-	-
		3+	-	0.20	0.48	0.80	0.53	0.53	-	-

Thinning Treatment	Tree No.	Foliage Age	% Total Height							
			90 - 100	80 - 90	70 - 80	60 - 70	50 - 60	40 - 50	30 - 40	20 - 30
6	43	1	0.67	1.82	1.61	0.81	0.70	0.06	-	-
		2	0.21	0.65	0.83	0.59	0.51	0.04	-	-
		3+	-	0.60	0.63	0.53	0.59	0.05	-	-
	44	1	0.64	0.92	1.17	1.13	0.59	-	-	-
		2	0.19	0.33	0.61	0.82	0.43	-	-	-
		3+	-	0.15	0.50	0.76	0.47	-	-	-
	45	1	0.50	1.15	0.98	0.51	0.52	-	-	-
		2	0.14	0.41	0.53	0.37	0.38	-	-	-
		3+	-	0.20	0.46	0.33	0.44	-	-	-

APPENDIX 3

Effect of thinning on the distribution of needles in the crown of radiata pine. Results expressed as percentages of total foliage weight in the crown.

Thinning Treatment	Foliage Age (yr)	% Total Height																	
		90-100		80-90		70-80		60-70		50-60		40-50		30-40		2 20-30		Combined	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
1	1	2.5	1.3	7.6	3.7	12.0	3.3	11.3	4.3	7.1	0.9	2.8	0.7	3.2	1.0	1.6	1.0	48.0	2.5
	2	0.7	0.4	2.3	1.3	5.3	1.6	8.1	3.0	5.1	0.7	2.5	0.7	3.0	0.9	1.4	0.9	28.9	0.6
	3+	-	-	0.8	0.4	2.8	1.0	7.7	3.0	5.4	0.8	2.8	0.7	2.7	1.2	1.0	0.7	23.1	2.0
	Total	3.2	1.6	11.2	0.8	20.1	5.8	27.1	10.3	17.4	2.2	8.2	2.1	8.9	3.2	4.1	2.6		
3	1	3.2	1.6	10.6	3.7	12.3	3.7	8.0	1.3	7.0	1.9	3.6	0.8	3.1	0.9	1.5	1.2	49.2	1.9
	2	1.0	0.4	3.8	1.4	5.7	1.5	5.8	0.9	5.1	1.4	3.1	0.7	2.9	0.8	1.4	0.4	28.8	0.6
	3+	-	-	1.3	0.4	3.4	0.7	5.4	0.9	5.2	1.3	3.5	0.8	2.9	0.8	1.1	0.8	22.0	1.5
	Total	4.2	2.1	15.1	5.5	21.1	5.8	19.2	3.1	17.3	4.3	10.1	2.3	8.1	2.4	4.0	3.0		
4	1	4.0	1.7	9.4	3.2	11.2	2.4	10.2	3.5	7.6	1.6	3.1	0.8	2.4	0.9	1.1	1.2	49.1	1.7
	2	1.0	0.4	3.4	1.2	5.2	1.1	7.4	2.5	5.5	1.1	2.7	0.8	2.3	0.8	1.0	1.2	28.6	0.5
	3+	-	-	1.1	0.4	3.1	0.7	6.9	2.4	5.9	0.8	3.0	0.8	1.7	0.7	0.7	0.9	22.3	1.3
	Total	5.0	2.1	13.9	4.7	19.5	4.0	24.6	8.4	19.0	3.4	8.8	2.4	6.5	2.4	2.8	3.3		
5	1	4.4	1.8	10.9	5.0	12.0	3.9	8.8	3.2	8.0	3.2	3.3	1.7	2.2	1.5	0.3	0.8	49.8	2.8
	2	1.3	0.5	4.0	1.8	5.1	1.9	6.4	2.3	5.8	2.3	2.7	1.5	2.1	1.4	0.3	0.7	28.2	0.9
	3+	-	-	1.4	0.7	3.7	1.3	5.8	2.2	6.0	2.4	3.1	1.7	1.6	1.2	0.2	0.5	22.0	2.0
	Total	5.7	2.3	16.3	7.5	21.4	6.9	21.0	7.8	19.8	7.7	9.1	7.7	5.9	4.0	0.8	2.1		
6	1	6.8	3.8	12.6	4.2	14.9	3.3	9.0	3.5	7.7	3.3	1.5	1.6	-	-	-	-	52.4	2.8
	2	1.9	0.9	5.3	2.9	7.4	1.8	6.5	2.5	5.5	2.4	1.3	1.4	-	-	-	-	27.0	0.9
	3+	-	-	1.9	0.8	5.3	1.7	6.0	2.4	5.9	2.2	1.5	1.5	-	-	-	-	20.6	2.0
	Total	8.7	4.7	18.9	6.2	27.5	6.5	21.5	8.5	19.1	8.0	4.3	4.4	-	-	-	-		

APPENDIX 4

Estimated weight of foliage by age class, and overall, in crowns of all sample trees within thinning treatments

Thinning Treatment	Tree No.	D.B.H.O.B. (cm)	D (cm)	Foliage weights (kg) 1-yr	2-yr	3-yr(+)	Total
1	3	45.3	38.0	17.47	10.93	9.32	37.72
	4	47.1	36.3	19.47	11.67	9.17	40.31
	19	48.4	40.1	22.68	15.15	12.75	50.58
	20	41.9	33.0	12.19	6.73	4.79	23.71
	35	42.3	33.4	12.92	7.38	5.67	25.97
	36	40.4	30.4	11.99	6.89	5.42	24.30
	55	52.7	42.5	22.37	13.02	9.83	45.22
	56	45.9	35.4	16.37	10.89	9.48	36.74
3	1	40.8	34.3	12.91	7.65	5.95	26.51
	2	32.5	26.2	10.77	5.93	4.30	21.00
	21	44.4	36.9	17.13	9.87	7.18	34.18
	22	38.2	30.6	11.66	6.60	4.99	23.25
	23	33.4	26.6	9.75	5.74	4.53	20.02
	24	36.4	26.9	10.39	5.64	4.02	20.05
	50	45.0	36.0	21.13	13.58	11.16	45.87
	51	36.4	29.2	9.29	5.69	4.46	19.44
4	5	39.7	29.5	14.70	7.98	6.08	28.76
	6	36.8	29.6	12.35	6.95	5.43	24.73
	7	37.2	29.2	11.71	7.28	5.73	24.74
	16	53.1	41.7	28.24	16.90	13.50	58.64
	17	44.0	34.6	19.16	11.12	8.52	38.80
	18	39.6	30.5	12.94	7.60	5.95	26.49
	37	35.3	25.9	8.84	5.09	4.00	17.93
	38	40.9	30.2	11.55	6.43	4.79	22.27
	39	35.1	26.0	10.61	6.71	5.58	22.90
	52	46.0	35.7	19.20	11.38	8.85	39.43
	53	34.3	25.6	9.73	5.18	3.73	18.64
	54	32.4	23.8	8.15	6.75	4.21	19.11
5	8	38.4	30.1	10.38	6.74	6.11	23.23
	9	35.2	25.3	9.13	5.11	3.98	18.22
	10	31.5	23.8	8.61	4.93	3.92	17.46
	11	27.7	16.1	6.26	3.06	2.05	11.37
	12	40.2	29.7	17.08	10.11	8.09	35.28
	13	35.6	25.4	7.91	4.70	3.88	16.49
	14	33.0	24.4	10.94	6.74	5.60	23.28
	15	34.4	21.8	7.03	3.69	2.83	13.55
	31	40.1	30.6	13.11	7.42	5.68	26.21
	32	35.8	28.7	11.51	7.14	5.52	24.17
	33	32.2	23.3	7.36	4.12	3.16	14.64
	34	25.2	15.0	3.46	1.64	1.13	6.23
	46	35.6	32.3	10.06	5.83	4.54	20.43
	47	34.3	26.8	7.51	4.27	3.35	15.13
	48	30.7	21.8	8.53	4.95	3.81	17.29
	49	28.3	22.0	7.26	4.14	2.97	14.37

APPENDIX 4 (Continued)

2

Thinning Treatment	Tree No.	D.B.H.O.B. (cm)	D (cm)	Foliage weights (kg) 1-yr	2-yr	3-yr(+)	Total
6	25	43.8	29.1	15.84	9.09	7.13	32.06
	26	33.7	23.6	9.30	4.85	3.59	17.74
	27	33.8	21.2	8.68	4.93	3.94	17.55
	28	27.7	18.5	5.50	2.98	2.35	10.83
	29	29.8	19.0	7.61	3.75	2.64	14.00
	30	24.5	14.4	4.08	1.72	1.12	6.92
	40	35.6	23.7	8.52	4.52	3.58	16.62
	41	32.1	21.9	8.13	4.13	3.08	15.34
	42	29.2	19.0	6.09	3.26	2.54	11.89
	43	31.5	20.0	5.67	2.83	2.40	10.90
	44	25.3	16.7	4.45	2.38	1.88	8.71
	45	21.9	14.1	3.66	1.83	1.43	6.92

APPENDIX 5

Effect of thinning on the stem form index "b" of each sample tree. A value of 2.00 indicates a conoidal shape, 1.00 a second degree paraboloid, and 0.67 a third degree paraboloid.

