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THE GNANGARA FREE GROWTH TRIAL

by

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SUMMARY AND CONCLUSIONS

A trial incorporating free growth principles was established in 5 year old *Pinus pilaster* plantation in Western Australia in 1958. The major objective for the trial was to determine early thinning and green pruning requirements for the species. Secondary objectives were to assist in the development of site productivity systems for the region and to provide expertise to develop basal area (fixed density) thinning trials in more mature stands.

Fixed stockings of 1880, 1320, 1270, 950, 740, 450 and 247 stems per hectare (s ha^{-1}) were progressively established by thinning (step wise) to avoid the onset of mutual competition within each final stocking. The process was staged from age 5 (1880, 1320, 1270, 950 s ha^{-1}) to age 17 at which time the final thinning to provide 247 s ha^{-1} was completed. A final crop of 247 s ha^{-1}, marked to include the best well spaced dominants in 1985, served as a common base of comparison between all treatments. Measurements were carried out at intervals over the period 1962 to 1985.

The trial was established as a continuous series to embrace the full range of site classes in the area. As such it has proved useful for evaluating ecologic site classifications and site index systems considered for pine management.

Height growth on the area was independent of stand density and dominance was established early and maintained in the populations throughout the life of the crop. Site index based on either Top height or Predominant height proved an excellent procedure for classifying and stratifying site variation in the crop. Comparison of the substantial height-age data obtained for the trial with that generally available for the area confirms that it represents only the poorer and average to good site potential for the species. It is however, typical of much of the area planted since 1953. Height-age curves are reasonably similar to previous data published. They require further data covering a wider range of site and age classes to provide a general model for the species within the State. Response to fertiliser application must also be considered. This additional data is available from the subsequent basal area trials.

Height-diameter ratios were found to be most sensitive to stocking and sensitive to site. Simple regressions were provided to indicate limits for height and diameter at 100 per cent (1880 s ha^{-1}), 50 per cent (950 s ha^{-1}), 25 per cent (470 s ha^{-1}) and 12.5 per cent (247 s ha^{-1}) of full site occupancy. Ratios for free grown trees can also be obtained from the data.

Basal area production of the three heaviest stockings was very similar suggesting that they approach full site occupancy. On this basis, maximum BAob-age and volume-age curves were prepared for the 5 site classes separated. Current Annual Increment (CAI) and Mean Annual Increment (MAI) curves showed that basal area and volume production were very sensitive to

stand density. CAI peaked at about age 14 years and at age 32 years the CAI of the unthinned stand still exceeded that of the lower stockings. CAI and MAI intersected for the densest stockings at about age 24 years and for 450 s ha^{-1} at age 32 years. It is probable that the curves for MAI and CAI of the 247 s ha^{-1} treatment would not intersect until age 40 years or more. At age 32 years the MAI of the lowest stocking tested was still increasing.

Increments for volume of the final crop (247 s ha^{-1}) responded most dramatically to stocking and were opposite in effect to those for the total stand. CAI peaked at about 24 years of stand age and only the highest stand density (1880 s ha^{-1}) had intersected the MAI by the age of 32 years. The MAI's for final crop in the lightest stockings were still increasing appreciably at stand age 32 years.

Competition had the major impact on tree diameter, particularly on diameter of final crop trees. Significant differences between means for final crop trees were found for 1880, 1320, 1270, 950 and 740 s ha^{-1} by age 14 years and between 740 and 247 s ha^{-1} by age 18 years. Significant difference between diameters for the 450 and 247 s ha^{-1} treatments was not identified until age 24 years. These limits demonstrate the effect of mutual suppression within the range of densities but offer little guidance to assess the minimum age for thinning to avoid loss in diameter production. Comparisons of H/D ratios for whole stands (rather than the final crop) in fact indicate that the dominant stand is least sensitive to competition and improved procedures for detecting the onset of competition in a stand should measure the least vigorous stems (inferior genotypes). Prescriptions developed for plantation stocking in practice since the trial was established are well in advance of the range provided in the trial and realistic in meeting objectives to optimise the diameter of a defined final crop.

Droughts were severe during the trial period and mortalities were considerable at stand ages of 20 to 25 years. Deaths were largely concentrated in the unthinned stands of the highest site classes. No simple relationship between stand density and drought was obtained and only in the widest spacings (247 s ha^{-1}) were mortalities absent on all site classes. Current plantation practice has stocking in the mature stand well below this limit and hence drought should not be a future problem to older managed stands in the area.

The data were used to explore Moller's theory that increment in total volume is the same over a wide range of stockings. It had little application for the plantations on the sites concerned as stockings favoured of less than 1000 s ha^{-1} suffer significant losses in total volume production. The data clearly demonstrates however, the improved efficiency of stands subject to heavy, selective thinning to favour the desirable genotypes. In the trial, 50 per cent of the stand density for full occupancy (15 per cent of stem numbers) had 75 per cent of the CAI for total volume at age 32 years. Final crop data clearly demonstrate that in commercial plantation practice based on a sawlog market, increment in volumes of merchantable sizes is more relevant than increment in total volume.

Data obtained are most useful for stand modelling. Combined with data to be provided available from the basal area thinning series, all requirements for effective stand modelling for the species should be available. The free growth trial has particular value in defining the patterns of growth over the range of sites and stand densities and covers a major part of the rotation age for the species.

INTRODUCTION

In 1958, a trial incorporating "free growth" principles was commenced in *Pinus pinaster* plantations at Gnangara in Western Australia. The trial was located in five year old pine and preceded major thinning studies based on basal area control established in older pine (Hopkins 1971). These latter have been most successful (Butcher and Havel, 1976) and developed to provide necessary thinning information to plan and manage *Pinus pinaster* plantations. Limited assistance to maintain all trials, problems in analysis and the relatively young nature of pines in the free growth experiment prevented earlier analysis and reporting. In 1985 an opportunity was provided to appraise the trial which embraces most age classes and site conditions relevant to plantation management in the area.

Free growth, based on the Correlative Curve Trend (CCT) method of O'Connor (O'Connor 1935; Marsh 1957) was extensively used in Queensland (Harvey 1983) and South Africa to assess tree and stand characteristics of plantation species grown to rotation ages over a wide range of fixed stockings (stem numbers). The trials assessed the age at which competition set in between stems at any spacing and defined the nature of the stand produced without significant competition i.e. while growing free. A major feature of the approach, at that time, was its accent on heavy, early thinning of plantation grown trees. This was generally contrary to silvicultural philosophy and practice of the period.

The original CCT method maintained 8 plots representing stockings of 2965, 1483, 988, 741, 494, 371, 247 and 124 stems per hectare (s ha^{-1}) respectively, for the full rotation.

Variable genetics and weed competition prevent plots with these numbers of stems to be established, on a comparative basis, from the start. Consequently all plots were established at a spacing of 1.8 m x 1.8 m (2965 s ha^{-1}) and thinned in steps, in advance of competition, to their final stocking. O'Connor avoided competition by thinning plots 2 to 8 to 1483 s ha^{-1} in the second year before there was any sign of competition. The mean diameter at breast height (DBH) on these plots was matched with 1483 trees in the unthinned plot 1. When the mean diameter of the unthinned, selected 1483 trees fell below that of plots 2 to 8, competition was assumed to have set in plot 1. Plots 3 to 8

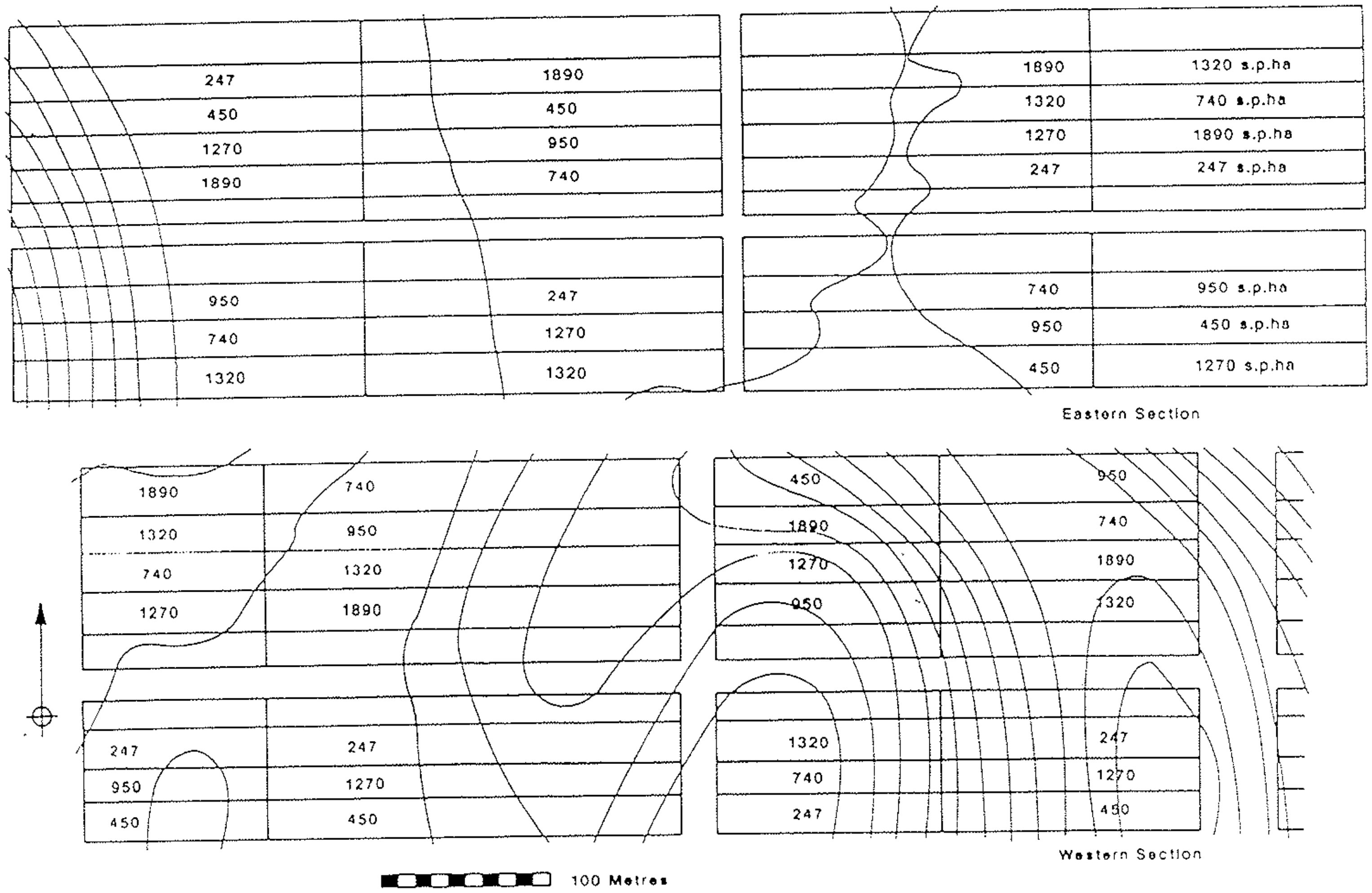

Figure 1.

Field layout of the trial showing contours, breaks and plots. the eastern section adjoins onto the western section as indicated.

were then thinned to 988 s ha^{-1} and monitoring was continued with 988 stems of equal mean DBH in plot 2. The process was continued until the series was established prior to competition becoming evident at the final stocking level for the plot.

The approach provides the means to determine:

1. The age at which competition sets in between different stocking levels of a particular species in a particular site.

2. Volume and stem form characteristics of final crop stems, freely grown and maintained at fixed stockings.

3. Conditions of stem and stand growth between maximum competition and minimum competition for a species and site. This data can be useful for stand modelling procedures.

4. If replicated and developed further, a unique opportunity to study the response of competing stems to subsequent release by thinning i.e. by further thinning after competition has set in for different lengths of time at the different spacings.

The Western Australian trial focused onto obtaining requirements for early thinning and pruning the species over the range of sites concerned.

PROCEDURE

Location

Gnangara plantation is situated some 30 kilometres north east of the city of Perth. The trial was established in *Pinus pinaster* of Portuguese origin, planted at 2.1 m x 2.1 m spacing in 1953 in the West Gironde section of the plantation. The site covers deep sands transitional between the grey, heavily leached Bassendean Series and the younger, yellow to brown, Spearwood Series which often have a limestone influence. Details of soils and vegetation of the area are provided by Havel (1968).

The trial was selected to lie either side of a major (20 m) east-west fire break which successively traverses a low swale on grey sands, a low dune, a flat, a high dune and a gradual decline to a typical swamp on the yellow sands to the west (Fig. 1).

Major objectives in the location and siting were:

i) to sample a recently planted area typical of *Pinus pinaster* in the region;

ii) to include all significant site types known in the planting area;

iii) to provide a trial area which could be used for a range of future silvicultural and soil studies;

iv) to obtain experience to cater for site variation in designing further thinning trials required.

Establishment

The trial extends over an area of 37 ha (1.54 x 0.24 km) with a treatment area of 22 ha (1.54 x 0.14 km). Details of establishment are shown in Figure 1 and Table 1.

Table 1: Progressive thinning procedure for establishing the trial

Thinning	Treatment stocking at increasing age (years)					
Level	0(1953)	5(1958)	8(1961)	12(1965)	17(1970)	32(1985)
1	Control	Contr	Contr	Contr	Contr	1760
2	Control	1323	1323	1323	1323	1270
3	Control	1268	1268	1268	1268	1230
4	Control	950	950	950	950	822
5	Control	950	740	740	740	731
6	Control	950	740	460	460	449
7	Control	950	740	460	247	242

Planting was in 20 m bays, separated by unplanted outrows parallel to the central east-west fire break. Minor fire breaks and cross tracks separate the area into 8 blocks, ranging from 100 to approximately 200 metres in length in an east-west direction and 220 m (9 bays) in a north-south direction (Figure 1). The bays adjacent to the central break were maintained as buffers and the adjoining four bays (plots) in the northern section and three in the southern section were employed for trial plots.

Seven treatment stockings - control (2180 s ha^{-1}), 1480, 1240, 990, 740, 490 and 247 s ha^{-1} were randomly allocated to the plots in each of the blocks. The stockings correspond to 890, 600, 500, 400, 300, 200 and 100 stems per acre on the non-metric scale.

Thinnings were carried out as scheduled in Table 1. The large size of the trial and the desire to embrace all site qualities in the area prevented use of the measurement procedure to determine safety from competition; as carried out by O'Connor (Marsh, 1957). Thinning times were set from results for the onset of competition attained in South Africa and Queensland.

In 1958 at age 5 years, stockings of the control (unthinned), 1480, 1230 and 950 s ha^{-1} treatments were attained by thinning. All other treatments were maintained at 950 s ha^{-1} (Table 1). The temporary 950 s ha^{-1} plots were thinned to 740 s ha^{-1} in 1961 and two of the 740 s ha^{-1} plots were thinned to 490 s ha^{-1} at stand age 12 years. The final thinning to 247 s ha^{-1} was completed at age 17 years.

The area was fertilised with 60 grams of superphosphate per tree at planting in 1953 and with 0.5 tonnes of superphosphate ha^{-1} , broadcast in August 1962 and August 1969. Low pruning to 2.1 m height was commenced in 1962 and completed on the poorer sites in 1966.

In the early years following thinning it was necessary to suppress regrowth from the thinned pine stumps, particularly at the wide spacings, by hand slashing.

Measurement

The planting bays contained from 9 to 11 rows of pines established by machine planting. Only the central three rows in each bay (plot) were measured, allowing approximately a 15 m buffer between adjacent measurement plots.