Thin. Treat.	Tree No.	Before treat.	Year 1963	1964	1965	1966	1967	1968	1969	1970
1	3	1.62	1.69	1.74	1.74	1.67	1.61	1.62	1.60	1.52
	4	1.41	1.31	1.47	1.53	1.41	1.41	1.44	1.49	1.47
	19	1.70	1.52	1.49	1.52	1.44	1.45	1.59	1.54	1.52
	20	1.65	1.57	1.53	1.55	1.44	1.45	1.61	1.60	1.50
	35	1.25	1.24	1.23	1.24	1.29	1.28	1.28	1.31	1.27
	36	1.30	1.35	1.27	1.25	1.27	1.26	1.29	1.34	1.31
	55	1.39	1.18	1.13	1.23	1.25	1.28	1.33	1.41	1.42
	56	1.48	1.61	1.50	1.42	1.46	1.51	1.56	1.61	1.57
3	1	1.76	1.75	1.67	1.64	1.41	1.33	1.32	1.31	1.26
	2	1.32	1.34	1.32	1.56	1.61	1.47	1.47	1.43	1.37
	21	1.17	1.17	1.12	1.05	1.15	1.16	1.23	1.24	1.25
	22	1.39	1.38	1.05	1.20	1.20	1.18	1.21	1.22	1.17
	23	1.58	1.29	1.24	1.12	1.03	1.21	1.20	1.24	1.21
	24	1.33	1.40	1.18	1.17	1.21	1.22	1.24	1.25	1.23
	50	1.35	1.49	1.40	1.50	1.46	1.44	1.46	1.50	1.44
	51	1.34	1.32	1.28	1.15	1.26	1.30	1.33	1.36	1.35
4	5	1.55	1.45	1.49	1.44	1.41	1.31	1.30	1.27	1.22
	6	1.43	1.53	1.31	1.24	1.22	1.17	1.17	1.19	1.15
	7	1.54	1.67	1.47	1.37	1.37	1.31	1.29	1.29	1.25
	16	1.77	1.65	1.80	1.70	1.69	1.65	1.67	1.66	1.60
	17	1.52	1.38	1.58	1.40	1.39	1.31	1.31	1.33	1.32
	18	1.33	1.33	1.40	1.37	1.31	1.33	1.34	1.42	1.40
	37	1.43	1.35	1.34	1.31	1.21	1.27	1.34	1.33	1.20
	38	1.37	1.47	1.41	1.47	1.54	1.52	1.53	1.50	1.43
	39	1.26	1.15	1.25	1.32	1.37	1.42	1.45	1.47	1.42
	52	1.44	1.29	1.27	1.28	1.22	1.35	1.42	1.48	1.46
	53	1.48	1.43	1.42	1.47	1.38	1.35	1.35	1.32	1.26
	54	1.18	1.04	1.14	1.23	1.23	1.23	1.27	1.30	1.27
5	8	1.24	1.40	1.72	1.57	1.40	1.30	1.32	1.29	1.24
	9	1.48	1.57	1.66	1.43	1.28	1.20	1.21	1.18	1.14
	10	1.46	1.33	1.22	1.21	1.38	1.32	1.31	1.31	1.25
	11	1.48	1.44	1.30	1.21	1.06	0.98	1.01	1.04	1.05
	12	1.45	1.43	1.44	1.46	1.35	1.42	1.38	1.33	1.28
	13	1.35	1.38	1.35	1.32	1.32	1.34	1.39	1.47	1.50
	14	1.53	1.60	1.52	1.48	1.41	1.35	1.37	1.32	1.39
	15	1.40	1.34	1.27	1.41	1.18	1.16	1.18	1.20	1.20
	31	1.09	0.93	0.64	0.77	0.70	0.61	0.55	0.48	0.42
	32	1.45	1.34	1.05	0.91	1.05	1.05	1.07	1.08	1.04
	33	1.44	1.37	1.35	1.39	1.31	1.27	1.29	1.29	1.23
	34	1.19	1.15	1.10	1.08	1.08	1.08	1.13	1.17	1.18
	46	1.55	1.57	1.58	1.54	1.39	1.48	1.50	1.50	1.48
	47	1.39	1.30	1.04	0.93	1.12	1.15	1.16	1.12	1.09
	48	1.66	1.82	1.70	1.31	1.29	1.27	1.29	1.30	1.30
	49	1.26	1.25	1.31	1.27	1.16	1.04	1.03	1.10	1.09

APPENDIX 5 (Contd)

Thinn. Treat.	Tree No.	Before treat.	Year							
			1963	1964	1965	1966	1967	1968	1969	1970
6	25	1.44	1.23	1.26	1.49	1.47	1.44	1.48	1.45	1.43
	26	1.62	1.32	1.19	1.17	1.04	1.06	1.13	1.20	1.22
	[1]27		-	-	-	-	-	-	-	-
	28	1.37	1.44	1.34	1.33	1.22	1.18	1.19	1.19	1.19
	29	1.38	1.24	1.14	1.13	1.08	1.05	1.07	1.09	1.09
	30	1.45	1.03	0.94	0.89	0.84	0.80	0.81	0.86	0.92
	40	1.39	1.45	1.34	1.26	1.17	1.19	1.24	1.21	1.16
	41	1.76	1.46	1.45	1.40	1.29	1.22	1.22	1.19	1.15
	42	1.38	1.24	0.86	1.10	1.04	1.10	1.16	1.17	1.17
	43	1.29	1.24	1.17	1.16	1.12	1.08	1.11	1.97	1.07
	44	1.17	1.24	1.16	1.26	1.17	1.13	1.14	1.10	1.06
	45	1.88	1.33	1.31	1.33	1.12	1.13	1.17	1.16	1.16

[1] Accidently destroyed.

APPENDIX 6

Effect of thinning on stem taper index of each sample tree based on the height in tree/diameter squared relationship (m/m^2)

Thinn. Treat.	Tree No.	Before treat.	1963	1964	1965	1966	1967	1968	1969	1970
1	3	366	337	300	268	230	205	191	171	160
	4	404	358	311	271	245	218	202	177	162
	19	312	276	252	233	211	192	177	156	142
	20	365	350	316	287	260	246	231	211	201
	35	408	363	317	285	257	239	227	208	199
	36	425	381	345	314	288	262	240	210	196
	55	286	259	222	196	174	152	138	120	112
	56	387	299	263	236	214	192	180	163	156
3	1	332	310	292	270	250	230	216	196	186
	2	619	554	484	448	419	375	345	307	281
	21	339	322	295	269	249	234	220	198	183
	22	430	401	362	321	293	272	258	238	223
	23	371	372	379	372	361	349	333	308	293
	24	446	447	426	396	366	324	319	292	270
	50	369	336	304	270	248	226	214	189	179
	51	505	482	462	413	370	334	313	276	251
4	5	313	301	279	264	248	239	229	214	206
	6	441	414	394	362	337	316	303	279	269
	7	526	488	436	400	359	325	305	265	245
	16	226	208	194	175	185	145	136	124	115
	17	325	295	275	258	241	225	210	186	170
	18	538	523	477	426	375	338	303	255	224
	37	415	404	377	363	350	334	323	310	298
	38	491	445	396	352	323	295	279	248	231
	39	511	454	406	353	323	297	284	266	257
	52	312	281	253	232	211	196	187	172	165
	53	391	390	387	376	365	347	334	316	310
	54	597	581	549	498	449	413	386	354	330
5	8	280	262	254	241	237	233	232	225	223
	9	436	408	388	376	365	350	338	324	314
	10	394	408	392	393	387	371	362	346	331
	11	417	430	427	423	431	439	441	442	443
	12	377	359	344	330	316	299	287	268	251
	13	414	397	370	348	334	311	296	277	269
	14	445	430	423	409	398	380	370	340	321
	15	536	508	465	449	442	414	394	367	344
	31	374	370	369	350	327	309	294	275	261
	32	445	419	397	381	372	365	354	336	324
	33	403	392	381	368	363	351	339	328	322
	34	621	625	597	562	543	530	522	505	506
	46	367	343	326	318	300	278	269	251	236
	47	503	470	441	410	385	365	350	328	306
	48	436	423	412	420	412	404	396	371	354
	49	508	533	534	519	504	493	483	444	418

APPENDIX 6(Continued)

Thinn. Treat.	Tree No.	Before treat.	1963	1964	1965	1966	1967	1968	1969	1970
6	25	266	248	240	225	216	208	204	197	191
	26	249	248	250	256	263	273	277	278	280
	[1]27	-	-	-	-	-	-	-	-	-
	28	378	414	426	434	440	446	454	454	461
	29	550	528	507	498	491	472	455	431	411
	30	621	648	653	659	671	694	689	686	677
	40	322	325	326	325	319	312	308	294	280
	41	355	368	369	374	380	372	369	356	342
	42	476	492	486	486	482	471	469	448	436
	43	549	534	519	495	479	448	436	408	383
	44	547	512	509	511	516	523	527	530	529
	45	630	660	681	700	699	686	678	652	632

[1] Accidently destroyed.