Each tree in the three central rows was tagged and numbered and the measurement point at breast height (BH) marked. Measurements of height, diameter and bark thickness were carried out at intervals (Table 2).

Table 2: Measurement history of the trial

Date Measured	Age (Yrs)	Height	DBH	Bark Thick	Silvic Class	Veget. Type	Site Index
Feb 1962	8.6	x	x				
Feb 1965	11.6	x	x				
Jan 1967	13.5	x	x	x			
Jan 1969	15.5	x	x		x	x	
Jan 1971	17.5	x	x	x	x		
Jan 1975	21.5	x	x	x	x		
Feb 1977	23.6		x		x		
Feb 1985	31.6	F C	x	x	x		x

The silvicultural status of each tree was recorded as dominant, co-dominant, dominant or suppressed and any mortality was noted at each measurement.

Foliar sampling - In February 1970, following fertiliser addition in August 1969, foliar samples were taken from 6 dominant trees in 28 plots and 4 adjacent unfertilised areas. Individual samples were analysed for per cent N, P and K. Forty nine plots including 8 unfertilised controls were sampled in January 1971 and analysed for P and K content. A further 12 plots over the range of stocking classes and 2 unthinned, unfertilised controls were similarly sampled and analysed for N, P and K in February 1972.

Soil moisture studies, soil-site associations, topographic relationships and vegetative surveys were also conducted on the trial area.

Site Classification

The randomised block design was employed in establishment to ensure that all treatments were randomly located over the major site variation. It was never intended to use this design for trial analysis due to often excessive site changes within plots and, in some instances, between plots in a block. Variation in a north-south direction (along the contours) is relatively small (Fig. 1) but east-west variation in site quality is often considerable.

When the trial was established it was intended to use a site index system to allow the effects of the thinning treatments to be compared within definable and uniform site classes. Site analysis was a major interest for the research program at that time and three major approaches to site definition, topographic relationships, soil mapping and vegetative indexing were developed partly from work on the trial.

Topographic relationships - For the Gnangara Plantation on the Bassendean Sands the general relationship between good pine growth on the flats (interdunal swales) and a decline in growth with increasing elevation up the dune slopes had long been observed. The use of this relationship for practical management was examined in the trial as part of site quality investigation.

Table 3: Mean dominant height of pines (m) occurring within 1.5 m (5-foot) topographic contour intervals.

Contour interval(Ft)	Number of assessment points	Mean height (m)
90 - 94	20	5.30
95 - 99	148	3.82
100 - 104	93	3.63
105 - 109	22	3.10
110 - 114	14	2.68
115 - 119	8	2.59
120 - 124	13	2.58
125 - 129	5	2.56
130 - 134	8	2.55
135 - 139	6	2.59
140 - 144	7	3.44
145 - 149	5	3.84
150 - 155	5	3.09
Total	354	

A topographic survey (Fig. 1) and a detailed assessment of predominant height of the pine crop was carried out on the trial area in 1960 when the pines were 7 years of age. The topographic survey was based on a 40 m x 40 m grid and provided for a 0.3 m (1 foot) contour interval. Top heights for pines were based on the measurement of the three tallest

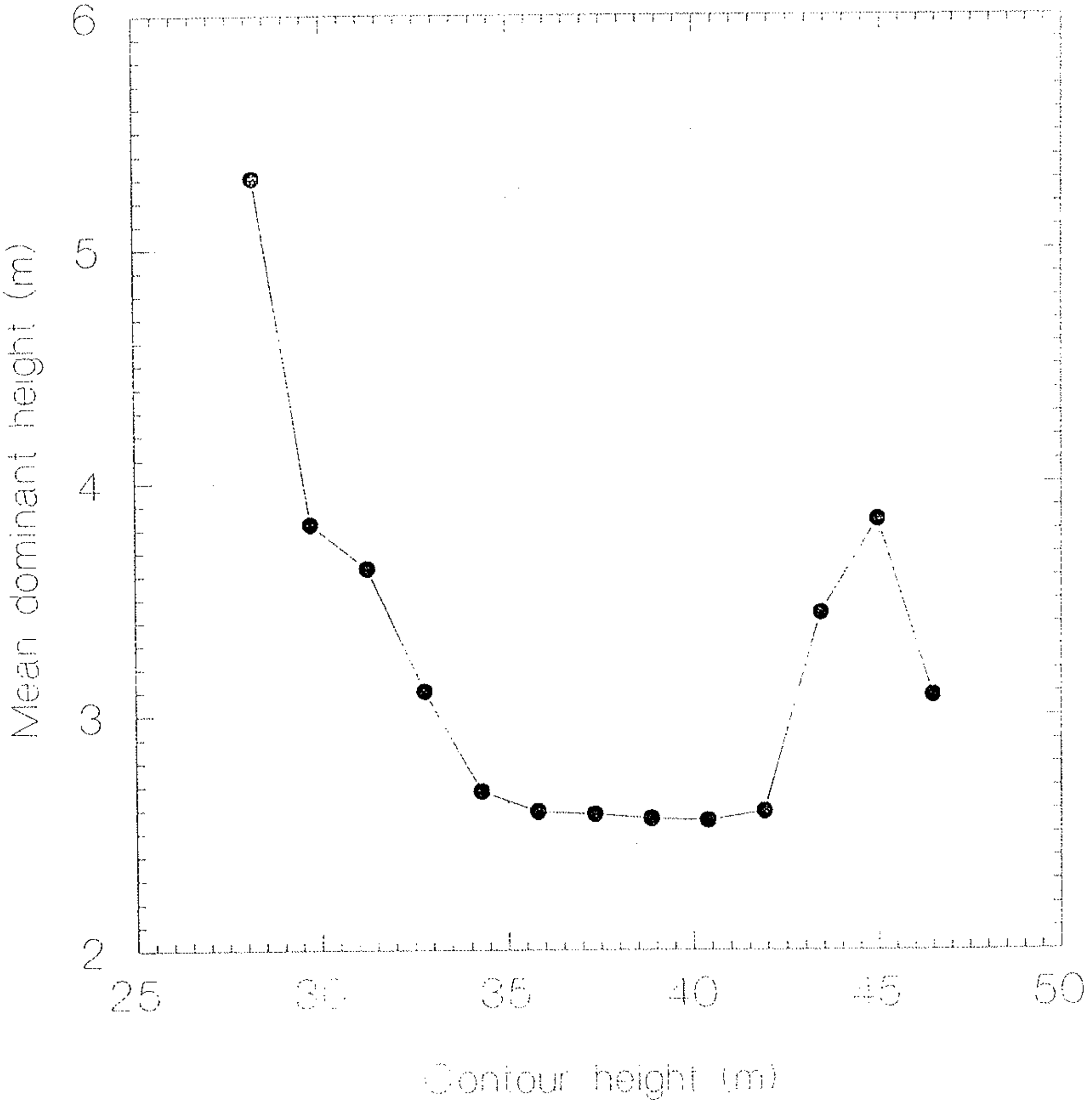

Figure 2.

Trends for dominant height growth of pines with increasing elevation in topography.

dominant trees near each 20 m x 20 m node on the topographic grid.

The trend of the results can be appreciated from summarised data in Table 3 and Figure 2. The datum for the contour survey was arbitrarily fixed at 30.5 m (100 feet) to correspond to the main level of landform in the area.

Vegetative classification - The site investigations which included the previous topographic study pointed to the use of vegetation as an indicator of pine growth potential in the region. As part of this follow up work (Havel 1968), a vegetation survey was carried out on the trial area in May 1969. The area was divided into 7 categories (Table 4) and the position of every tree within each site type was noted and recorded. Efforts were made to obtain plots (preferably two) of 20 m x 20 m size from each site type covering the range of thinning treatments and representative of the stocking for the particular thinning treatment. Owing to the small areas of some types, this was not successful. Some results were employed in the site study of Havel (loc. cit.) but analysis of the trial effects was not continued at that time.

Table 4: Species-soil classification used for site differentiation in the trial.

Site	Soil	Indicators
1	Moist White Sand	*Hypocalymna angustifolia* - *Dasypogon bromeliaefolius*
2	Humoid White Sand	*Xanthorrhoea preissii* - *Dasypogon bromeliaefolius*
3	Moist-Dry White Sand	*Xanthorrhoea preissii* - *Leucopogon conostephioides*
4	Leached Dry White Sand	*Leucopogon conostephioides* - *Scholtzia involucrata*
5	Poorer Leached Dry White Sand	*Eremaea pauciflora* - *Astroloma xerophyllum* - *Scholtzia involucrata*
6	Yellow Sand	*Synaphaea polymorpha* - *Mesomelaena stygia* - *Conospermum stoechadis*
7	Moist Yellow Sand	*Xanthorrhoea preissii* - *Synaphaea polymorpha* - *Dasypogon bromeliaefolius*

Site index - The problem confronting the 1985 measurement of the trial was to provide a practicable system to compare the effects of the thinning treatments. Variability limited useful comparisons of results within blocks. Several methods

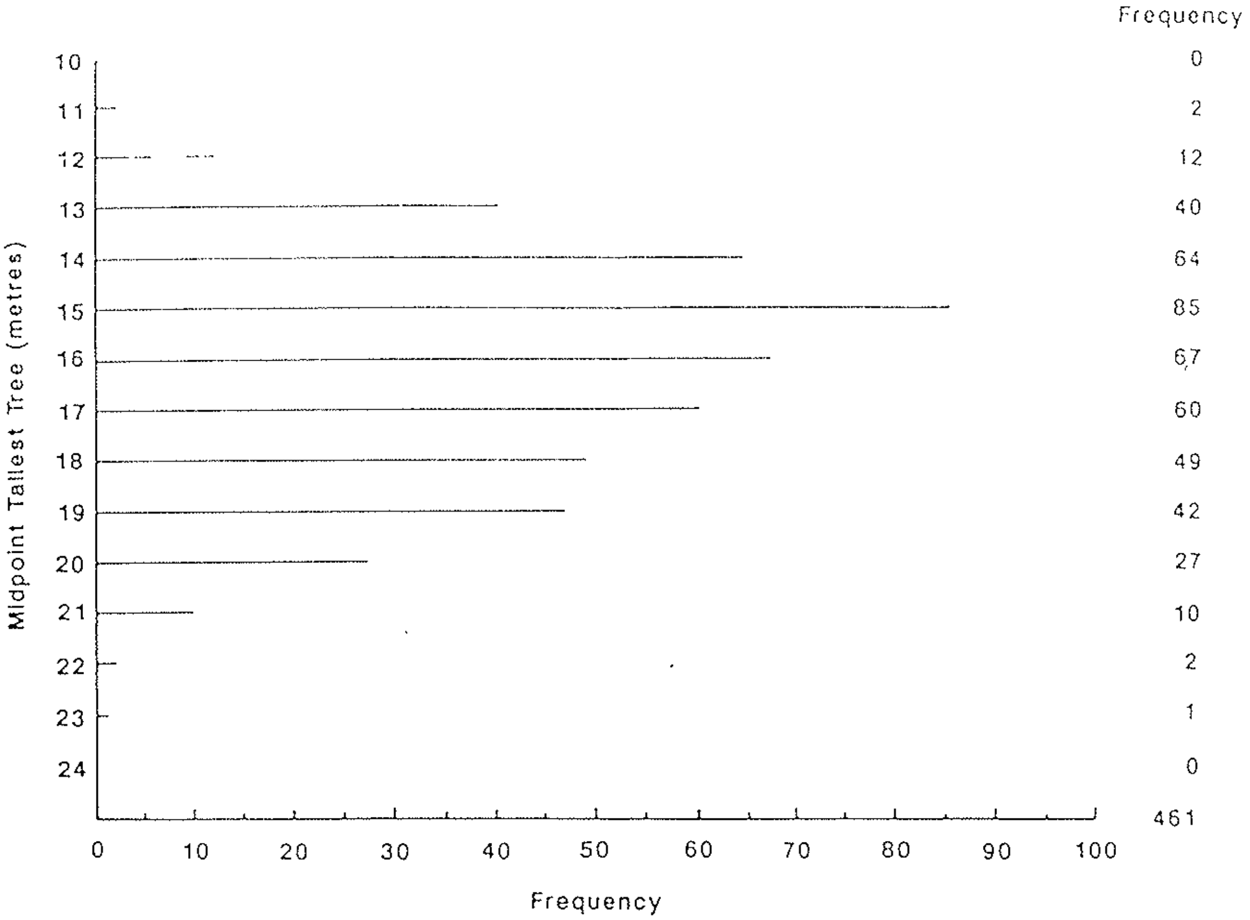

Figure 3. Range and distribution of top heights for subplots.

of analysis were possible and it has been mentioned that site definition by topography and vegetative classification were, initially, inadequate.

The first analysis procedure considered compared tree growth by regression procedures against treatment type, silvicultural class, stand age, tree height, basal area, etc., as independent variables. This however, provides results from components of a stand (i.e. dominants only) and requires synthesis for application to practicable systems. The system used avoided individual trees and assumed a minimum, uniform stand (subplot) which related to a Top height measured for the unit. Results were then compared within convenient site classes. To achieve this, measurements in 1985 were recorded in consecutive 20 m subplots along each plot. Plot number, subplot number, tree number, DBHob and bark thickness of the trees in the three central measurement rows were recorded for each 20 m length of subplot. In each subplot the most suitable trees representing a final crop of 247 s ha^{-1} were selected and recorded. The tallest tree in each plot and the final crop trees were measured for height.

To account for variable lengths of the end subplots in each treatment plot, terminal lengths of less than 10 m were included as part of the previous subplot. Where the odd length exceeded 10 m it was designated as a full subplot. The lengths of these odd subplots were measured and recorded to allow calculations of stand density, stem numbers, volume etc to be expressed accurately on a per hectare basis.

The tallest tree in the three central rows per 20 m x 20 m subplot (74 s ha^{-1}) was used as the Top (index) height for the population in that subplot. Subplots were ranked in height within 1 metre height intervals (Fig. 3) and by proceeding from the highest to the lowest ranking, allocated to five site classes each containing equal numbers (92) of subplots .

Table 5: Distribution of subplots within treatment and site classes

Treatment	Site class					Total
	1	2	3	4	5	
1	11	9	17	12	20	69
2	8	12	15	17	16	68
3	12	4	11	19	22	68
4	13	17	12	14	12	68
5	16	13	17	10	12	68
6	13	15	16	13	9	66
7	22	21	11	6	7	67
Total	95	91	99	91	98	474

The distribution of these subplots (plus 13 not available for the initial ranking due to requirements for field checking) within the treatment-site class matrix (Table 5) randomised treatments over the area and provided uniform subplot numbers relative to treatment and site classes. The minimum replication to provide a mean value for a treatment-site cell was 4 and the maximum was 22. Variation can be expected when any two such means are compared. Treatment and site means are robust.

Analysis of Measurement Data

Validation of measurement data was an excessive task which had prohibited previous check analyses at earlier measurements. Later use of a computer validation program isolated possible errors and inconsistencies but the checking of these back to the original field sheets was difficult and tedious. Analysis was restricted to data from the 1962, 1967, 1971, 1977 and 1985 measurements at stand ages of 8.7 (9), 13.4 (13), 17.7 (18), 23.7 (24) and 31.7 (32) years, respectively.

For each subplot total stem numbers, basal area over bark (BAob) and under bark (BAub), mean diameter at breast height under bark (Dub), mean height and total stem volume under bark were calculated. These values were also calculated for the final crop (247 s ha^{-1}) portion of each subplot.

Table 6. Transformations required to obtain homoscedasticity for data analysis. In the table 'yes' indicates that the data were homoscedastic using the particular transform indicated.

Attribute	Transform	Year of measurement				
		1962	1967	1971	1977	1985
Height	Normal	yes	yes	yes	-	yes
Diameter	Normal	yes	yes	No	yes	no
	Sqrt	yes	yes	yes	yes	yes
H/D	Normal	No	No	No	-	No
	Sqrt	No	No	No	-	No
	Log	No	No	No	-	No
	Arcsine	yes	No	No	-	No
	Reciprocal	yes	yes	yes	-	yes
BAob	Normal	No	No	No	No	No
	Sqrt	yes	yes	yes	yes	yes
Volume	Normal	No	No	No	-	No
	Sqrt	yes	No	No	-	No
	Log	yes	yes	yes	-	yes

Data analysis for the unequal numbers of cells in treatment and site classes (Table 5) used the General Linear Model. The means for height, diameter, height/diameter (H/D), basal area and volume were examined for heterogeneity of variance (Levine's Test) and homoscedasticity. Results and requirements for data transformation are summarised in Table 6 and results of the main analyses of variance (ANOVA) are summarised in Table 7.

Table 7. Summary of results for analysis of variance for measurement data. Values for Treatment, Site and Treatment x Site at each measurement date are the probabilities that the F value obtained would be exceeded by chance. The error term is the error mean square for each analysis.

Attribute	DF	Year of measurement				
		1962	1967	1971	1977	1985
		Height (m)				
Treatment	6	.000	.000	.000	-	.146
Site	4	.000	.000	.000	-	.000
Treat x site	24	.339	.364	.131	-	.051
Error	438	.929	1.093	1.244	-	.499
		Diameter under bark (cm) - Square root transformation				
Treatment	6	.000	.000	.000	.000	.000
Site	4	.000	.000	.000	.000	.000
Treat x site	24	.253	.091	.048	.132	.081
Error	438	.091	.053	.048	.039	.044
		Height/Dub for the final crop - Reciprocal transformation				
Treatment	6	.000	.000	.000	-	.000
Site	4	.000	.016	.649	-	.002
Treat x site	24	.022	.534	.125	-	.091
Error	438	.013	.012	.011	-	.012
		Stand basal area (m^2 ha^{-1}) - Square root transformation				
Treatment	6	.000	.000	.000	.000	.000
Site	4	.000	.000	.000	.000	.000
Treat x site	24	.079	.159	.139	.368	.365
Error	438	.242	352	376	.403	.473
		Stand volume (m^3 ha^{-1}) - Log transformation				
Treatment	6	-	.000	.000	-	.146
Site	4	-	.000	.000	-	.000
Treat x site	24	-	.289	.058	-	.014
Error	438	-	.215	.167	-	.088
		Volume of final crop (m^3 ha^{-1}) - Log transformation				
Treatment	6	.002	.000	.000	-	.000
Site	4	.000	.000	.000	-	.000
Treat x site	24	.285	.123	.064	-	.197
Error	438	.556	.187	.145	-	.091

RESULTS

Height Growth

Heights were measured in the early stages of stand development by a height stick and in the latter stages with a clinometer. Heights were not measured in the 1977 measurement and values included in results for stand age 24 years were computed from height over diameter (H/D) ratios of final crop trees calculated from the 1971 and 1985 measurements.

The range and distribution of the 1985 Top height measurements (74 tallest stems ha^{-1}) are depicted in Figure 3. The mean final crop heights (Predominant heights) are entered in Table 8. Procedure for analysis of the trial assumes that these Top height measurements at age 32 years represent the height development of the respective subplots, over the life of the stand. The 5 arbitrary site classes separated have equal numbers of consecutive subplots ranked by Top height in a descending manner.

Data for height increment were also analysed (Table 11). As a final check for trends over the trial period data sets were combined and analysed in a repeated analyses model with site classes nested within measurement years (Table 31).

Table 8: Distribution of height means (Predominant height) for final crop stems within treatment and site classes. Age 32 Years

Treatment	Site class (age 32 years)					Mean
(s ha^{-1})	1	2	3	4	5	(m)
1 (1880)	17.6	16.4	15.0	14.0	12.6	15.1
2 (1320)	18.4	16.4	15.1	14.3	12.9	15.4
3 (1270)	18.4	16.6	15.4	14.0	12.9	15.4
4 (950)	18.9	16.5	14.9	14.0	12.9	15.4
5 (745)	18.7	16.6	14.9	14.0	12.7	15.3
6 (450)	18.6	16.5	15.2	14.0	12.8	15.4
7 (244)	18.1	16.6	15.2	14.2	12.7	15.3
Mean (m)	18.3	16.5	15.1	14.0	12.8	

Stability of site classes - The mean Predominant height (247 tallest s ha^{-1} is equal to final crop selection) of stems selected in the 1985 assessment is plotted for each site class and measurement in Figure 4. The pattern of development with age was consistent for all five classes. Height data was homogeneous in variance (Levine's Test) and homoscedastic. The mean of Predominant heights within site classes defined in the 1985 measurement were highly significantly (0.001 level) different at all measurements (Table 7). These site group means were also significantly different to each other, except

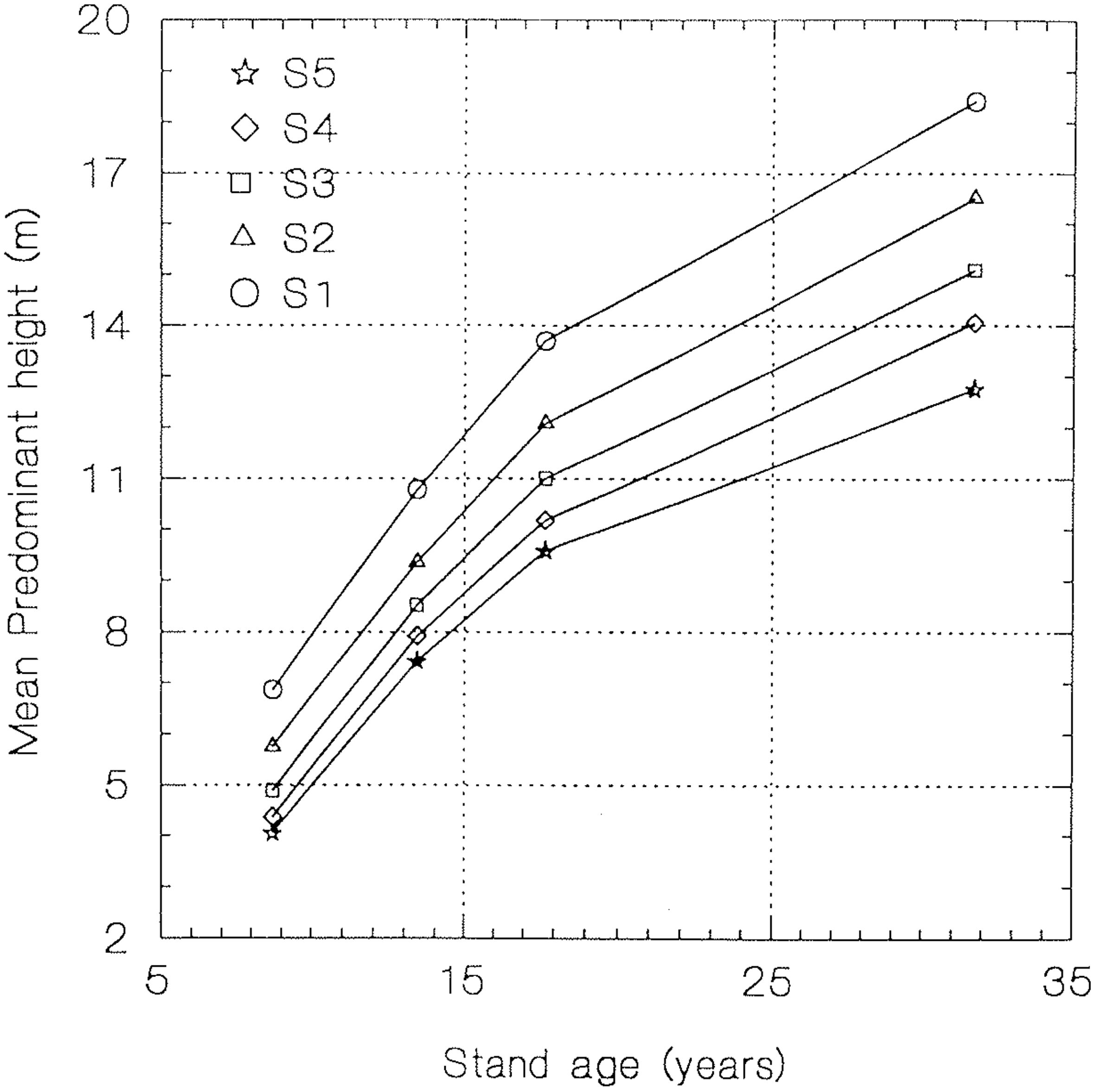

Figure 4.

Predominant heights of site classes with increasing stand age.

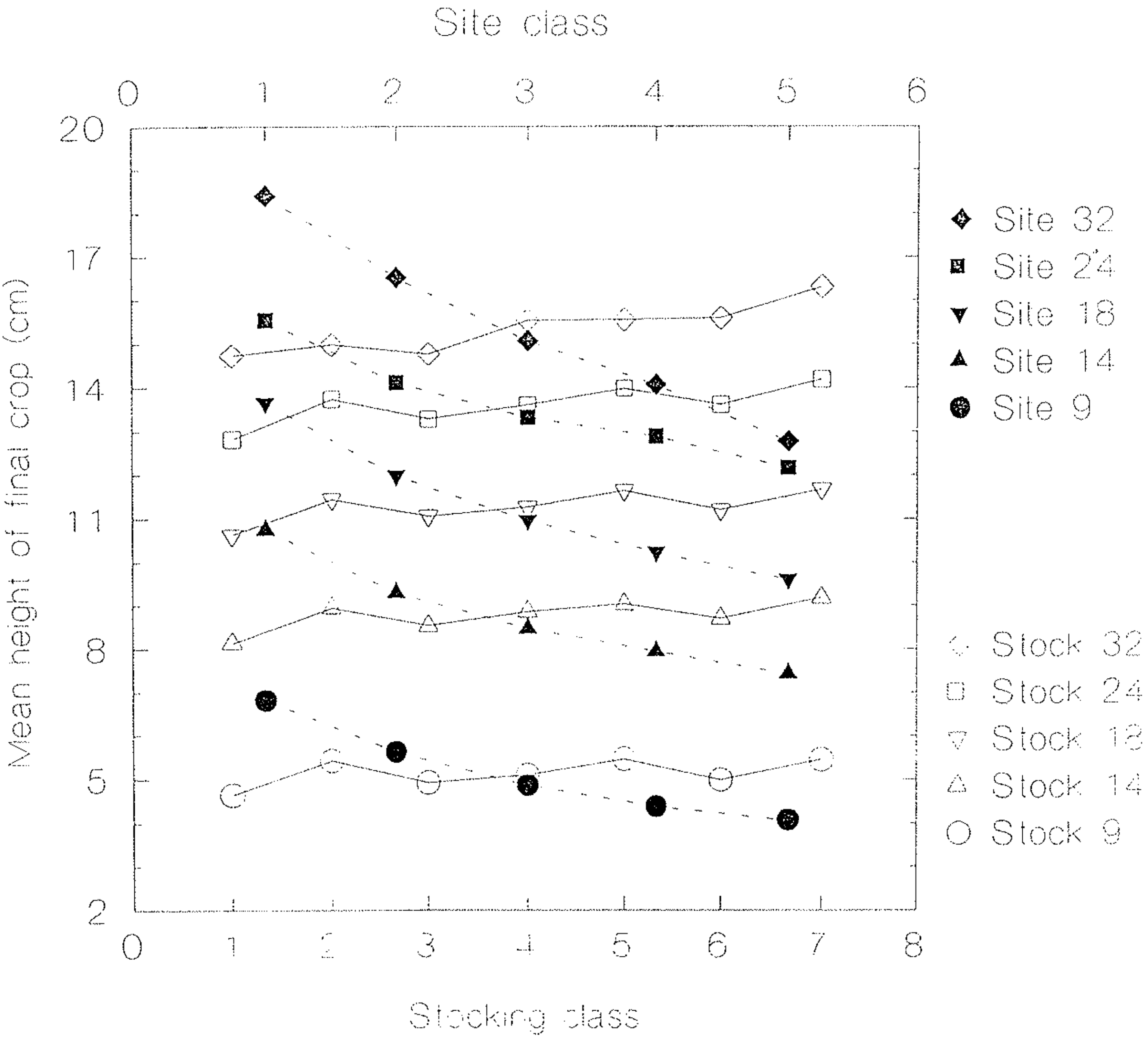

Figure 5.

Interactions for site class and stocking treatment means for different stand ages.

Site class	1	2	3	4	5
1962	-------	-------	-------	------------------	
1967	-------	-------	-------	-------	-------
1971	-------	-------	-------	-------	-------
1985	-------	-------	-------	-------	-------
Site class	1	2	3	4	5

Figure 6.

Significance of height means for final crop stems within the site class groupings established from top height at age 32 years. Dashed lines join means which are not significantly different at the 0.05 level of probability on the basis of Bonferroni comparisons.

in 1962 when the poorest Site 5 was not different to the next poorest Site 4 (Table 9, Figs. 5 and 6).

Impact of stocking on height growth - Analysis of variance of mean final crop heights in 1985 (Table 8) showed the treatment effect to be non-significant at the .05 level and the site x treatment interaction to be significant at the .05 level (Table 7). The interaction in 1985 was due to abnormally high values for Treatment 4 (950 s ha^{-1}) in Site 1 and abnormally low values for Treatment 1 (1880 s ha^{-1}) in Site 1 (Table 8).

For previous measurements (Tables 7 and 9) differences between treatments for Predominant height were highly significant and mainly associated with a consistently high value for Treatment 2 and a consistently low value for Treatment 1 (Fig. 5). Treatment 2 was significantly different to Treatment 1 in 1962, 1967 and 1971, Treatment 3 differed from treatment 1 in 1967 and 1971 and Treatment 5 differed from 1 in 1962 and 1971. Treatments 6 and 7 differed significantly from treatment 2 in 1962 and 1971. If Treatments 1 and 2, which were abnormal at the commencement of measurement in 1962 (Table 9), are removed from the data set, Treatments 3 to 7 did not differ significantly in Predominant height during the trial.

Table 9. Predominant heights (m) of treatments and site classes at different measurements.

Treatment	Year of measurement			
(s ha^{-1})	1962	1967	1971	1985
1 (1880)	4.84	8.36	10.89	15.05
2 (1320)	5.68	9.23	11.78	15.45
3 (1270)	5.36	8.98	11.61	15.44
4 (950)	5.08	8.83	11.23	15.42
5 (745)	5.36	8.91	11.50	15.36
6 (450)	4.95	8.66	11.14	15.41
7 (244)	5.02	8.63	11.01	15.34
Site Class	1962	1967	1971	1985
1	6.86	10.78	13.70	18.34
2	5.75	9.36	12.07	16.51
3	4.89	8.52	11.00	15.09
4	4.37	7.92	10.18	14.06
5	4.06	7.42	9.58	12.76
ALL	5.19	8.80	11.31	15.35

Differences in height means for some treatments were present at the inception of the trial and were generally maintained through the trial history (Fig. 5). They relate mainly to the two highest stocking levels and cannot be associated with any treatment effect or process of stand development.