APPENDIX 7

Maximum density within annual growth sheaths at different heights in the stem - average of all trees per treatment

Thinn. Treat.	% Height in Tree	Before Treat.	1963	1964	1965	1966	1967	1968	1969	1970
1	80	-	-	.55	.56	.57	.71	.65	.66	.67
	70	.63	.59	.64	.66	.66	.74	.65	.67	.67
	60	.64	.66	.67	.71	.67	.75	.64	.69	.69
	50	.71	.71	.70	.75	.70	.81	.64	.70	.70
	40	.75	.72	.73	.77	.70	.81	.66	.71	.71
	30	.77	.73	.75	.79	.71	.83	.68	.73	.71
	20	.78	.76	.75	.77	.72	.85	.68	.73	.72
	10	.78	.75	.76	.78	.72	.86	.68	.71	.72
	B.H.	.76	.72	.73	.76	.69	.83	.70	.70	.71
3	80	-	-	.64	.65	.62	.64	.61	.65	.67
	70	.62	.64	.64	.70	.68	.74	.64	.67	.68
	60	.62	.65	.68	.74	.71	.78	.71	.68	.68
	50	.68	.70	.70	.77	.73	.80	.67	.68	.71
	40	.71	.71	.73	.79	.73	.83	.66	.73	.74
	30	.74	.75	.75	.81	.77	.87	.69	.74	.74
	20	.77	.77	.76	.82	.76	.86	.69	.74	.73
	10	.79	.82	.79	.82	.79	.90	.71	.73	.75
	B.H.	.79	.79	.78	.80	.74	.84	.69	.70	.72
4.	80	-	-	.60	.64	.60	.70	.62	.66	.65
	70	.62	.71	.69	.71	.68	.74	.67	.69	.69
	60	.62	.68	.69	.75	.70	.77	.67	.69	.70
	50	.69	.72	.71	.80	.72	.82	.68	.71	.72
	40	.76	.76	.74	.80	.75	.86	.70	.74	.74
	30	.78	.81	.77	.83	.75	.87	.71	.73	.76
	20	.79	.81	.78	.82	.78	.88	.73	.74	.76
	10	.81	.83	.78	.81	.77	.88	.72	.72	.75
	B.H.	.80	.80	.78	.82	.73	.86	.71	.70	.72
5	80	-	-	.60	.65	.61	.70	.62	.65	.68
	70	.65	.57	.64	.72	.71	.70	.64	.69	.72
	60	.62	.70	.71	.79	.75	.79	.66	.71	.75
	50	.71	.74	.73	.82	.78	.86	.68	.72	.76
	40	.77	.77	.75	.83	.80	.87	.68	.75	.77
	30	.80	.81	.76	.84	.79	.86	.70	.74	.77
	20	.80	.82	.78	.83	.79	.86	.69	.74	.77
	10	.81	.84	.80	.84	.81	.89	.69	.76	.77
	B.H.	.81	.84	.81	.84	.80	.89	.70	.75	.77
6	80	-	-	.57	.60	.62	.69	.59	.65	.67
	70	.62	.56	.65	.72	.71	.79	.61	.68	.73
	60	.64	.70	.71	.75	.74	.82	.63	.72	.75
	50	.70	.74	.72	.76	.78	.83	.64	.73	.76
	40	.75	.75	.74	.77	.77	.84	.66	.75	.77
	30	.77	.78	.76	.76	.78	.84	.69	.75	.78
	20	.81	.83	.81	.79	.80	.86	.68	.74	.79
	10	.81	.83	.81	.80	.81	.88	.71	.77	.80
	B.H.	.81	.84	.83	.84	.81	.89	.68	.76	.81

APPENDIX 8

Minimum density within growth sheaths at different heights in the stem - average of all trees per treatment

Thinn. Treat.	% Height in Tree	Before Treat.	1963	1964	1965	1966	1967	1968	1969	1970
1	80	-	-	.29	.27	.28	.28	.30	.29	.31
	70	.27	.28	.28	.28	.29	.29	.30	.29	.33
	60	.27	.27	.27	.28	.28	.28	.30	.30	.32
	50	.27	.28	.28	.29	.29	.30	.31	.30	.33
	40	.28	.29	.28	.30	.29	.29	.31	.30	.32
	30	.29	.31	.30	.31	.29	.31	.32	.30	.32
	20	.32	.34	.31	.32	.29	.31	.32	.30	.32
	10	.33	.35	.32	.33	.31	.32	.33	.31	.32
	B.H.	.35	.37	.34	.35	.33	.32	.34	.33	.34
3	80	-	-	.28	.30	.28	.28	.29	.28	.32
	70	.27	.29	.28	.27	.28	.29	.28	.29	.32
	60	.27	.27	.27	.27	.28	.29	.29	.29	.32
	50	.27	.28	.28	.30	.29	.29	.31	.29	.33
	40	.27	.28	.28	.30	.28	.29	.31	.30	.32
	30	.28	.30	.29	.31	.29	.31	.32	.31	.32
	20	.29	.30	.29	.31	.29	.31	.31	.30	.31
	10	.32	.33	.30	.33	.31	.31	.32	.31	.32
	B.H.	.34	.35	.32	.34	.32	.32	.34	.33	.33
4	80	-	-	.28	.28	.29	.29	.31	.29	.32
	70	.28	.28	.28	.29	.30	.29	.31	.30	.32
	60	.28	.28	.28	.29	.29	.30	.32	.30	.32
	50	.28	.29	.28	.31	.29	.31	.32	.31	.33
	40	.28	.30	.29	.32	.30	.32	.33	.31	.33
	30	.30	.32	.30	.33	.29	.32	.33	.32	.33
	20	.32	.33	.32	.34	.31	.32	.33	.32	.34
	10	.34	.35	.33	.35	.32	.32	.34	.34	.34
	B.H.	.37	.38	.36	.37	.35	.34	.36	.35	.36
5	80	-	-	.26	.27	.28	.27	.29	.28	.31
	70	.28	.26	.27	.27	.27	.28	.30	.29	.32
	60	.28	.28	.28	.29	.30	.29	.31	.30	.33
	50	.28	.29	.29	.30	.30	.30	.32	.32	.33
	40	.28	.30	.29	.31	.31	.31	.33	.32	.34
	30	.30	.31	.31	.33	.32	.32	.32	.32	.34
	20	.32	.32	.31	.33	.31	.32	.32	.32	.34
	10	.33	.34	.33	.34	.32	.33	.35	.34	.35
	B.H.	.36	.37	.35	.37	.34	.34	.37	.35	.37
6	80	-	-	.28	.28	.28	.29	.30	.29	.32
	70	.30	.28	.29	.29	.29	.29	.31	.30	.33
	60	.30	.29	.29	.30	.30	.31	.31	.32	.35
	50	.28	.29	.29	.31	.31	.31	.33	.33	.36
	40	.28	.29	.29	.32	.31	.31	.33	.34	.36
	30	.30	.30	.31	.32	.32	.33	.35	.36	.38
	20	.32	.32	.32	.34	.33	.34	.36	.36	.37
	10	.34	.34	.35	.35	.34	.35	.37	.37	.38
	B.H.	.37	.36	.36	.37	.35	.37	.40	.39	.39

APPENDIX 9

Range of wood density within annual growth sheaths at different heights in the stem - average of all trees per treatment