Table 10. Mean periodic annual increment in Predominant height (m) for treatment and site classes. The 1977 data were not measured and were calculated to indicate trends.

	Increment period					
Treatment	1962-67	1967-71	1971-77	1977-85	1971-85	1962-85
1	0.70	0.63	0.35	0.26	0.30	0.45
2	0.71	0.64	0.37	0.18	0.26	0.42
3	0.72	0.66	0.31	0.25	0.27	0.44
4	0.75	0.60	0.39	0.23	0.30	0.45
5	0.71	0.65	0.40	0.19	0.28	0.43
6	0.74	0.62	0.40	0.23	0.31	0.46
7	0.72	0.60	0.43	0.22	0.31	0.45
Site class	62-67	67-71	71-77	77-85	71-85	62-85
1	0.78	0.73	0.31	0.35	0.34	0.50
2	0.72	0.68	0.31	0.32	0.32	0.47
3	0.73	0.62	0.39	0.22	0.29	0.44
4	0.71	0.57	0.45	0.15	0.28	0.42
5	0.67	0.54	0.43	0.08	0.23	0.38
Age (years)	9-14	14-18	18-24	24-32	18-32	9-32

Table 11. Results of analysis of variance for height and basal area increment between measurements. Height in 1977 was calculated and is included to indicate trends. Values for Treatment, Site and Treatment x Site for each measurement period are the probabilities that the F value obtained would be exceeded by chance. The error term is the error mean square for each analysis.

Predom. height		62-67	67-71	71-77	77-85	71-85	62-85
Source	DF	P	P	P	P	P	P
Treat	6	0.120	0.043	0.366	0.135	0.000	0.000
Site	4	0.000	0.000	0.001	0.000	0.000	0.000
Treat*Site	24	0.206	0.472	0.775	0.708	0.292	0.263
Error	438	0.0112	0.0132	0.0716	0.0390	0.0056	0.0019
Total	472						

Basal area (Sqrt)		53-62	62-67	67-71	71-77	77-85
Treat	6	0.000	0.000	0.000	0.000	0.000
Site	4	0.000	0.000	0.000	0.000	0.001
Treat*Site	24	0.013	0.056	0.489	0.574	0.004
Error	438	0.0473	0.0417	0.0289	0.0146	0.0173
Total	472					

Height increment Mean annual increments in Predominant height for site and treatment classes with stand development are presented in Table 10. Treatment differences in height were not significant for the 1962-67 period, significant at the .04 level for the 1967-71 period but highly significant for the 1971-85 increment period (Table 11). Differences in Predominant height growth between treatments for the whole 1962-85 measurement period were highly significant. Treatment means for height growth differed very little (Table 10) and the tallest plot at inception of the trial, Treatment 2, had the smallest increment over the period of the trial.

Table 12: Best subsets regression for log of Predominant height.

Response is LOGPDHT

1892 cases used 4 cases contain missing values.

Vars	R^2	Adj. R^2	C-p	s	Treat	Site	AgE	1/Age	S/AgE	T*S	T*Age	S*Age	1/S*Age
1	81.2	81.2	1E+04	0.198				X					
1	67.5	67.5	2E+04	0.260			X						
2	96.8	96.8	414.7	0.081				X	X				
2	90.3	90.3	5023.7	0.141		X		X					
3	97.2	97.2	121.3	0.076			X	X				X	
3	96.9	96.9	316.3	0.080		X		X	X				
4	97.3	97.3	34.0	0.074				X	X			X	X
4	97.3	97.3	73.7	0.075		X		X	X			X	
5	97.3	97.3	23.1	0.074		X	X	X	X			X	
5	97.3	97.3	25.8	0.074			X	X	X			X	X
6	97.4	97.4	8.6	0.074		X	X	X	X			X	X
6	97.3	97.3	20.6	0.074		X	X	X	X		X	X	
7	97.4	97.4	6.2	0.074		X	X	X	X		X	X	X
7	97.4	97.4	7.1	0.074	X	X	X	X	X			X	X
8	97.4	97.4	8.1	0.074		X	X	X	X	X	X	X	X
8	97.4	97.4	8.2	0.074	X	X	X	X	X		X	X	X
9	97.4	97.4	10.0	0.074	X	X	X	X	X	X	X	X	X

Site classes - To quantify the relationships of stand height with environmental parameters, Predominant height per subplot was related to treatment, site class and age and reciprocal and square transforms which may have relevance in a model for site index. Best subsets regression procedures were examined for the original data and the square root and natural log transforms which were indicated as advantageous from residuals analysis. Maximum variation in the height data explained (R^2) was 95 per cent. This was increased to 97 per cent with the square root or log transform which provided for better homoscedasticity. Eighty one per cent of variation was explained by 1/Age and 97 per cent by 1/Age and Site class/Age (Table 12).

Inclusion of the stocking treatments in the model (Table 12) had no influence on explaining the variation in height or reducing the standard deviation about the regression (s).

The regression model adopted was

LogPDHt = 3.21 - 0.0168 SClass - 26.7 1/Age + 1.17 Site*1/Age

Predictor	Coef	Stdev	t-ratio	p
Constant	3.2104	0.0071	449.61	0.000
Site Class	-0.0168	0.0018	-9.28	0.000
1/Age	-26.7435	0.2164	-123.59	0.000
Site*1/Age	1.1727	0.0184	63.57	0.000

$s = 0.08014$ $R^2 = 96.9\%$ $R^2(\text{adj}) = 96.9\%$

Measured Predominant heights at age 17.7 were substituted in the model for the site class independent variable and predicted values for stand ages ranging from 10 to 30 years were calculated and plotted as height - age curves for site index with 17.7 years of growth (Fig. 7). As both Predominant height and Top height were of interest models were calculated for both stand height expressions (Table 13).

Table 13. Regressions obtained for Predominant and Top heights for site index at age 17.7 years

Dependent variable	Constant	SI 17.7	1/Age 17.7	SI/Age	n	s	R^2 Adj.
PDHt	6.208	1.0785	-84.235	-3.097	1892	0.877	95.3
THt	7.380	1.0081	-97.644	-2.346	1892	0.999	94.5
SqrPDt	3.321	0.1037	-25.344	0.488	1892	0.122	96.7
SqrTHt	3.382	0.1017	-26.084	0.498	1892	0.124	96.7
LogPDt	2.860	0.0266	-24.469	0.971	1892	0.080	97.0
LogTHt	2.910	0.0246	-25.028	0.978	1892	0.082	96.9

The role of treatment effects on height was also examined by separating the stocking treatments within a General Linear Model. When examined individually only Treatments 1 and 2 had significant 't' values within the regression. For all treatments the regression was as follows -

$$\begin{aligned}\text{Height} = {} & 10.2 - 0.366\,X2 + 0.359\,X3 + 0.182\,X4 - 0.0124\,X5 \\ & + 0.118\,X6 - 0.125\,X7 + 2.27\,X8 + 0.760\,X9 - 0.291\,X10 \\ & - 1.03\,X11 - 4.98\,X12 - 1.36\,X13 + 1.14\,X14\end{aligned}$$

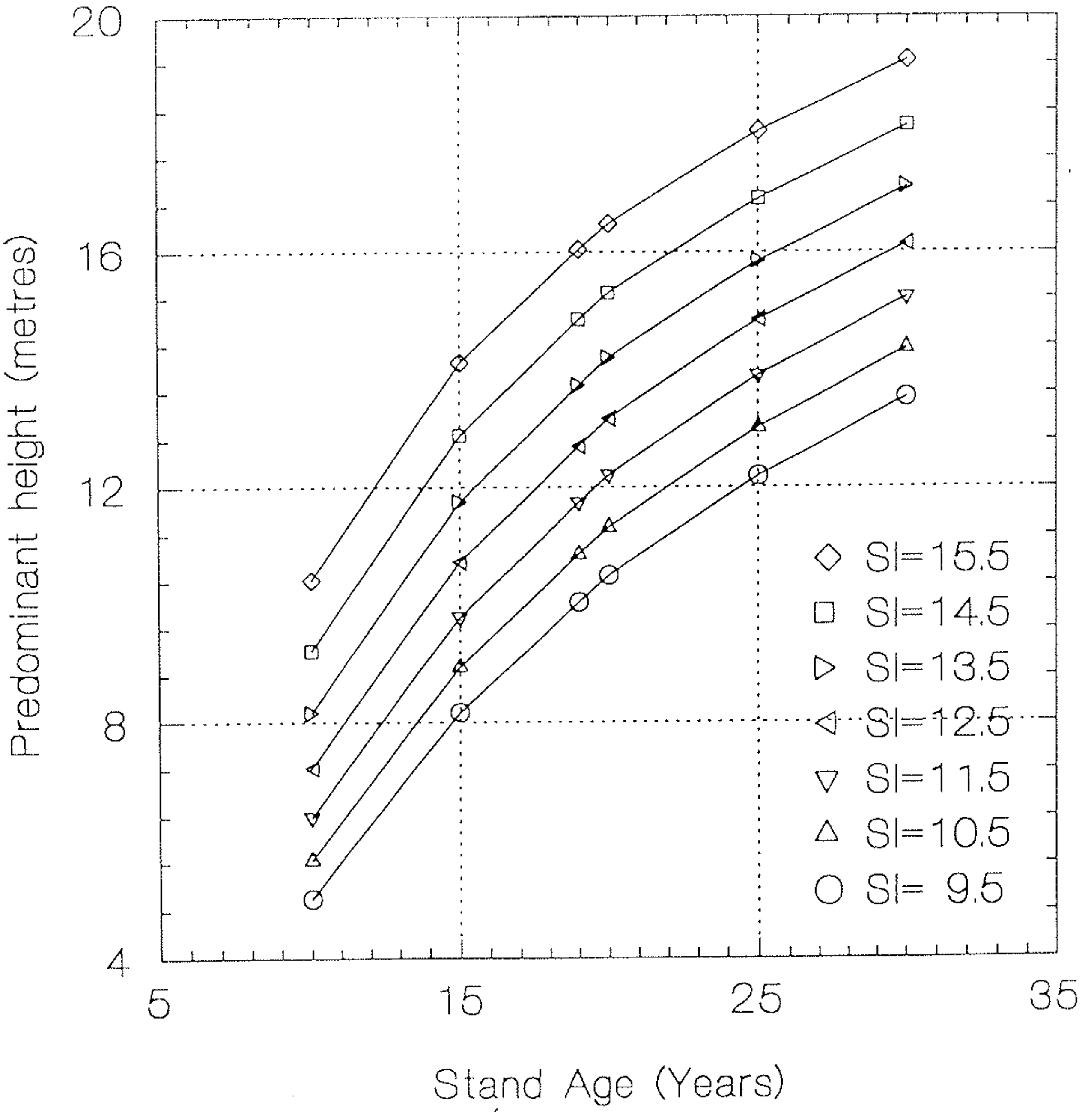

Figure 7:

Site index curves developed for the Free Growth data.

Predictor	Seq. SS	Stdev	t-ratio	p	Source
Constant		0.0405	251.10	0.000	T7,S5,Age 32
X2	0.43	0.0991	-3.69	0.000	Treatment 1
X3	5.13	0.0991	3.62	0.000	Treatment 2
X4	0.84	0.0991	1.84	0.068	Treatment 3
X5	0.00	0.0991	-0.12	0.901	Treatment 4
X6	0.23	0.0991	1.19	0.235	Treatment 5
X7	0.36	0.0991	-1.26	0.211	Treatment 6
X8	221.69	0.0809	28.06	0.000	Site 1
X9	4.27	0.0809	9.38	0.000	Site 2
X10	11.26	0.0809	-3.60	0.000	site 3
X11	37.25	0.0809	-12.74	0.000	Site 4
X12	1813.05	0.0701	-71.02	0.000	Age 9 years
X13	50.65	0.0701	-19.45	0.000	Age 13 years
X14	61.00	0.0701	16.31	0.000	Age 21 years

s = 0.4789 R^2 = 98.7% R^2(adj) = 98.6%

The only appreciable contribution to the sum of squares by stocking levels was by the second densest stand in Treatment 2.

Table 14: Residual numbers of stems per hectare for treatment and site classes in 1971 (18 years of age) on the completion of progressive thinning.

Treatment (s ha^{-1})	Site class 1	2	3	4	5	Mean
			Whole stand			
1 (1880)	1840	1668	2057	1867	1968	1902
2 (1320)	1281	1249	1435	1336	1307	1323
3 (1270)	1338	1394	1145	1297	1173	1243
4 (950)	1078	878	867	966	951	941
5 (745)	768	719	727	795	708	740
6 (450)	442	452	391	461	505	444
7 (244)	299	238	265	219	196	256
Mean	897	787	1025	1088	1133	988
			Final crop			
1 (1880)	273	229	264	231	248	250
2 (1320)	213	241	275	242	228	242
3 (1270)	239	257	250	250	249	248
4 (950)	253	247	258	247	229	247
5 (745)	243	254	251	242	235	246
6 (450)	251	263	252	245	257	254
7 (244)	291	238	265	219	196	254
Mean	2571	247	260	242	238	249
Site Class	1	2	3	4	5	

Stocking and Stand Density

Treatment plots were of the order of 100-200 m x 20 m in extent (Fig. 1) and although the practical intention was to obtain the required treatment stockings over comparable (20 m x 20 m) sections of each plot, both natural and operator variation were present. Subplot counts, which are the basis for the comparison of treatment site cells, refer only to the central three rows of each subplot i.e. to approximately 0.013 ha units. Some variation in stem numbers (expressed on a per hectare basis) from that of the treatment ideal was expected over the large trial area.

Stem numbers - Stockings achieved in the trial following thinning and prior to drought losses are shown in Table 14. Each treatment-site value in the table is the mean of at least 4 and up to 22 subplots (Table 5). For the thinning Treatments 1 to 7, variation in stem numbers for site classes around the overall treatment mean are 11, 9, 10, 13, 7, 13 and 22 per cent, respectively. This variation is sufficient within Treatments 2 and 3 (intended stockings of 1480 and 1240, respectively) for Site 1 and 2 cells in Treatment 3 to exceed the actual stocking in Site 1 and Site 2 cell in Treatment 2. For Treatments 4 to 7 however, the variation is within the intended range of differences between treatments and treatment stockings are distinct from those adjacent within the same site class.

Variation is also present in the number of final crop stems (intended 247 s ha^{-1}) expressed on a per hectare basis (Table 14). The variation around the intended mean within Treatments 1 to 7 is 8, 15, 4, 7, 5, 6 and 21 per cent, respectively. Again, this largely arises from the selection process where 3.3 stems were to be marked as final crop in the three measurement rows of each subplot. Overall means for treatments and site classes are within 5 per cent of the intended number of 247 s ha^{-1}.

Table 15: Drought deaths (s ha^{-1}) recorded from 1977 and 1985 measurements

Treatment (s ha^{-1})	Site class 1	2	3	4	5	Total
1 (1880)	242	143	73	93	77	628
2 (1320)	53	34	89	10	11	197
3 (1270)	56	43	0	27	28	154
4 (950)	130	20	20	0	0	170
5 (745)	10	7	20	0	14	51
6 (450)	20	17	5	6	29	77
7 (244)	0	0	0	0	0	0
Total	511	264	207	136	159	1277

Table 16. Analysis of variance for drought deaths recorded up to 1985.

```
 Analysis of Variance for DROUGHT

 Source       DF     Seq SS   Adj SS  Adj MS     F      P
 Treat         6     582072   645554  107592   13.09  0.000
 Site          4     157633   162498   40624    4.94  0.001
 Treat*Site   24     333539   333539   13897    1.69  0.023
 Error       439    3608802  3608802    8221
 Total       473    4682046

 One-Way Analysis of Variance for Treatment classes.

 Analysis of Variance on DROUGHT
 Source     DF        SS        MS        F        p
 Treat       6    582072     97012    11.05    0.000
 Error     467   4099974      8779
 Total     473   4682046
                               Individual 95% CIs For Mean
                               Based on Pooled StDev
Level  N    Mean  StDev  -----+---------+---------+---------+
 1     69  114.03 151.81                         (----*---)
 2     68   35.74  62.04          (---*-----)
 3     68   28.50  69.54        (----*---)
 4     68   34.05 161.74         (----*---)
 5     68   11.35  36.01     (---*-----)
 6     66   14.29  41.43     (----*---)
 7     67    0.00   0.00   (---*---)
                         -----+---------+---------+---------+
 Pooled StDev =    93.70      0        50       100       150

 One-Way Analysis of Variance for site classes.

 Analysis of Variance on DROUGHT
 Source     DF        SS        MS        F        p
 Site        4     97935     24484     2.50    0.042
 Error     469   4584112      9774
 Total     473   4682046
                       Individual 95% CIs For Mean
                       Based on Pooled StDev
Level  N   Mean  StDev  ----------+---------+---------+-----
  1   95  61.85 178.23                   (-------*-------)
  2   91  27.74  74.83     (-------*-------)
  3   98  33.03  64.28       (-------*-------)
  4   93  20.29  54.24  (-------*-------)
  5   97  28.29  66.34     (-------*-------)
                        ----------+---------+---------+-----
 Pooled StDev = 98.86            25        50        75
```

Stocking and drought - At the onset of the severest drought recorded for the northern Swan Coastal Plain in 1977, stands in the trial were 23 years of age. Extensive deaths in sections of the trial were first measured in the 1977 assessment. Further deaths due to the continuation of the drought were recorded in the 1985 measurement.

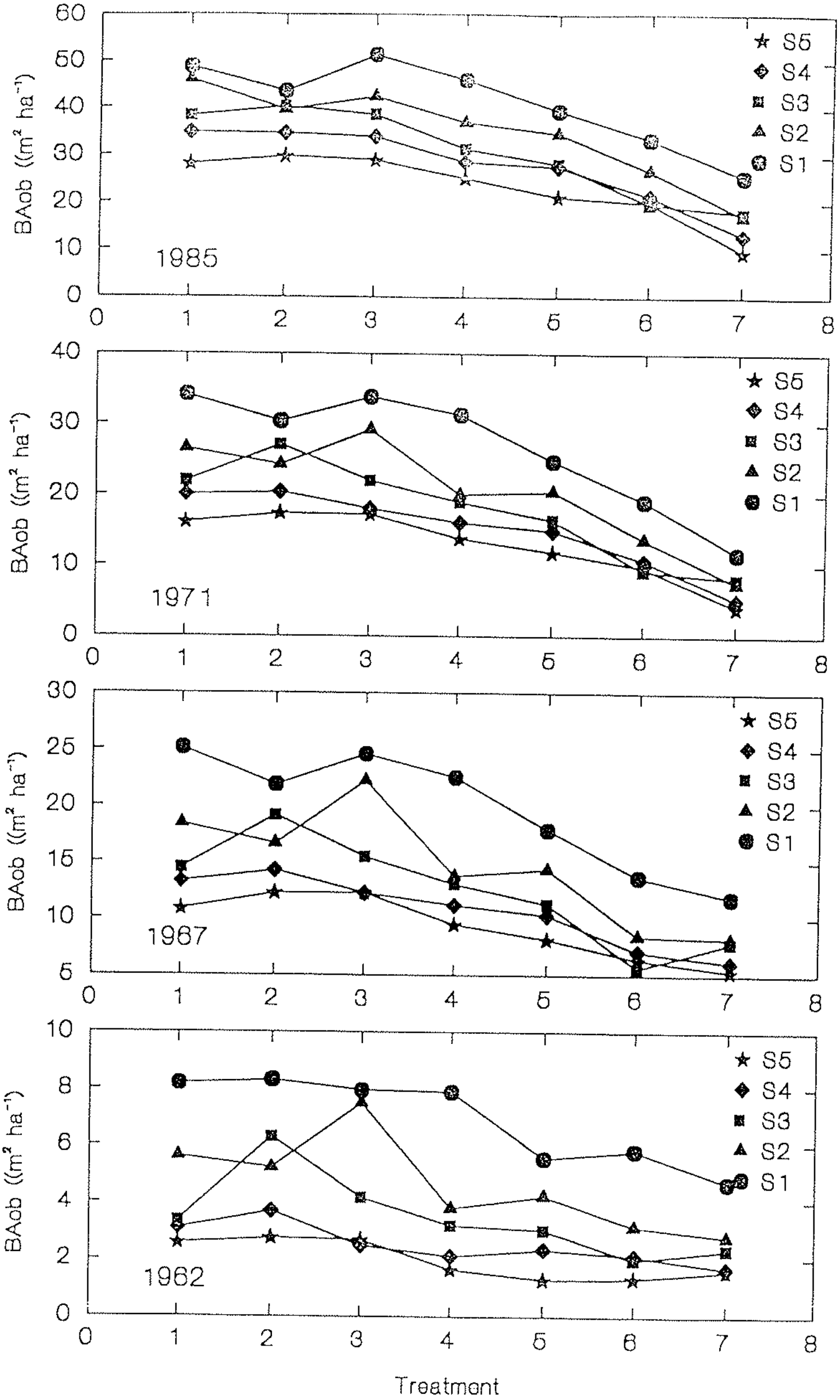

Figure 8.

Interaction of stocking treatment and site class means for basal area with stand development.

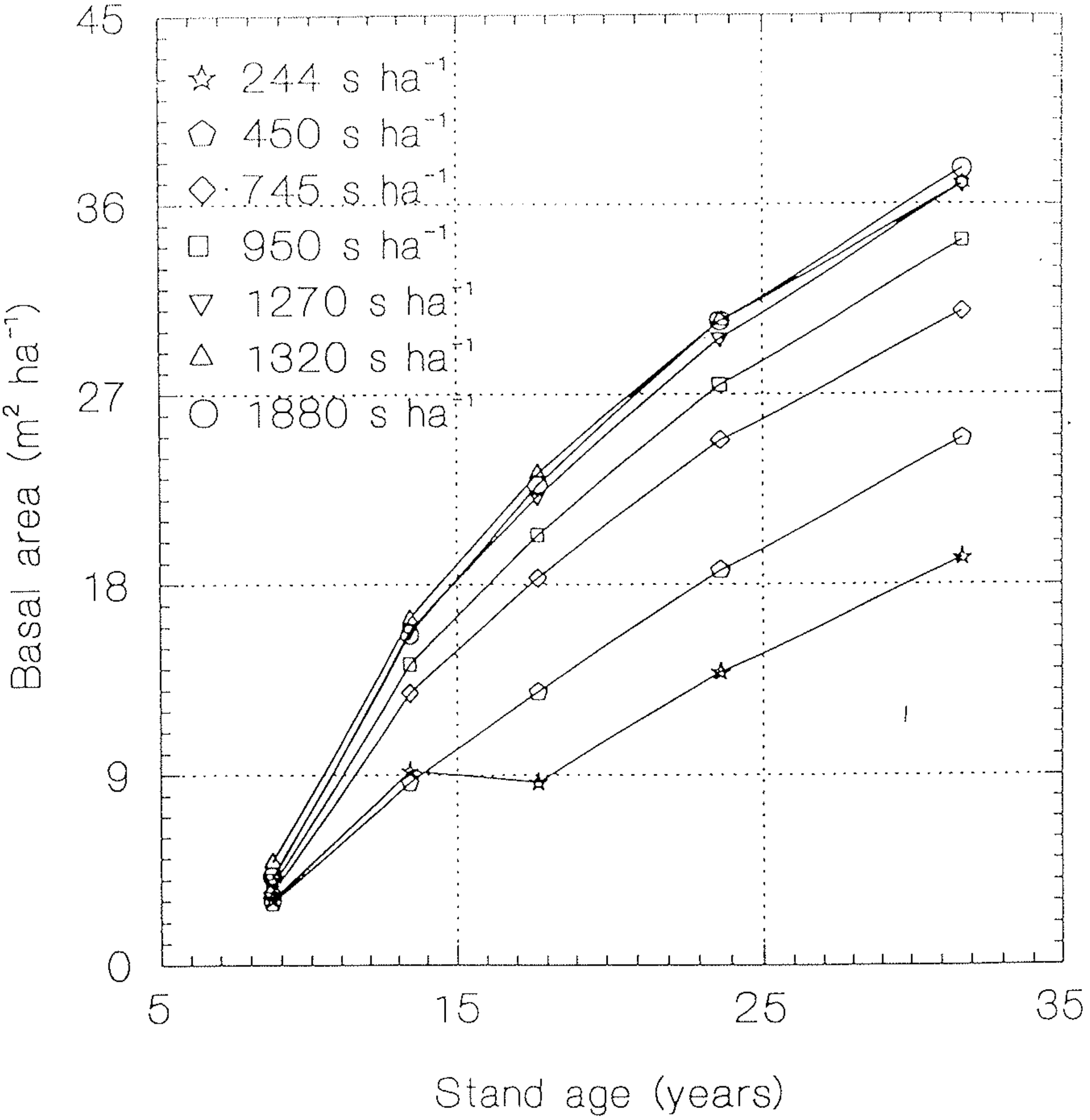

Figure 9.

Development of basal area of stocking treatments with increasing stand age.

Drought deaths were concentrated in the heavily stocked treatments and were totally absent from the lowest stocking treatment of 244 s ha^{-1} (Table 15). Mortalities were also concentrated in the highest site class which has significantly superior height and volume growth to the other four site classes. Mortalities were spread over these lesser four site classes with higher mortalities in Sites 2 and 3.

For the Havel Site Classification most mortality occurred in the Index 7 (Table 4). Seven subplots representing this type were within the superior Site class 1 and all deaths were from three plots at stocking level 950 s ha^{-1}. There were no mortalities in the four other plots with the lower stocking densities of 450 and 244 s ha^{-1}.

Analysis of variance showed treatment and site effects to be highly significant and the site x treatment interaction was significant (Table 16).

The overall impact of drought on the trial, from the viewpoint of stocking, was minimal (Table 17).

Table 17 Residual stems per hectare in the trial at age 32 years.

Thinning (s ha^{-1})	Site class 1	2	3	4	5	Mean
1 (1880)	1575	1543	1999	1807	1887	1804
2 (1320)	1153	1208	1362	1327	1296	1286
3 (1270)	1285	1286	1145	1288	1153	1221
4 (950)	979	868	845	966	951	922
5 (745)	742	706	711	795	693	728
6 (450)	442	452	386	461	505	443
7 (244)	291	238	265	219	196	254
Mean	829	761	997	1076	1109	956

Basal Area

There was some non-significant interaction between site x stocking treatments (Table 7) but the pattern for site classes was constant throughout the trial (Fig. 8).

Mean BAob development with age for each stocking treatment is shown in Figure 9. Differences between the means for Treatments 1,2 and 3 and Treatments 3 and 4 were not significant throughout the trial (Figs. 9 and 10, Table 7) Up to 1967 the final treatment had yet to be released from 450 to 247 s ha^{-1} and was not significantly different to Treatment 6 at that stage. The difference was significant within 4 years of the final thinning.

BAob development at age 32 years (Table 18) ranged from 51.4 m^2 ha^{-1} for Treatment 3 Site Class 1 (T3SC1) to 10.1 m^2 ha^{-1}

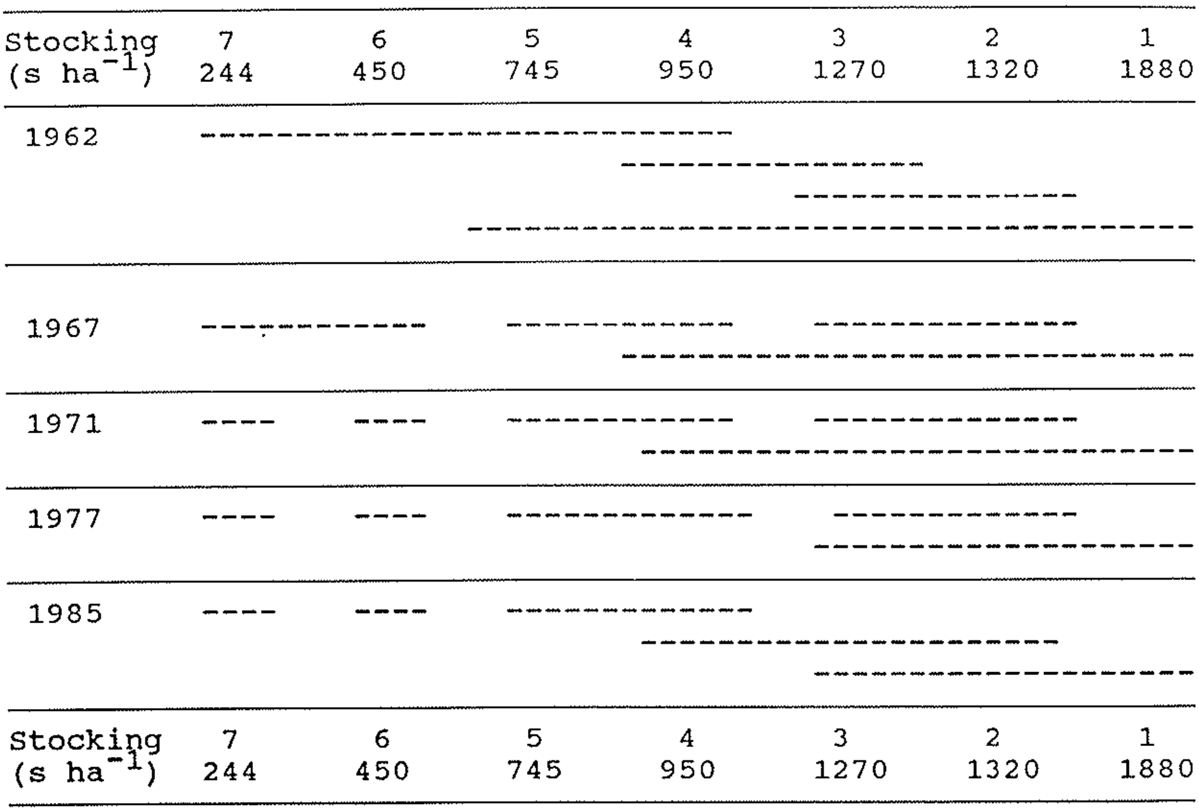

Figure 10.

Significance of basal area means for the whole stand with variable stocking and stand age. Dashed lines join means which are not significantly different at the 0.01 level of probability on the basis of Bonferroni comparisons.

for T7SC5. Although the 1985 data was influenced by drought impacts which were high in Treatment 1, this does not alter the similarities in totals for the three dense treatments since 1967 (Table 19).