Thinn. Treat.	% Height in Tree	Before Treat.	1963	1964	1965	1966	1967	1968	1969	1970
1	80	-	-	.27	.29	.30	.43	.35	.38	.36
	70	.35	.31	.36	.37	.37	.46	.35	.37	.35
	60	.38	.39	.40	.43	.39	.47	.34	.39	.36
	50	.44	.43	.42	.46	.41	.51	.34	.40	.38
	40	.46	.44	.45	.47	.41	.52	.36	.41	.38
	30	.48	.43	.45	.47	.42	.53	.37	.44	.39
	20	.46	.44	.43	.45	.42	.54	.36	.44	.40
	10	.46	.41	.44	.45	.41	.55	.36	.40	.40
	B.H.	.41	.35	.39	.41	.36	.51	.35	.38	.37
3	80	-	-	.33	.32	.32	.36	.33	.37	.35
	70	.35	.35	.36	.43	.40	.46	.36	.38	.36
	60	.35	.38	.42	.47	.43	.50	.34	.39	.37
	50	.41	.42	.42	.48	.44	.51	.35	.38	.39
	40	.45	.43	.45	.49	.44	.53	.35	.43	.41
	30	.46	.46	.45	.50	.48	.56	.38	.44	.42
	20	.48	.46	.48	.50	.47	.55	.38	.44	.42
	10	.48	.49	.48	.50	.49	.58	.39	.42	.43
	B.H.	.45	.45	.44	.46	.43	.53	.36	.38	.40
4	80	-	-	.32	.35	.32	.39	.32	.37	.32
	70	.29	.32	.35	.42	.39	.47	.37	.39	.36
	60	.34	.40	.41	.46	.42	.48	.36	.39	.37
	50	.41	.44	.44	.49	.45	.55	.36	.40	.39
	40	.48	.46	.45	.48	.46	.54	.37	.42	.41
	30	.49	.49	.48	.50	.46	.55	.38	.41	.42
	20	.48	.48	.47	.48	.46	.55	.39	.42	.42
	10	.47	.48	.46	.46	.45	.55	.39	.39	.41
	B.H.	.43	.42	.42	.45	.39	.52	.35	.36	.36
5	80	-	-	.34	.38	.34	.43	.33	.37	.37
	70	.32	.32	.36	.45	.43	.51	.34	.40	.40
	60	.35	.42	.42	.51	.45	.54	.34	.41	.42
	50	.43	.45	.45	.52	.48	.56	.35	.42	.43
	40	.49	.48	.46	.51	.50	.56	.35	.43	.43
	30	.51	.49	.46	.52	.49	.55	.37	.43	.43
	20	.48	.49	.47	.49	.48	.54	.36	.41	.43
	10	.48	.50	.48	.50	.50	.56	.35	.42	.42
	B.H.	.45	.47	.46	.47	.46	.55	.34	.40	.41
6	80	-	-	.29	.31	.32	.41	.29	.36	.36
	70	.31	.29	.34	.44	.42	.50	.31	.38	.40
	60	.35	.41	.42	.46	.44	.52	.32	.41	.41
	50	.43	.46	.43	.46	.47	.53	.32	.41	.40
	40	.47	.46	.45	.45	.46	.52	.33	.41	.41
	30	.47	.48	.45	.44	.46	.52	.34	.40	.41
	20	.49	.51	.48	.45	.47	.52	.32	.38	.42
	10	.48	.50	.47	.45	.47	.53	.34	.39	.42
	B.H.	.45	.48	.47	.47	.46	.53	.29	.37	.42

APPENDIX 10

Mean density within annual growth sheaths at different heights in the stem - average of all trees per treatment

Thinn. Treat.	% Height in Tree	Before Treat.	1963	1964	1965	1966	1967	1968	1969	1970
1	80	-	-	.36	.35	.36	.40	.40	.41	.42
	70	.36	.36	.38	.38	.39	.43	.40	.42	.44
	60	.36	.37	.38	.40	.40	.42	.40	.42	.44
	50	.38	.39	.40	.42	.43	.45	.42	.44	.46
	40	.40	.41	.42	.43	.43	.45	.43	.44	.46
	30	.43	.45	.44	.44	.43	.47	.44	.45	.46
	20	.46	.46	.46	.46	.45	.48	.44	.45	.47
	10	.48	.49	.47	.48	.46	.49	.47	.47	.48
	B.H.	.52	.53	.51	.51	.51	.52	.49	.49	.49
3	80	-	-	.39	.38	.38	.39	.39	.40	.43
	70	.36	.38	.37	.39	.39	.39	.40	.41	.44
	60	.37	.36	.36	.38	.39	.41	.40	.42	.44
	50	.39	.39	.40	.42	.43	.43	.42	.43	.46
	40	.39	.40	.41	.43	.43	.45	.43	.45	.48
	30	.42	.44	.44	.44	.46	.48	.46	.46	.48
	20	.45	.45	.45	.46	.48	.48	.46	.47	.48
	10	.49	.50	.49	.49	.50	.51	.48	.48	.50
	B.H.	.51	.52	.50	.50	.48	.53	.49	.49	.50
4	80	-	-	.36	.37	.37	.42	.40	.41	.42
	70	.36	.35	.38	.40	.41	.44	.41	.42	.44
	60	.36	.38	.38	.41	.43	.45	.42	.42	.46
	50	.39	.40	.40	.43	.44	.46	.43	.44	.48
	40	.41	.43	.43	.44	.48	.48	.45	.47	.49
	30	.45	.47	.46	.48	.47	.50	.47	.48	.51
	20	.48	.49	.49	.49	.50	.51	.48	.48	.52
	10	.52	.53	.52	.51	.51	.53	.50	.50	.52
	B.H.	.54	.56	.54	.55	.52	.54	.52	.51	.52
5	80	-	-	.36	.36	.37	.38	.39	.40	.43
	70	.36	.34	.37	.39	.41	.42	.41	.43	.46
	60	.37	.38	.39	.42	.43	.44	.42	.44	.49
	50	.40	.40	.42	.44	.45	.45	.44	.47	.50
	40	.42	.42	.44	.46	.48	.49	.46	.48	.51
	30	.46	.45	.47	.48	.49	.50	.49	.48	.52
	20	.49	.48	.49	.50	.48	.51	.48	.49	.52
	10	.51	.51	.52	.52	.53	.49	.53	.52	.53
	B.H.	.54	.56	.56	.55	.55	.57	.53	.54	.54
6	80	-	-	.38	.36	.38	.40	.39	.40	.42
	70	.36	.35	.41	.40	.41	.43	.41	.42	.46
	60	.39	.39	.40	.41	.43	.45	.42	.46	.49
	50	.40	.40	.40	.43	.47	.47	.44	.48	.50
	40	.41	.41	.42	.46	.48	.49	.46	.50	.52
	30	.44	.43	.45	.46	.48	.51	.48	.52	.54
	20	.47	.48	.48	.49	.52	.53	.49	.53	.54
	10	.51	.51	.52	.51	.54	.56	.52	.54	.56
	B.H.	.55	.54	.55	.55	.56	.58	.53	.57	.58

APPENDIX 11

Ring width at different heights in the stem - average of all trees per treatment.

Thinn. Treat.	% Height in Tree	Before Treat.	1963	1964	1965	1966	1967	1968	1969	1970
1	80	-	-	.81	.78	.92	.86	.70	.72	.94
	70	.95	.95	.94	.88	1.10	.94	.76	.76	.95
	60	1.10	1.03	1.03	.89	1.07	.88	.73	.72	.85
	50	1.10	1.04	.97	.80	.95	.81	.71	.76	.83
	40	.97	.98	.94	.83	.93	.84	.72	.86	.81
	30	.75	1.00	1.00	.92	1.00	.89	.76	.97	.84
	20	.66	.96	1.02	.99	1.04	.94	.80	1.03	.80
	10	.55	.95	1.04	1.08	1.03	.93	.71	1.04	.83
	B.H.	.49	1.00	1.21	1.13	1.15	1.01	.79	1.10	.90
3	80	-	-	.91	.70	.87	.85	.60	.65	.82
	70	1.01	1.03	.95	.83	1.04	.90	.68	.69	.80
	60	1.10	1.06	.97	.80	.97	.86	.60	.64	.76
	50	1.07	.98	.89	.77	.89	.80	.60	.63	.70
	40	.93	.85	.82	.72	.79	.72	.56	.65	.71
	30	.72	.72	.73	.70	.69	.68	.57	.74	.73
	20	.61	.73	.73	.73	.74	.77	.58	.86	.80
	10	.53	.70	.76	.78	.73	.71	.54	.85	.75
	B.H.	.53	.69	.82	.82	.81	.78	.60	.89	.84
4	80	-	-	.86	.77	.98	.83	.69	.74	.93
	70	1.08	.97	.76	.76	1.01	.73	.68	.67	.78
	60	1.15	1.02	.94	.79	.85	.65	.63	.63	.67
	50	1.09	.95	.83	.72	.76	.70	.53	.59	.63
	40	.92	.84	.78	.71	.71	.63	.53	.69	.67
	30	.67	.74	.72	.66	.66	.64	.52	.68	.64
	20	.56	.65	.68	.69	.69	.68	.53	.71	.61
	10	.50	.64	.72	.78	.74	.69	.52	.76	.68
	B.H.	.51	.77	.88	.88	.85	.77	.59	.83	.74
5	80	-	-	.98	.83	.94	.88	.59	.65	.76
	70	1.10	.98	.93	.81	.96	.83	.53	.56	.60
	60	1.12	1.02	.88	.75	.79	.70	.48	.52	.52
	50	.99	.90	.79	.64	.65	.58	.44	.49	.49
	40	.78	.71	.67	.56	.54	.50	.40	.48	.45
	30	.60	.64	.60	.52	.65	.52	.41	.52	.48
	20	.50	.54	.55	.49	.54	.49	.37	.50	.46
	10	.43	.52	.53	.48	.46	.50	.35	.52	.48
	B.H.	.42	.49	.57	.51	.46	.47	.35	.52	.48
6	80	-	-	.92	.73	.85	.84	.53	.63	.67
	70	1.02	1.08	.99	.82	.83	.71	.43	.54	.48
	60	1.08	.98	.88	.68	.64	.56	.38	.47	.44
	50	1.01	.78	.68	.52	.47	.45	.32	.40	.35
	40	.84	.62	.56	.45	.43	.42	.29	.38	.36
	30	.68	.54	.52	.43	.38	.38	.27	.39	.38
	20	.50	.43	.44	.39	.33	.36	.25	.38	.37
	10	.46	.40	.41	.38	.32	.36	.31	.41	.38
	B.H.	.42	.37	.38	.36	.30	.34	.23	.39	.36