Table 18: Development of basal area over bark (m^2 ha^{-1}) of stands at age 32 years

Treatment	Site class					Mean
(s ha^{-1})	1	2	3	4	5	
1 (1880)	46.3	46.0	38.5	35.6	28.4	37.3
2 (1320)	43.7	40.3	40.4	34.9	29.9	36.9
3 (1270)	51.8	42.7	38.7	34.1	29.3	36.9
4 (950)	46.7	37.4	31.5	28.8	25.5	34.3
5 (745)	39.8	34.6	28.2	27.6	21.5	30.9
6 (450)	33.7	27.3	20.6	21.8	20.1	24.9
7 (244)	25.9	17.5	18.4	13.1	10.2	19.3
Mean	39.3	32.2	31.1	29.8	25.6	

Table 19. Mean standing basal areas (m^2 ha^{-1}) for treatments within progressive measurements. The means are adjusted by the General Linear model.

Treatment	Year of measurement				
	1962	1967	1971	1977	1985
1 (1880)	3.16	15.62	22.76	30.76	38.07
2 (1320)	4.85	16.61	23.61	31.03	37.31
3 (1270)	4.49	16.95	23.59	31.38	38.60
4 (950)	3.25	13.65	19.56	26.53	33.14
5 (745)	2.89	12.14	17.33	23.71	29.71
6 (450)	2.49	8.03	12.14	17.83	23.87
7 (244)	3.34	7.71	7.05	11.57	16.14

Basal areas of Treatments 1, 2 and 3 approximate the maximum expected from "full" site occupancy for the area. This maximum is estimated for each site class in Figure 11 by plotting the means for the aggregate of Treatments 1, 2 and 3. At Gnangara where ground water recharge and transpiration loss are important to management of the ground water resource, such basal area-age information can be useful.

Increment - PAI peaked in all treatments by age 14 and showed a net decline after that age (Fig. 12). MAI peaked at about age 18 years for Treatments 1 to 5 and has either remained constant or decreased since that time. For Treatment 6 (450 s ha^{-1}), MAI peaked at about age 24 while it was still increasing at age 32 for Treatment 7 (247 s ha^{-1}), the heaviest thinning.

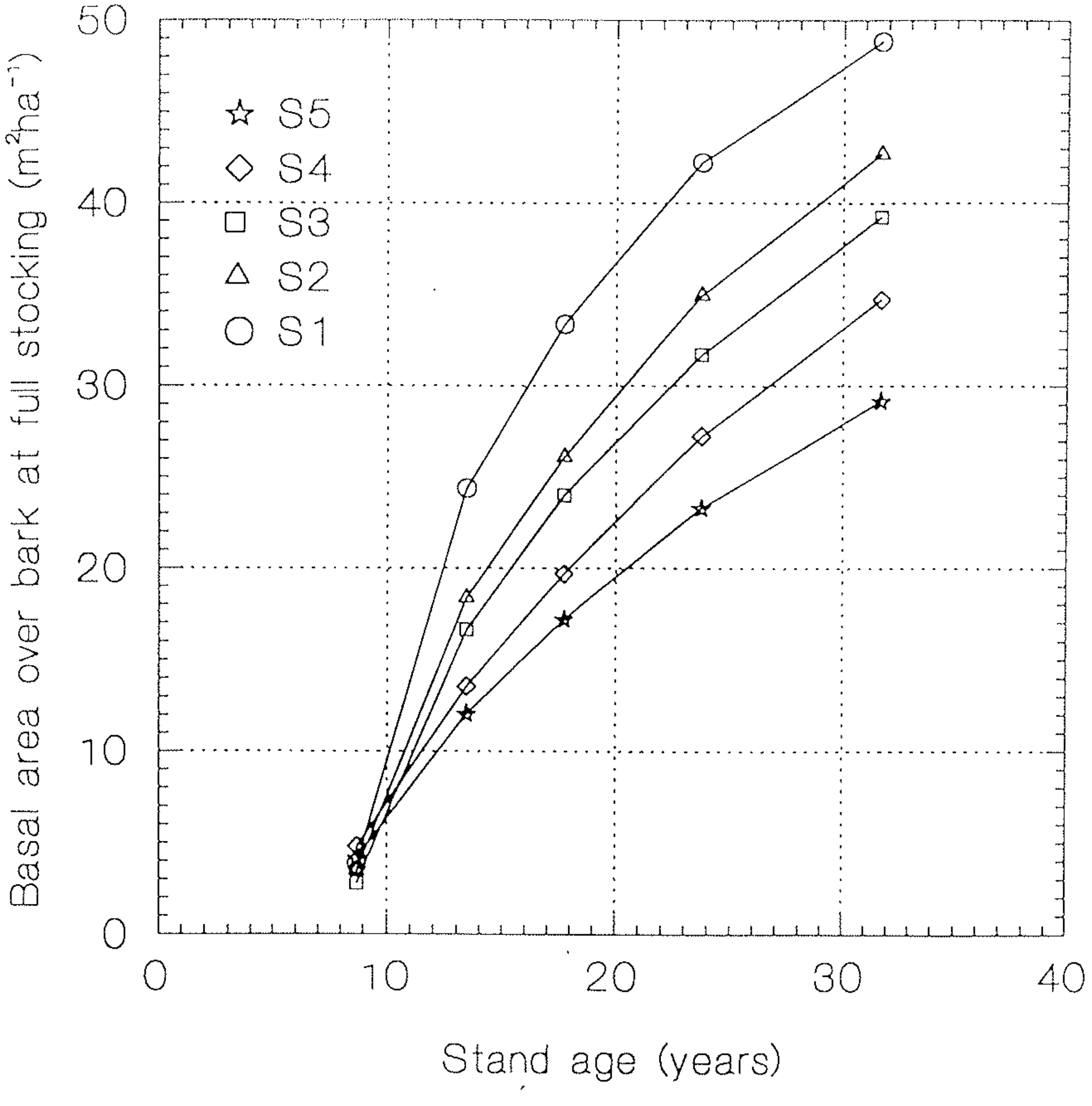

Figure 11.

Maximum production in BAob for each site class with stand age.

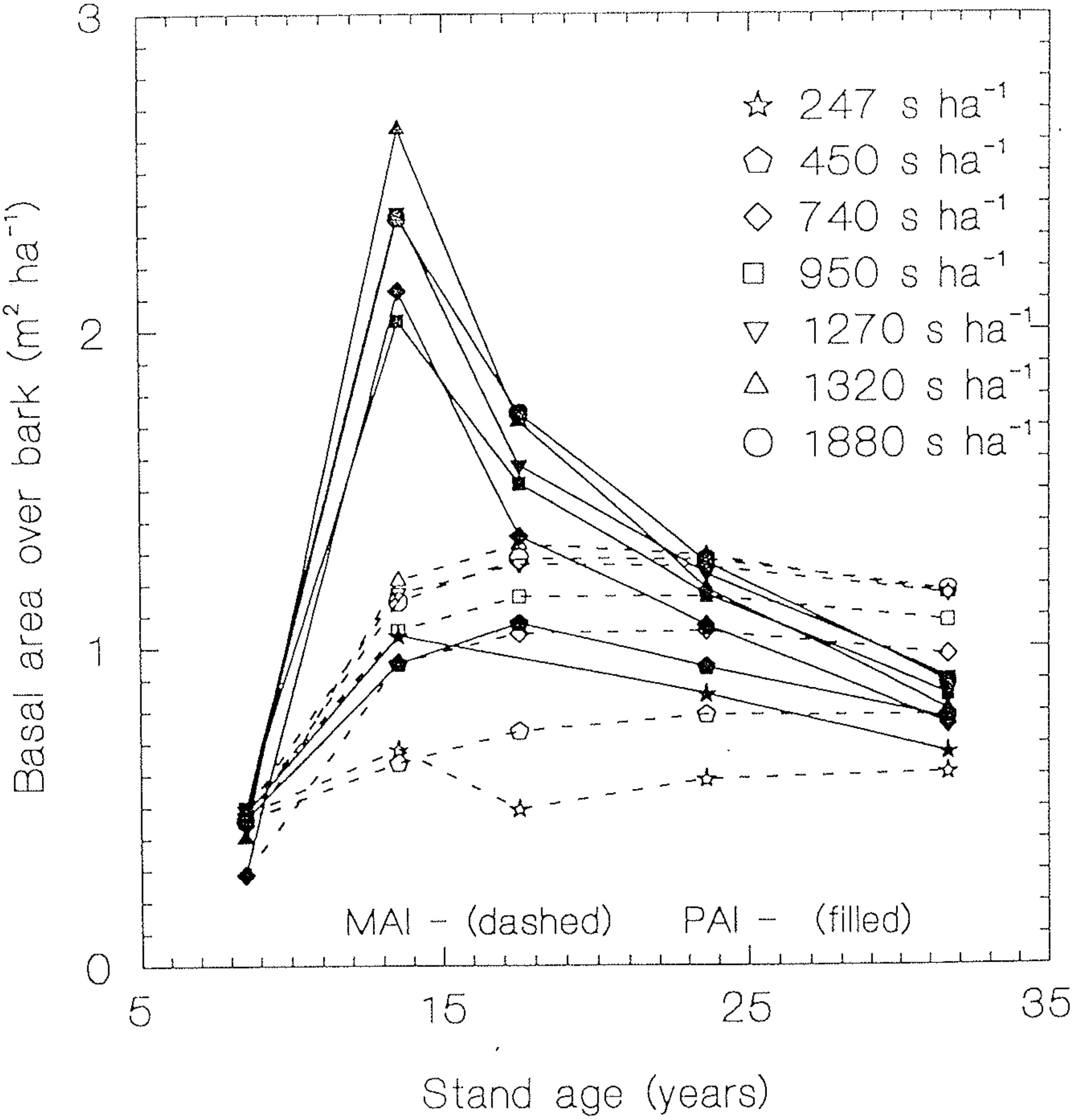

Figure 12.

Mean annual increment (MAI) and current annual increment (CAI) for stand basal area within treatments.

The PAI and MAI curves intersected at age 23 to 24 for Treatments 1, 2 and 3, at 24.5 years for Treatment 4, at 25 years for Treatment 5 and at 32 years for Treatment 6. Culmination of the curves for Treatment 7 could be delayed to the vicinity of age 40, from the current trends.

Diameter Growth

The portion of the stand separated as a final crop comprised the 247 dominant and co-dominant stems ha^{-1} most suitable to maximising growth and value yield for sawlog markets. Height growth on a specific site has been shown to be independent of stocking and stand density and therefore the value of the final crop will depend on the quality (straightness, knot size, symmetry) of the dominant stem selected and its diameter. The trial objective centred on requirements to maximise this diameter.

Table 20: Mean diameters under bark (cm) of final crop stems at age 32 years. Diameters are adjusted by the General Linear Model.

Treatment	Site class					Mean
(s ha^{-1})	1	2	3	4	5	
1 (1880)	18.8	17.1	14.8	14.7	13.1	15.7
2 (1320)	20.3	17.1	16.1	15.9	14.6	16.8
3 (1270)	19.6	17.1	18.0	15.7	15.0	17.1
4 (950)	21.0	19.6	17.5	16.1	15.6	17.9
5 (745)	22.1	20.5	17.9	17.2	16.8	18.9
6 (450)	25.4	21.4	19.5	18.6	16.9	20.3
7 (244)	26.2	23.5	22.7	20.9	18.9	22.4
Mean	21.9	19.5	18.1	17.0	15.8	

Treatment effects - Diameter under bark was very sensitive to both site and stand density (Table 7), increasing with improved site class and with decreased stand density (Tables 20 and 21). Square root transformations were required for all except the 1985 data sets to obtain homoscedasticity. For the 1985 data the natural log transform was required. The development pattern was regular for all site conditions (Figure 13).

The influence of treatment on Dub development is shown in Figure 14 where the site effect is taken at its mean value. By age 9 years the unthinned stand (1880 s ha^{-1}) was already experiencing competition between stems and trees released to 1320 s ha^{-1} or less (Treatments 2-7) displayed a growth superiority which continued through the age of the stand. All treatments were significantly superior to the unthinned control (Figure 15). At 14 years (1967 measurement) competition had set in to treatments with more than 950 s ha^{-1} (T1 to T3). The 950, 740, 450 and 247 stockings (Treatments 5,

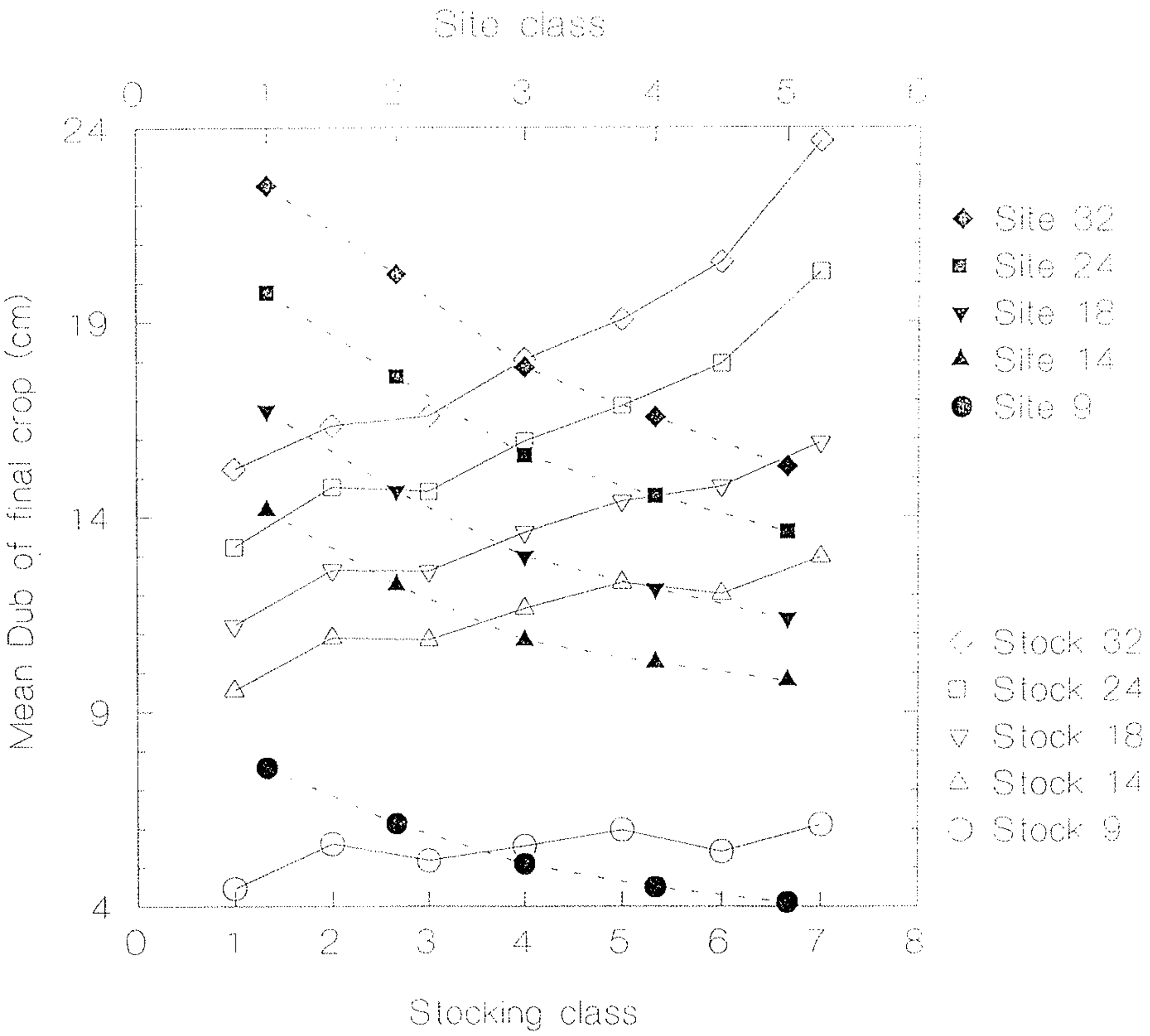

Figure 13.