APPENDIX 12

Percent latewood at different heights in the - stem - average of all trees per treatment.

Thinn. Treat.	% Height in Tree	Before Treat.	1963	1964	1965	1966	1967	1968	1969	1970
1	80	-	-	28.3	28.0	27.8	28.8	29.0	32.2	32.6
	70	24.0	23.9	27.7	27.0	27.9	30.8	28.6	34.4	33.4
	60	26.6	24.6	27.8	27.0	29.7	30.2	31.7	33.6	32.8
	50	26.1	25.3	28.3	26.8	30.4	29.0	33.7	33.8	34.8
	40	27.4	27.9	30.1	26.3	32.8	30.1	34.4	34.3	36.6
	30	30.4	30.4	30.7	27.5	34.0	30.7	34.6	34.1	36.8
	20	32.9	31.4	33.4	29.7	36.3	31.4	34.3	36.1	37.0
	10	35.7	40.0	36.0	30.9	37.8	32.7	38.3	38.2	39.5
	B.H.	39.4	44.0	41.3	36.1	44.1	38.7	41.5	42.7	42.2
3	80	-	-	27.7	25.7	29.8	28.0	31.4	32.7	33.4
	70	24.9	24.6	27.2	26.9	28.7	27.0	29.6	32.3	34.6
	60	25.5	25.6	26.9	25.4	30.8	25.5	31.5	33.9	34.8
	50	28.0	27.2	29.8	26.0	32.6	27.0	32.5	35.0	35.0
	40	27.3	27.7	30.0	26.1	33.2	30.1	33.0	34.5	37.0
	30	30.2	30.3	35.1	27.2	34.9	29.5	36.6	35.6	39.5
	20	33.6	31.5	34.7	29.0	39.9	30.2	38.9	37.0	39.0
	10	36.2	34.9	37.6	31.5	39.0	33.7	38.8	38.8	42.2
	B.H.	40.3	41.6	41.8	35.6	44.8	37.9	44.3	44.1	42.4
4	80	-	-	28.3	27.1	27.1	26.5	30.1	32.1	32.3
	70	26.8	23.4	27.7	25.8	28.7	26.7	29.3	30.6	33.7
	60	26.7	23.2	26.3	25.7	28.9	28.3	30.9	32.3	36.4
	50	26.7	25.0	28.7	25.9	30.8	27.0	33.2	32.8	39.2
	40	27.8	27.5	31.4	26.3	35.0	30.0	35.5	36.0	39.6
	30	31.6	30.1	34.2	29.4	39.0	32.2	38.3	39.7	41.7
	20	34.4	33.5	37.8	32.0	40.6	33.7	38.8	38.0	42.1
	10	38.0	38.2	41.1	34.4	41.9	36.4	42.2	43.2	43.9
	B.H.	41.6	44.0	43.4	39.2	44.7	39.2	45.6	45.1	44.9
5	80	-	-	28.3	26.6	26.6	26.6	31.5	33.0	33.0
	70	25.0	25.6	27.2	26.7	28.1	26.5	33.1	35.4	35.2
	60	28.6	24.9	26.5	26.3	30.4	27.7	38.2	34.9	37.6
	50	26.6	26.0	28.6	25.9	31.7	28.1	35.9	36.7	39.3
	40	28.2	26.0	31.5	27.5	35.1	31.7	37.6	38.7	40.7
	30	30.8	28.2	35.0	30.2	37.1	32.2	39.4	38.8	41.2
	20	35.3	31.1	37.6	32.7	41.0	34.9	41.0	40.5	42.4
	10	37.8	34.4	39.8	36.9	42.9	35.9	44.1	43.1	42.6
	B.H.	41.5	40.2	44.4	39.1	46.7	41.9	48.7	48.2	44.4
6	80	-	-	28.2	25.7	28.3	27.0	31.3	30.8	29.4
	70	28.0	26.4	27.2	25.6	29.6	26.9	31.8	34.1	33.3
	60	27.8	23.9	26.8	25.2	29.4	27.7	35.1	36.0	36.3
	50	26.5	23.2	28.0	26.8	32.7	30.1	37.5	38.5	38.4
	40	28.0	25.8	31.5	31.6	35.5	33.2	40.2	39.7	40.3
	30	29.6	27.9	34.0	32.4	36.4	34.7	41.7	41.8	42.4
	20	32.4	30.5	35.5	34.7	39.6	37.6	43.1	43.6	42.4
	10	36.0	34.7	38.2	37.5	42.1	40.0	45.9	45.1	43.4
	B.H.	40.1	37.4	40.2	39.0	44.4	41.8	48.1	48.2	45.5

REFERENCES

ANON, 1970. Log supply key to plywood expansion. Aust. Timb. J. 35(12): 13-15.

ART, H.W. and MARKS, P.L. 1971. A summary table of biomass and net annual primary production in forest ecosystems of the world. *In: Forest Biomass Studies.* Miscell. Publ. 132, Life Sciences and Agric. Expt. Stn., Univ. of Maine, Orono. pp 3-32.

ASSMANN, E. 1970. *The principles of forest yield study. Studies in the organic production, structure, increment and yield of forest stands.* Pergamon Press, Oxford. Transl. by S.H. Gardiner.

AUSTRALIA. Census and Statistics, Bureau of. Official year book of the Commonwealth of Australia.

BALODIS, V. 1966. Co-ordinate systems based on the age of growth rings and internodes in trees. J. Inst. Wood Sci. No. 16 : 35-42.

BANNISTER, M.H. 1962. Some variations in the growth pattern of *Pinus radiata* in New Zealand. N.Z.J. Sci. 5(3) : 342-370.

BASKERVILLE, G.L. 1965. Dry-matter production in immature Balsam Fir stands. For. Sci. Monogr. No. 9.

BASKERVILLE, G.L. 1972. Use of logarithmic regression in the estimation of plant biomass. Can. J. For. Res. 2(1) : 49-53.

BASSETT, J.R. 1969. Growth of widely spaced Loblolly pine. J. For. 67(9) : 634-636.

BEEKHUIS, J. 1965. Crown depth of radiata pine in relation to stand density and height. N.Z.J. For. 10(1) : 43-61.

BEHRE, C.E. 1927. Form class taper curves and volume tables and their application. Jour. Agr. Res., 35 : 673-744. (cited by Carron, 1968).

BESLEY, L. 1969. A review of the woodlands research programme. Trend 14 : 4-8.

BOOTH, H.E. 1964. Shrinkage of New South Wales timbers. Bull. N.S.W. For. Comm. Div. Wood. Technol. No. 3.

BOYD, J.D. 1967. Effect of plantation conditions on wood properties and utilization. World Symposium on Man-Made Forests. Canberra, 1967. FO / MMF : 67-18/1.

BRAY, J.R. and GORHAM, E. 1964. Litter production in forests of the world. Advanc. ecol. Res., Lond 2 : 101-157.

BRAZIER, J.D. 1969. Some considerations in appraising within-ring density. Pap. FAO/IUFRO World Consult. For. Tree Breed., Washington 1969. No. FO-TTB - 69-4/2.

BROWN, C.L. and GODDARD, R.E. 1961. Silvical considerations in the selection of plus phenotypes. J. For. 59(6) : 420-426.

BROWN, A.G. and HALL, N. 1968. *Growing trees on Australian farms*. Department of National Development. Commonwealth Government Printer, Canberra.

BÜSGEN, M. and MÜNCH, E. 1929. *The structure and life of forest trees*. John Wiley & Sons, New York. (Transl. from German by T. Thomson.)

CAMERON, J.F., BERRY, P.F. and PHILLIPS, E.W.J. 1959. The determination of wood density using beta rays. Holzforschung 13(3) : 78-84.

CANADA. UNIV. OF TORONTO 1971. Research in Forestry and Botany. Glendon Hall Laboratory. Annual Report 1970-71.

CARRON, L.T. 1968. *An Outline of Forest Mensuration*, A.N.U. Press, Canberra.

CHAPMAN, H.H. and MEYER, W.H. 1949. *Forest Mensuration*. McGraw-Hill Book Company, Inc., New York, Toronto, London.

COOLEY, W.W. and LOHNES, P.R. 1962. *Multivariate Procedures for Behavioral Sciences*. Wiley, London.

CROMER, D.A.N. and PAWSEY, C.K. 1957. Initial spacing and growth of *Pinus radiata*. Bull. For. Timb. Bur. Aust. No. 36.

CURTIN, R.A. 1968. The dynamics of growth in even-aged stands of *Eucalyptus obliqua* (L'Hérit.) Ph.D. thesis, Univ. of Melb. Unpub.

CURTIN, R.A. 1970. Dynamics of tree and crown structure in *Eucalyptus obliqua*. For. Sci. 16(3) : 321-328.

CZARNOWSKI, M.S. 1961. Dynamics of even-aged forest stands. Louisiana State University Press, Baton Rouge.

DARGAVEL, J.B. 1970. Provisional tree weight tables for Radiata Pine. Aust. For. 34(2) : 131-140.

DAY, W.R. 1966. Biological aspects of thinning in conifer plantations. Forestry 39(2) : 191-212.

DELL, T.R. and COLLICOTT, L.V. 1968. Growth in relation to density for Slash Pine plantations after first thinning. For. Sci. 14(1) : 7-12.

DOERNER, J.R. Karl, 1964. Some causes and effects of horizontal density variation in tree stems. For. Sci. 10(1) : 24-27.

DUFF, G.H. and NOLAN, N.J. 1953. Growth and morphogenesis in the Canadian forest species. I. The controls of cambial and apical activity in *Pinus resinosa* Ait. Canad. J. Bot. 31(4) : 471-513.

DUFFIELD, J.W. 1968. An evolutionary view of wood. J. For. 66(4) : 354-357.

EDLIN, H.L. 1965. The summerwood : springwood ratio in conifers : how it arises, varies, and affects end use for timber, board and paper. Forestry 38(1) : 91-112.

ELLIOTT, G.K. 1970a. Wood density in conifers. Tech. Commun. For. Bur., Oxf. No. 8.

ELLIOTT, G.K. 1970b. Wood properties, silviculture and genetics In The wood we grow. Report of the tenth discussion meeting, Edinburgh, 20-22 March, 1970. Suppl. to Forestry, Oxford University Press, London.

ELLIOTT, G.K. and BROOK, S.E.G. 1967. Microphotometric technique for growth-ring analysis. J. Inst. Wood Sci. (18) : 24-43.

FARRAR, J.L. 1961. Longitudinal variation in the thickness of the annual ring. For. Chron. 37 : 323-331.

FIELDING, J.M. 1960. Branching and flowering characteristics of Monterey pine (Pinus radiata). Bull. For. Timb. Bur. Aust. No. 37.

FIELDING, J.M. 1967a. Some characteristics of the crown and stem of Pinus radiata. Bull. For. Timb. Bur. Aust. No. 43

FIELDING, J.M. 1967b. The influence of silvicultural practices on wood properties. Int. Rev. For. Res., N.Y. 2 : 95-126.

FIELDING, J.M., BROWN, A.G. 1960. Variations in the density of the wood of Monterey pine from tree to tree. Leafl. For. Timb. Bur. Aust. No. 77.

FORD-ROBERTSON, F.C. (Editor) 1971. Terminology of forest science, technology, practice and products. English-language version. (The Multilingual Forestry Terminology Series No. 1), Society of American Foresters, Washington, D.C.

FORWARD, D.F. and NOLAN, N.J. 1961. Growth and morphogenesis in the Canadian forest species IV. Radial growth on branches and main axis of Pinus resinosa Ait. under conditions of open growth, suppression, and release. Canad. J. Bot. 39(2) : 385-409.

FORREST, W.G. 1968. The estimation of oven dry weight. Aust. For. Res. 3 : 41-46.

FORREST, W.G. 1969. Variations in the accumulation, distribution and movement of mineral nutrients in Radiata Pine plantations. Ph.D. thesis, Australian National University, Canberra. Unpub.

FORREST, W.G. and OVINGTON, J.D. 1970. Organic matter changes in an age series of Pinus radiata plantations. J. appl. Ecol. 7 : 177-186.

FORREST, W.G. and OVINGTON, J.D. 1971. Variation in dry weight and mineral nutrient content of Pinus radiata progeny. Silvae. Genet. 20(5-6) : 174-179.

GOGGANS, J.F. 1961. The interplay of environment and heredity as factors controlling wood properties in conifers with special emphasis on their effects on specific gravity. Tech. Rep. Sch. For. N.C. St. Coll. No. 11.

GRAY, H.R. 1956. The form and taper of forest tree stems. Inst. Pap. imp. For. Inst. Oxf. No. 32.

GREEN, H.V. and WORRALL, J. 1964. Wood quality studies I. A scanning microphotometer for automatically measuring and recording certain wood characteristics. Tappi 47(7): 419-427.

HALL, G.S. 1965. Wood quality studies I. A scanning microphotometer for automatically measuring and recording certain wood characteristics. Tappi 47(7) : 419-427.

HALL, G.S. 1965. Wood increment and crown distribution relationships in Red Pine. For. Sci. 11(4) : 438-448.

HALL, G.S. 1966. Age distribution of needles in Red Pine crowns. For. Sci. 12(3) : 369-371.

HAMILTON, G.J. 1969. The dependence of volume increment of individual trees on dominance, crown dimensions, and competition. For. 42(2) : 133-144.

HAMILTON, J.R. and MATTHEWS, R.M. 1965. Wood characteristics of planted Loblolly and Shortleaf Pine. Res. Pap. Ga. For. Res. Coun. No. 27.

HARRIS, J.M. 1967. Latewood, earlywood and wood density. Proc. 14th Congr. Int. Union For. Res. Organ., Munich, 1967 Pt IX, Sect. 41.

HARRIS, J.M. 1969. The use of beta rays in determining wood properties. Parts 1-5. N.Z. J. Sci. 12(2) : 395-451.

HARRIS, J.M. and POLGE, H. 1967. A comparison of X-ray and beta ray techniques for measuring wood density. J. Inst. Wood Sci. 19 : 34-42.

HOLSOE, T. 1950. Profitable tree forms of Yellow Poplar. Bull. W. Va. agric. Exp. Sta. No. 341.

HONER, T.G. 1971. Crown shape in open- and forest-grown Balsam Fir and Black Spruce. Canad. J. For. Res. 1(4) : 203-207.

HUMMEL, F.C. 1953. The definition of thinning treatments. Proc. Cong. int. Union For. Res. Organ., Rome, 1953.

HUSCH, B. 1947. A comparison between a ground and an aerial photogrammetric method of timber surveying. Abstr. in J. For. 45(7) : 491. (seen F.A. IX : 1359).

HUSCH, B. 1963. *Forest Mensuration and Statistics*. The Ronald Press Company, New York.

HUTNIK, R.J. and HICKOK, K.H. 1967. Effect of spacing on dry matter production in Red Pine plantations. Proc. 14th Congr. Int. Union For. Res. Organ., Munich, 1967 Pt. IV Sect. 23.

HUXLEY, J.S. 1932. *Problems in relative growth*. Lincoln Macveagh, New York.

ILVESSALO, Y. 1950. On the correlation between the crown diameter and the stem of trees. Commun. Inst. for. Fenn. 38(2).

JACOBS, M. 1936. The detection of annual stages of growth in the crown of *Pinus radiata*. Bull. For. Timb. Bur. Aust. No. 19.

JACOBS, M.R. 1938. Observations on features which influence pruning. Bull. For. Timb. Bur. Aust. No. 23.