Effect of treatment and site on final crop diameter at each measurement.

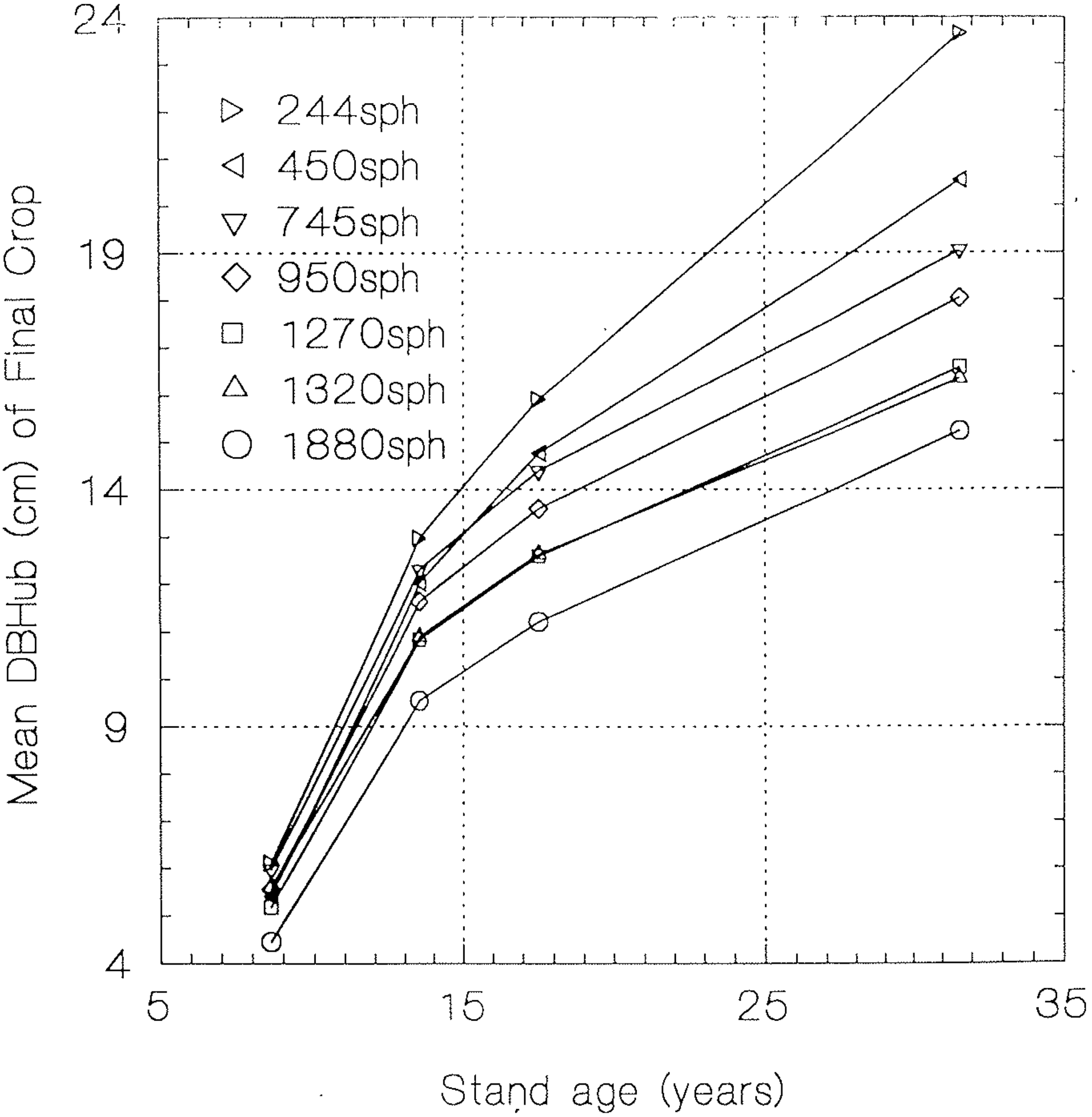

Figure 14.

Diameter under bark at breast height (Dub) development of the final crop.

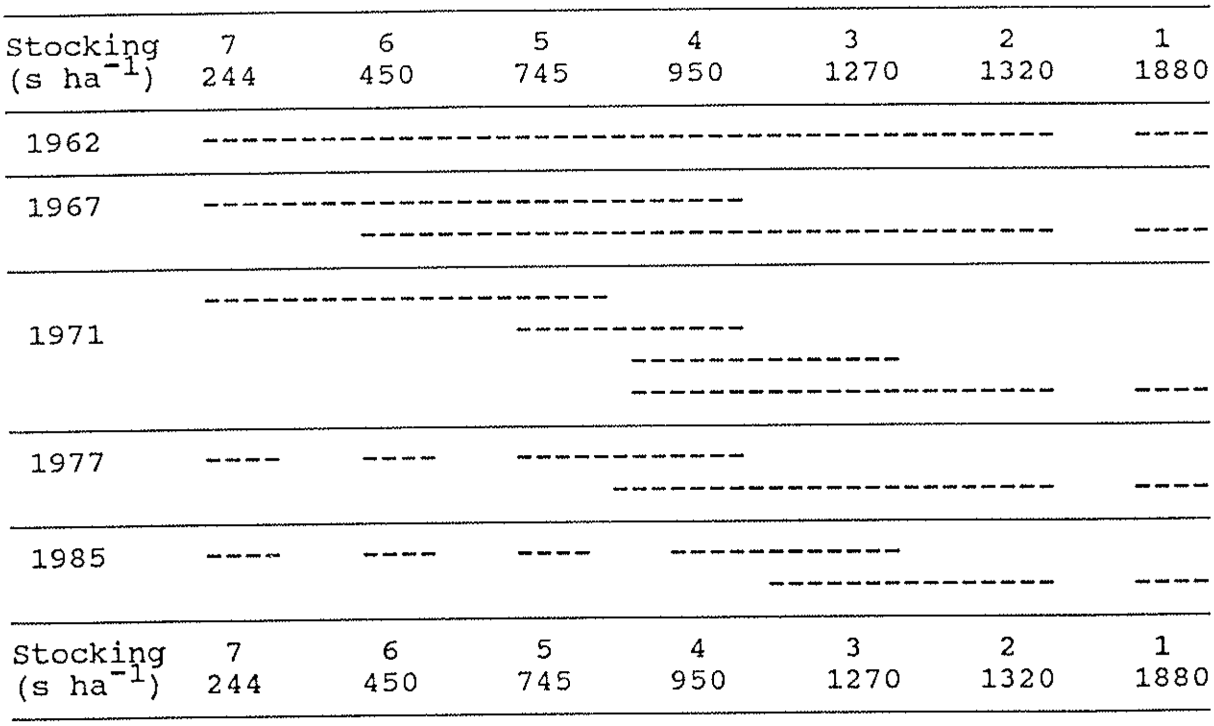

Figure 15.

Significance of Dub means for final crop stems with variable stocking treatments and stand development. Dashed lines join means which are not significantly different at the 0.01 level of probability.

6 and 7) had significantly greater Dub's than the 1320 s ha^{-1} treatment but showed no variation between themselves.

Table 21: Mean diameters under bark (cm) for the final crop stems for each treatment with progressive measurements.

Treatment	Year of measurement				
	1962	1967	1971	1977	1985
1 (1880)	4.7	9.9	11.6	13.66	15.7
2 (1320)	5.9	11.2	13.0	15.11	16.8
3 (1270)	5.7	11.3	13.1	15.14	17.1
4 (950)	5.5	11.6	13.6	15.89	17.9
5 (745)	5.9	12.2	14.2	16.70	18.9
6 (450)	5.4	12.0	14.7	17.80	20.3
7 (244)	5.6	12.3	15.1	19.20	22.4

The measurement at 18 years of age (1971) identified the effects of competition in both the 950 and 750 s ha^{-1} stockings (T4 and T5) with the 750 s ha^{-1} being significantly different to 1270 s ha^{-1} (T3). There was no significant difference between the 745 and 247 s ha^{-1} treatments. This latter was only released by thinning in the previous year (Table 1). At age 24 (1977) competition had also set in at 450 s ha^{-1} to allow significantly greater Dub in the 247 s ha^{-1}(Treatment 7).

Table 22: Ratios of the means for final crop diameter at each measurement to those attained at age 32 years (1985 measurement)

Stand age (Years)	Ratio of site class means				
	1	2	3	4	5
8.5	34	32	28	27	26
13.5	64	62	60	61	63
17.5	76	74	72	73	73
23.5	87	87	87	88	89
31.5	100	100	100	100	100

Site effects - In Figure 13, means for final crop Dub are aggregated for treatments and plotted for each site class at each measurement. Diameter development of the final crop had a uniform progression (Table 22) with time for the different site classes. Trends observed within one site index can be extrapolated to all site types.

Relationships Between Height and Diameter

Height over diameter (H/D) - Table 23 contains values for the ratio

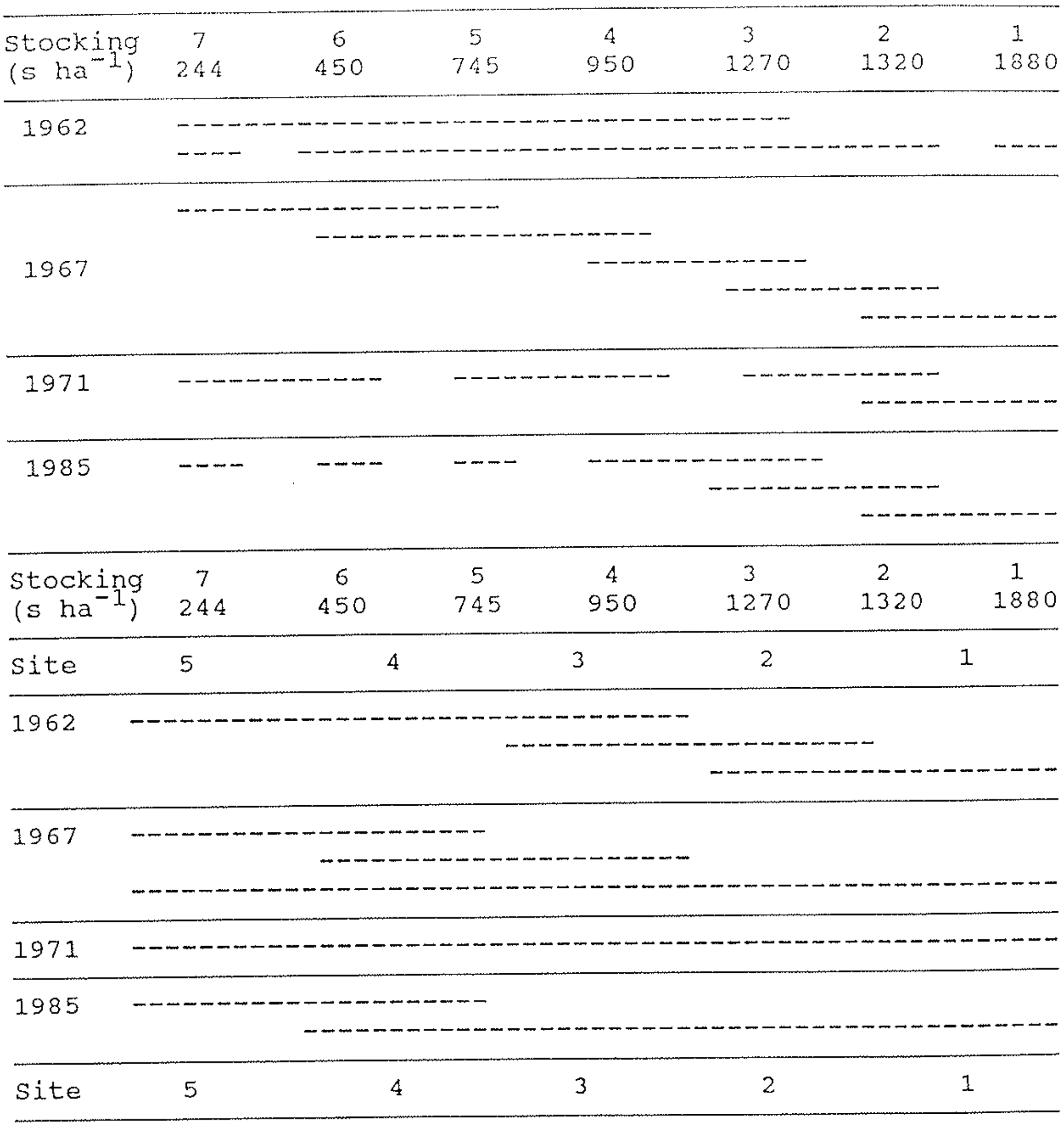

Figure 16.

Significance of Height/Dub means for final crop stems within stocking treatments and site classes. Analysis is by GLM for the reciprocal transform of H/D. Dashed lines join means which are not significantly different at the 0.05 level of probability on the basis of Bonferroni comparisons.

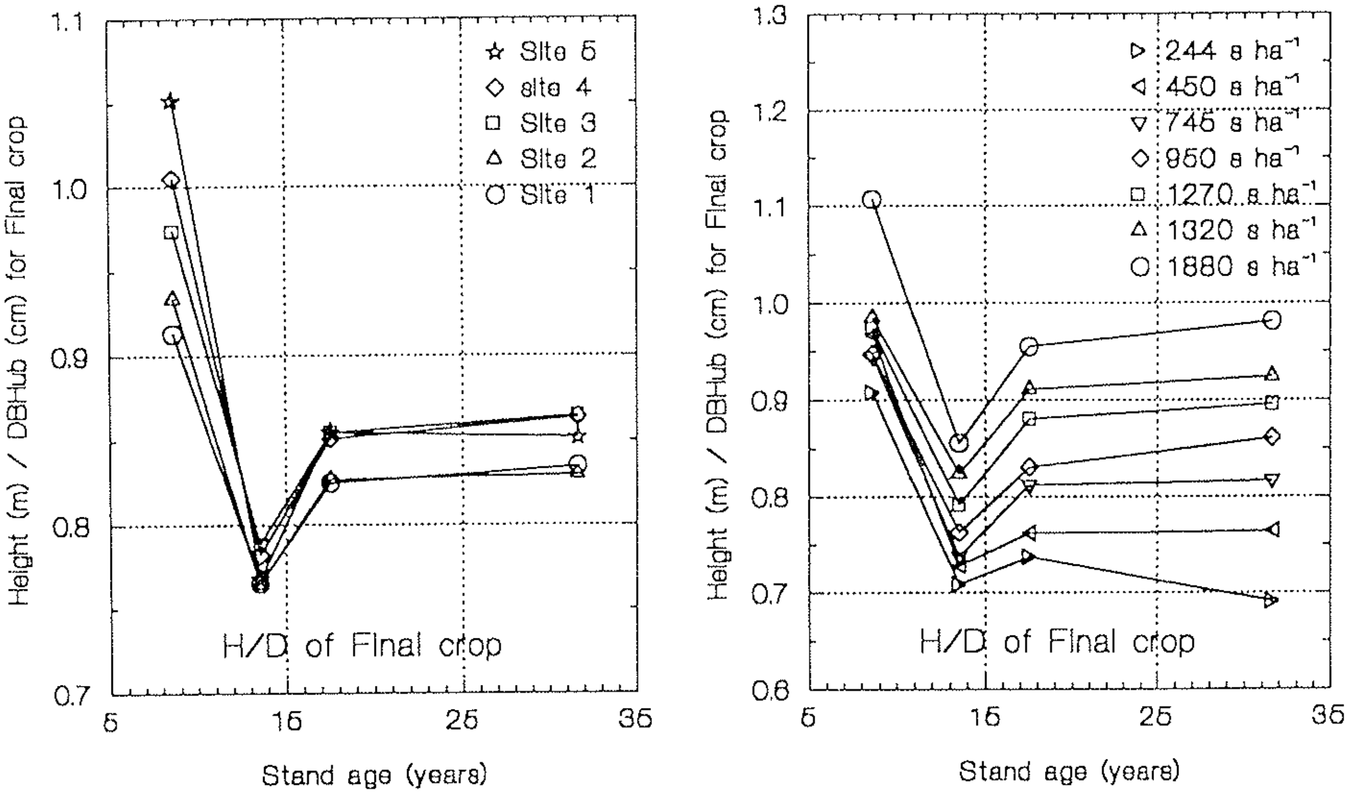

Figure 17.