JACOBS, M.R. 1954. The effect of wind sway on the form and development of *Pinus radiata* D.Don. Aust. J. Bot. 2 : 35-51.

JACOBS, M.R. 1962. The effect of grade of thinning on growth, ring width, and thinning yield in plantations of *Pinus radiata* in Australia. Leafl. For. Timb. Bur. Aust. No. 84.

JAMES, R.N. and TUSTIN, J.R. 1970. Diameter response of branches after thinning in radiata pine. *In*: *Pruning and Thinning Practice*, New Zealand For. Serv., For. Res. Inst., F.R.I. Symposium No. 12.

JERRAM, M.R.K. 1939. *Elementary Forest Mensuration*. Murby and Co., London.

JONSON, T. 1910-12. Taxatoriska undersokningar on skogstridens form. Skogs. Tidskr., 8(11) : 285-328; 9(9-10) : 285-329; 10(4) : 235-275. (cited by Carron, 1968).

JORGENSEN, S. SJOLITE, 1967. The influence of spacing on the growth and development of coniferous plantations. Int. Rev. For. Res. N.Y. 2 : 43-94.

JURASEK, L. and JOKEL, J. Absorption of Co^{60} gamma-rays in woods of various density. Drev. Vyskum 1962 (1) : 21-32. (seen F.A. 24 : 2702).

KEAY, J. and TURTON, A.G. 1970. Distribution of bio-mass and major nutrients in a Maritime Pine plantation. Aust. For. 34(1) : 39-48.

KEISTER, T.D. 1967. Effect of thinning on diameter growth of the largest trees in a Slash Pine plantation. LSU For. Note La. Sch. For. No. 71.

KEISTER, T.D., CROW, A.B. and BURNS, P.Y. 1968. Results of a test of classical thinning methods in a slash pine plantation. J. For. 66(5) : 409-411.

KEITH, C.T. 1961. Characteristics of annual rings in relation to wood quality. For. Prod. J. 11(3) : 122-126.

KITTREDGE, J. 1944. Estimation of the amount of foliage of trees and stands. J. For. 42 : 905-912.

KLEM, G.G. 1952. The influence of spacing on spruce quality. Medd. Norske Skogforsøkev 11 : 473-506. (cited by Larson, 1963a).

KLEUTERS, W. 1964. Optimal test conditions for determining local density of wood by the beta-ray method. For. Prod. J. 14(9) : 414-420.

KOZAK, A. 1970. Methods for ensuring additivity of biomass components by regression analysis. For. Chron. 46(5) : 402-404.

KRAMER, H. 1966. Crown development in conifer stands in Scotland as influenced by initial spacing and subsequent thinning treatment. Forestry 39(1) : 40-58.

KRAHMER, R.L. and SNODGRASS, J.D. 1967. A sampling procedure for estimating selected physical properties in a forest. For. Prod. J. 17(3) : 21-29.

KRAMER, P.J. and KOZLOWSKI, T.T. 1960. Physiology of Trees. McGraw-Hill Book Company, Inc., New York, Toronto, London.

LABYAK, L.F. and SCHUMACHER, F.X. 1954. The contribution of its branches to the main-stem growth of Loblolly Pine. J. For. 52(5) : 333-337.

LARSON, P.R., 1957. Effect of environment on the percentage of summerwood and specific gravity of Slash Pine. Bull. Yale Sch. For. No. 63.

LARSON, P.R. 1962. A biological approach to wood quality. Tappi 45(6) : 443-448.

LARSON, P.R. 1963a. Stem form development of forest trees. For. Sci. Monogr. No. 5.

LARSON, P.R. 1963b. Evaluating the environment for studies of the inheritance of wood properties. Pap. FAO World Consult. For. Genet., Stockholm 1963 No. FAO/FORGEN 63/7/1, 1963.

LARSON, P.R. 1965. Stem form of young Larix as influenced by wind and pruning. For. Sci. 11(4) : 412-424.

LARSON, P.R. 1969. Wood formation and the concept of wood quality. Bull. Yale Sch. For. No. 74.

LOHREY, R.E. 1961. Stand density influences stem taper in a thinned Red Pine plantation. Tech. Note Lake St. For. Exp. Sta. No. 607.

LOOMIS, R.M., PHARES, R.E. and CROSBY, J.S. 1966. Estimating foliage and branchwood quantities in Shortleaf Pine. For. Sci. 12(1) : 30-39.

LOOS, W.E., 1961. Application of the gamma-ray backscatter technique to the inspection of utility poles. For. Prod. J. 11(8) : 333-336.

McINTYRE, G.A. 1952. A method for unbiased selective sampling, using ranked sets. Aust. J. Agric. Res. 3 : 385-390.

McINTYRE, G.A. 1970. Non-orthogonal factorial designs. Div. Math. Stats. CSIRO Tech. Rep. No. 4.

McINTYRE, G.A. and WARD, M. 1970. Regression and correlation analysis. Div. Math. Stats. CSIRO Tech. Rep. No. 3.

MACKENZIE, A.M. 1950. Douglas fir sample plots at Beaufort, Inverness-shire. Scot. For. 4 : 94-97.

McKINNELL, F.H. 1970. Wood density studies in <u>Pinus radiata</u> D.Don. Ph.D. thesis, Aust. National Univ.. Unpub..

MADGWICK, H.A.I. 1962. Studies in the growth and nutrition of <u>Pinus resinosa</u> Ait. Unpub. Ph.D. thesis, Syracuse, New York. (cited by Wood, 1969).

MADGWICK, H.A.I. 1968. Some factors affecting the vertical distribution of foliage in pine canopies. <u>In</u>: <u>Primary productivity and mineral cycling in natural ecosystems</u>. (H.E. Young, Ed.). Orono: Univ. Maine Press. pp 233-245.

MADGWICK, H.A.I. 1970. Biomass and productivity models of forest canopies. <u>In</u>: <u>Ecological Studies I. Analysis of Temperate Forest Ecosystems</u>. (Ed. D.E. Reichie) Springer-Verlag, Berlin, Heidelberg, and New York.

MAEGLIN, R.R. 1967. Effect of tree spacing on weight yields for Red Pine and Jack Pine. J. For. 65(9) : 647-650.

MARUYAMA, I. and SATO, T. 1953. The estimation of the amount of foliage in trees and stands (Report 1). Akamatsu in the Iwate district. Bull. For. Exp. Sta. Meguro, Tokyo No. 65. (Seen F.A. 15 : 3882).

MÖLLER, C.M. 1947. The effect of thinning, age, and site on foliage, increment, and loss of dry matter. J. For. 45(6) : 393-404.

MYERS, C.A. 1963. Vertical distribution of annual increment in thinned Ponderosa pine. For. Sci. 9(4) : 394-404.

NEWNHAM, R.M. 1958. A study of form and taper of stems of Douglas fir, western hemlock, and western red cedar on the University Research Forest, Haney, British Columbia. Univ. B.C. unpublished M.F. thesis (cited by Newnham, 1965).

NEWNHAM, R.M. 1965. Stem form and the variation of taper with age and thinning regime. Forestry 38(2) : 218-224.

NICHOLLS, J.W.P. 1971. The effect of environmental factors on wood characteristics 2. The effect of thinning and fertilizer treatment on the wood of Pinus pinaster. Silvae Genet. 20(3) : 67-73.

NICHOLLS, J.W.P., and BROWN, A.G. 1971. The ortet-ramet relationship in wood characteristics of Pinus radiata. Appita 25(3) : 200-209.

NICHOLLS, J.W.P. and DADSWELL, H.E. 1965. Assessment of wood qualities for tree breeding III. In Pinus radiata D. Don. Div. For. Prod. technol. Pap. For. Prod. Aust. No. 37.

NORRIS, J.M. 1971. The application of multivariate analysis to soil studies. I. Grouping of soils using different properties. J. Soil. Sci. 22 : 69-80.

OVINGTON, J.D. 1957. Dry matter production of Pinus sylvestris L. Ann. Bot. 21(82) : 287-314.

OVINGTON, J.D. and MADGWICK, H.A.I. 1959. Distribution of organic matter and plant nutrients in a plantation of Scots Pine. For. Sci. 5(4) : 344-355.

PAUL, B.H. 1963. The application of silviculture in controlling the specific gravity of wood. Tech. Bull. U.S. Dep. Agric. No. 1288.

PEARSON, R.G. 1952. Variability of timber and the derivation of design stresses. Aust. J. appl. Sci. 3(2) : 144-155.

PETRINI, S. 1921. Stamforms undersokningar. Medd. from Statskogs 18(4). (cited by Carron, 1968).

PHILLIPS, E.W.J. 1960. The beta ray method of determining the density of wood and the proportion of summer wood. J. Inst. Wood Sci. No. 5 : 16-28.

PHILLIPS, E.W.J. 1968. A further contribution to the comparison of X-ray and beta-ray techniques for measuring wood density J. Inst. Wood Sci. 4(2) : No. 20, 64-66.

PHILLIPS, E.W.J., ADAMS, E.H. and HEARMON, R.F.S. 1962. The measurement of density variations within growth rings in thin sections of wood, using beta particles. J. Inst. Wood Sci. 10 : 11-28.

PLUTH, D.J. 1971. Parameters from stem analysis. Note in For. Sci. 17(1) : 102.

POLGE, H. 1963. A new method for determining latewood % : densitometer measurements on X-ray photographs. Ann. Éc. Eaux. For. Nancy 20(4) : 533-581.

POLGE, H. 1965. Study of wood density variations by densitometric analysis of X-ray negatives of samples taken with a Pressler auger. Proc. Meeting Section 41, IUFRO, Melbourne.

POLGE, H. 1966. Establishment of curves of wood density variation by "densitometric scanning" of radiographs of samples taken from living trees with a Pressler borer. Technological and physiological applications. Ann. Sci. for., Nancy 1966 23(1).

POLGE, H. 1969. Further considerations about the X-ray and beta-ray methods for determining wood density. J. Inst. Wood Sci. 4(5) : 39-44.

POLGE, H. and NICHOLLS, J.W.P. 1972. Quantitative radiography and the densitometric analysis of wood. Wood Sci. 5(1) : 51-59.

REUKEMA, D. 1961. Crown development and its effect on stem growth of six Douglas-Firs. J. For. 59(5) : 370-371.

RICHARDSON, S.D. 1961. A biological basis for sampling in studies of wood properties. Tappi 44; 170-173.

RUDMAN, P. 1968. Growth ring analysis. J. Inst. Wood Sci. 4(2) : 58-63.

RUDMAN, P., McKINNELL, F.H. and HIGGS, M. 1969. Quantitative determination of wood density by X-ray densitometry. J. Inst. Wood Sci. 4(6) : 37-43.

SATOO, T. 1966. Production and distribution of dry matter in forest ecosystems. Misc. Inform. Tokyo Univ. For. No. 16.

SATOO, T., NAKAMURA, K. and SENDA, M. 1955. Materials for the study of growth in stands, I. Young stands of Japanese Red Pine of various density. Bull. Tokyo Univ. For. No. 48 : 65-90.

SCHNIEWIND, A.D. 1962. Horizontal specific gravity variation in tree stems in relation to their support function. For. Sci. 8(2) : 111-113.

SEAL, H.L. 1964. *Multivariate statistical analysis for biologists*. John Wiley and Sons, New York.

SENDA, M. and SATOO, T. 1956. Materials for the study of growth in stands. II. White pine (*Pinus strobus*) stands of various densities in Hokkaido. Bull. Tokyo Univ. For. No. 52 : 15-31. (English summary).

SHELBOURNE, C.J.A. and RITCHIE, K.S. 1968. Relationships between degree of compression wood development and specific gravity and tracheid characteristics in Loblolly Pine (*Pinus taeda* L.) Holzforschung 22(6) : 185-190.

SHEPHERD, K.R. 1967. Influence of low pruning on first thinnings in Radiata Pine plantations. Aust. For. 31(1) 45-49.

SHEPHERD, K.R. 1970. Thinning practice in Australian plantations. In: Thinning and Mechanization, IUFRO Meeting, Royal College of Forestry, Stockholm, Sweden, 1969. pp 69-77.

SHEPHERD, K.R., FORREST, W.G. (In press). Growth of Radiata Pine following thinning. Submitted to Commonw. For. Rev.

SMITH, J.H.G. 1963. Analysis of crown development can establish biological and economic limits to growth of trees and stands. Commonw. For. Rev. 42(1) : 27-33.

SMITH, J.H.G. and BAILEY, G.R. 1964. Influence of stocking and stand density on crown widths of Douglas Fir and Lodgepole Pine. Commonw. For. Rev. 43(3) : 243-246.

SOKAL, R.R. and ROHLF, F.J. 1969. Biometry W.H. Freeman and Co., San Francisco.

SPURR, S.H. 1960. Photogrammetry and photo-interpretation. The Ronald Press Company, New York.

SPURR, S.H. and HSIUNG, W. 1954. Growth rate and specific gravity in conifers. J. For. 52 : 191-200.

STIELL, W.M. 1964. Twenty-year growth of Red Pine planted at three spacings. Publ. Dep. For. Can. No. 1045.

STIELL, W.M. 1966. Red Pine crown development in relation to spacing. Publ. Dep. For. Can. No. 1145.

TARAS, M.A. 1965. Some wood properties of Slash Pine (Pinus elliottii Engelm.) and their relationship to age and height within the stem. Ph.D. thesis, University of North Carolina, Raleigh.

TRENDELENBURG, R. 1932. Über die Eigenschaften des Rot- und Druckholzes der Nadelhölzer. Allgem. Forst- u. Jagdztg. 108 : 1-14. (cited by Larson, 1963a).

TRENDELENBURG, R. 1935. Schwankungen des Raumgewichts wichtiger Nadelhölzer nach Wuchsgebiet, Standort and Einzelstamm. Z. Ver. deut. Ingr. 79 : 85-89. (cited by Larson, 1963a).

TURNBULL, J.M. 1947. Some factors affecting wood density in pine stems. Pap. 5th Brit. Emp. For. Conf., London 1947.

VAN LAAR, A. 1963. The influence of stand density on crown dimensions of Pinus radiata D.Don. Bosb. Suid - Afr. No. 3 : 133-143.

VAN LAAR, A. 1969. Influence of tree parameters and stand density on diameter growth of Pinus radiata. S. Afr. For. J. 70; 5-14.

VOLKERT, E. 1941. Untersuchungen über Grösse und Verteilung des Raumgewichts in Nadelholzstämmen. Schriftenreihe Akad. deut. Forstwiss. Bd. 2. (cited by Larson, 1963a).

WALTERS, J. and SOOS, J. 1962. The gimbal-sight for the projection of crown radius. Res. Note Fac. For. Univ. B.C. No. 39.

WARD, W.W. 1964. Live crown ratio and stand density in young, even-aged, Red Oak stands. For. Sci. 10(1) : 56-65.

WEETMAN, G.F. and HARLAND, R. 1964. Foliage and wood production in unthinned Black Spruce in northern Quebec. For. Sci. 10(1) : 80-88.

WHITE, E.H. 1964. Uptake and distribution of nutrient elements in Red Pine plantations. Unpub. M.Sc. thesis, Syracuse, New York. (cited by Wood, 1969).

WHYTE, A.G.D. 1971. Sectional measurement of trees : a rationalized method. N.Z. Jl. For. Sci. 1(1) : 74-79.

WILL, G.M. 1964. Dry matter production and nutrient uptake by Pinus radiata in New Zealand. Commonw. For. Rev. 43(1) : 57-70.

WOLSKI, J. 1965. Rules for selecting sample trees representative of the Pine stands investigated, and determination of the number of such trees. Prace Inst. Tech. Drewna 12(1) : 87-103. (seen F.A. 27 : 2714).

WOLSKI, J. 1968. Selection of sample trees in investigating wood properties. Sylwan 112(12) : 53-58.

WOOD, G.B. 1969. Photosynthesis and growth in Pinus radiata D.Don as affected by environmental factors and inherent qualities. Ph.D. thesis, Aust. National Univ. Canberra. Unpub.

WRIGHT, W.G. 1927. Taper as a factor in the measurement of standing timber. Can. Dom. For. Serv. Bull. No. 79. (cited by Carron, 1968).

WRIGHT, J.P. 1971. Site and silvicultural influences on log quality in radiata pine. In: Radiata Pine Symposium, Department of Forestry, Australian National University, Canberra, 1970.

YOUNG, H.E., STRAND, L., and ALTENBERGER, R. 1964. Preliminary fresh and dry weight tables for seven tree species in Maine. Tech. Bull. Me. Agric. Exp. Sta. No. 12.

ZOBEL, B., RALSTON, J. and ROBERDS, J.H. 1965. Wood yields from Loblolly Pine stands of different age, site and stand density. Tech. Rep. Sch. For. N.C. St. Coll. No. 26.

ZOBEL, B., ROBERDS, J.H., and RALSTON, J. 1969. Dry wood weight yields of Loblolly Pine. J. For. 67(11) : 822-824.

ZAHNER, R. 1963. Internal moisture stress and wood formation in conifers. For. Prod. J. 13(6) : 240-247.

ZAR, J.H. 1968. Calculation and miscalculation of the allometric equation as a model in biological data.