Variations of the Height/Diameter relations with stand development.

Height (m) / Dub (cm)

of treatment means calculated for each measurement. Both total stand and final crop values were compared to show that the pattern was similar for the whole stand and the final crop. Data for the select crop which contained trees not subject to thinning throughout the trial were analysed.

Table 23: Height over diameter (H/D) ratios for stocking treatments obtained for the total stand and the final crop (F.C.). Values for site classes are for final crop only and those with similar letters indicate no significant difference between means within a year.

Treatment	1962		1967		1971		1985	
(s ha^{-1})	Stand	F.C	Stand	F.C.	Stand	F.C.	Stand	F.C.
1 (1880)	1.21	1.04	.98	.85	1.11	.96	.96	.96
2 (1320)	1.03	.97	.88	.83	.99	.91	.91	.92
3 (1270)	1.01	.95	.85	.80	.94	.88	.91	.90
4 (950)	.98	.93	.80	.76	.88	.82	.86	.86
5 (745)	.97	.93	.76	.74	.84	.81	.81	.82
6 (450)	.99	.93	.72	.72	.76	.76	.75	.76
7 (244)	.97	.90	.71	.70	.73	.73	.68	.68

Site class	Final crop			
1	.91 a	.77 a	.83 a	.84 a
2	.93 ab	.77 a	.83 a	.83 a
3	.97 bc	.79 ab	.86 a	.87 a
4	1.00 c	.78 abd	.85 a	.86 abc
5	1.05 c	.77 acd	.65 a	.85 bc
	1962	1967	1971	1985

The data for the ratios were homoscedastic with homogeneity acceptable by Levine's Test in the reciprocal transform (Table 6). Results for analysis of variance of the means for each measurement (Table 7, Figs. 16 and 17) revealed highly significant differences between treatments at each measurement and significant site differences in 1962, 1967 and 1985. With the onset of competition significance between the control (T1) and other stockings was established by age 9 years (Fig. 16) showing similar sensitivity to competition as in the analysis for Dub in Figure 15. Unique H/D values were progressively established for each level of stocking as competition within stands increased with time (Figs. 16 and 17). Treatment values at ages 18 and 32 years were almost identical suggesting stability of values for each stocking level with development (Figure 17). Data for the 1977 measurement (age 24 years) was not included as the heights were derived and not actually measured.

Height (m) was plotted against Dub (cm) for means in the treatment - site matrix for each measurement (Figs. 18 and

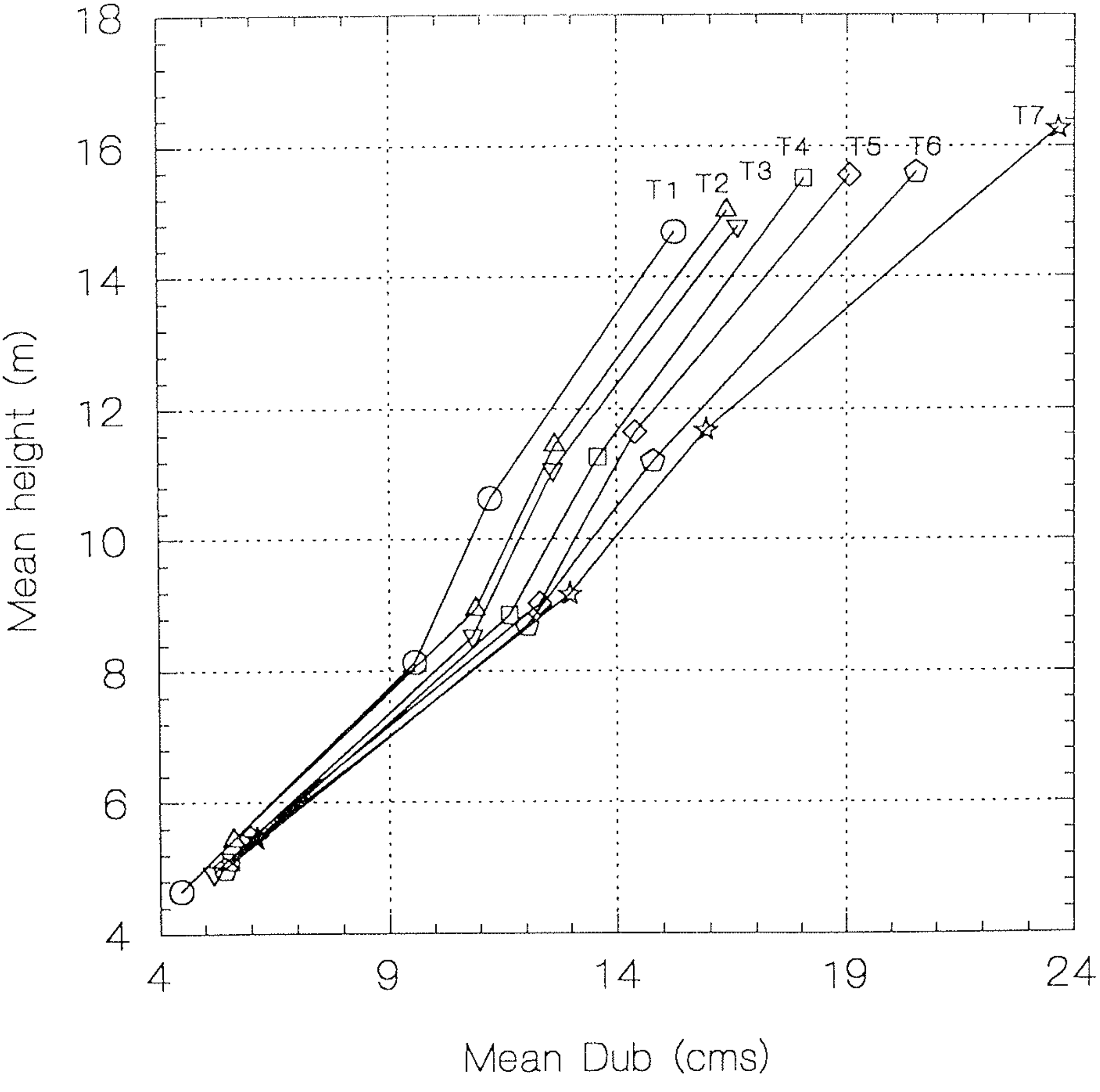

Figure 18.

Relationships between height and diameter for all stocking treatments for combined measurement data.

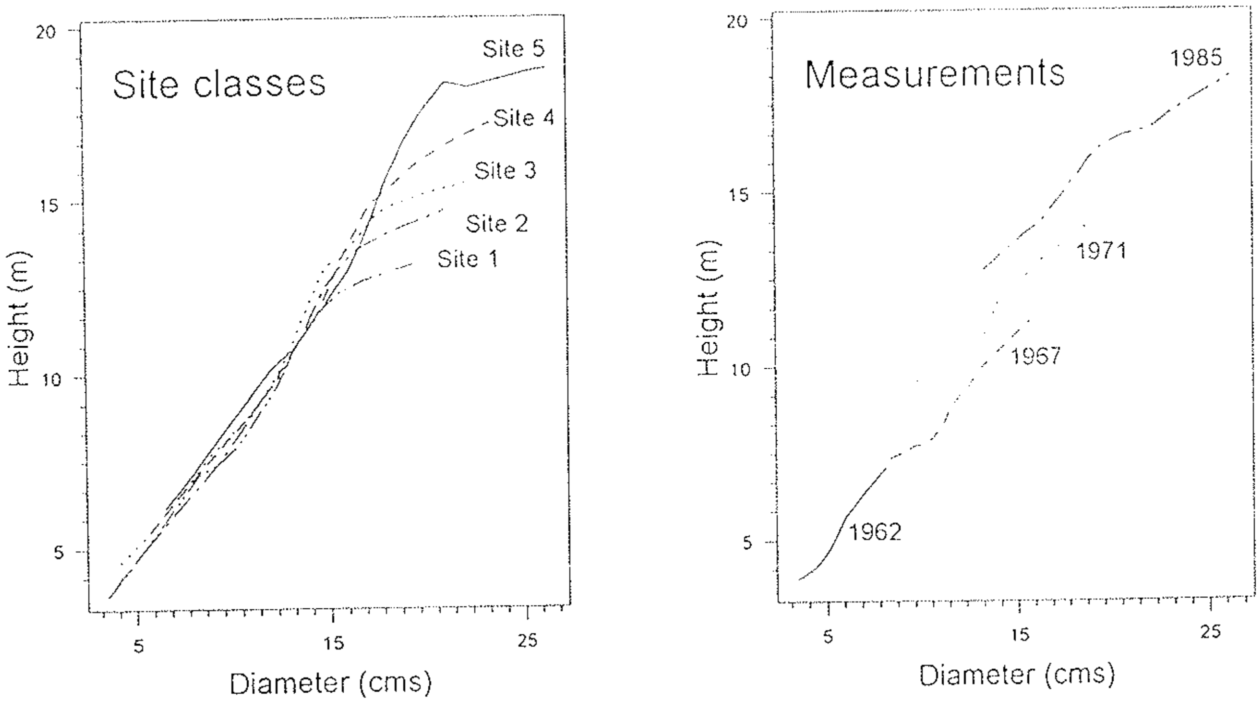

Figure 19.

Pattern of the H/D ratio for site classes and measurement years for combined data.

19). Plots were made for both the total stand and the final crop (selected dominant stems only). Apart from deviation at the base of treatment data, values plotted within each treatment were consistent and, once thinned to the required treatment level (Table 1), independent of age. The sets for all except possibly Treatments 1, 2 and 3 (light thinning only) appeared to be unique. Similarities in Figure 18 for treatments 3 to 7 at Dub's less than approximately 7 cm relate to a measurement history when thinning was progressing (Table 1) and plot stockings were identical.

Plots of height-diameter associations for the combined data for measurement times and site classes distinguish differences between years while pointing to a definite effect of site, similar to that previously shown for stocking treatments in Figure 18. In Figure 19 a common ratio is shown for H/D for all site classes up to approximately Dub 15 cm when height growth of the poorer site class 5 culminates and the ratio decreases with further development. Similarly, site classes 4 to 1 successively culminated and altered from a common H/D ratio to one unique for that site. Significance of differences of the H/D ratio with site were gradual in most cases and absent in 1971 (Fig. 16).

Height and Diameter Regressions -

(a) **Simple regression** - The straight lines of best fit for height and diameter data in each treatment were calculated (Table 24).

Table 24: Values for the regression of height in metres (Y) and diameter under bark in centimetres (X) for each stocking treatment

Treatment	X(Dub) coeffic.	S.D.	Y(Height) Constant	S.D	R^2	No Obs.	S.D. Regress
1 (1880)	0.867	0.016	0.773	0.180	91.2	275	1.198
2 (1320)	0.854	0.016	0.513	0.189	91.7	271	1.101
3 (1270)	0.823	0.014	0.515	0.169	92.8	271	1.052
4 (950)	0.801	0.011	0.366	0.149	94.9	271	0.933
5 (745)	0.757	0.012	0.623	0.161	94.1	271	0.995
6 (450)	0.683	0.009	1.112	0.129	95.7	263	0.875
7 (244)	0.629	0.008	1.466	0.125	96.1	263	0.842

All equations except T1 and T2 are significantly different.

Differences between regressions for Treatments 1 (1880 s ha^{-1}) T4 (950 s ha^{-1}), T6 (450 s ha^{-1}) and T7 (244 s ha^{-1}) provide H/D values for stands reduced from full stocking by successive decrements of 50 per cent down to 247 s ha^{-1} (i.e. 100, 50, 25 and 12.5 per cent stocking). A curve linking the lower extremes of the lines approximates the limit to ratios for non-competitive (free) growth (Fig. 18).

(b) **Multiple Regressions of height, diameter, site class and age** - Both site class and stand age have been shown to influence the height - diameter association and subsets regressions for all factors were examined to assess the best relationship for the data set. For the complete data set 93 per cent of variation in height was explained by Dub and stand age (Table 25). There was no advantage in using square or natural log transforms for the height data and homoscedasticity was satisfactory.

Treatment class data had only a minor impact in explaining the variation associated with height development.

Table 25. Best subsets regressions for height against diameter, treatment, site class and stand age for all subplots and means for site and treatment classes.

Response is height

Vars	R^2	Adj. R^2	C-p	s	Treatment	Site	Dub	Dubsqur	Age	1/Age	T*S	T*Age	S*Age	1/S*Age
Individual subplots			n = 1892											
1	89.1	89.1	4527.7	1.354			X							
1	80.1	80.1	9851.3	1.832				X						
2	92.7	92.7	2433.0	1.111			X		X					
2	92.1	92.1	2771.0	1.154	X		X							
3	95.0	95.0	1072.4	0.919			X		X		X			
3	94.6	94.6	1294.4	0.953			X		X			X		
4	96.1	96.1	413.4	0.810			X		X			X	X	
4	96.1	96.1	433.4	0.814			X	X	X				X	
5	96.7	96.7	43.6	0.742			X	X	X			X	X	
5	96.7	96.7	75.1	0.748	X		X	X	X				X	
6	96.8	96.7	36.1	0.740	X		X	X	X			X	X	
6	96.8	96.7	38.8	0.741		X	X	X	X			X	X	
7	96.8	96.8	19.4	0.737		X	X	X	X			X	X	X
7	96.8	96.8	32.5	0.739		X	X	X	X		X	X	X	
8	96.8	96.8	12.1	0.735	X	X	X	X	X			X	X	X
8	96.8	96.8	13.3	0.735		X	X	X	X		X	X	X	X
9	96.8	96.8	9.8	0.735	X	X	X	X	X	X		X	X	X
9	96.8	96.8	11.5	0.735		X	X	X	X	X	X	X	X	X
10	96.8	96.8	11.0	0.735	X	X	X	X	X	X	X	X	X	X

Regressions for the relationship for height, site class (S), year of measurement (Y) and diameter under bark for the select crop within each treatment class are as follows -

T1HT = 2.13 - 0.438 T1S + 1.82 T1Y + 0.427 T1Dub
T2HT = 3.22 - 0.595 T2S + 1.71 T2Y + 0.412 T2Dub
T3HT = 2.99 - 0.576 T3S + 1.79 T3Y + 0.388 T3Dub
T4HT = 1.87 - 0.407 T4S + 1.33 T4Y + 0.502 T4Dub
T5HT = 2.87 - 0.592 T5S + 1.61 T5Y + 0.403 T5Dub
T6HT = 1.95 - 0.331 T6S + 1.19 T6Y + 0.465 T6Dub

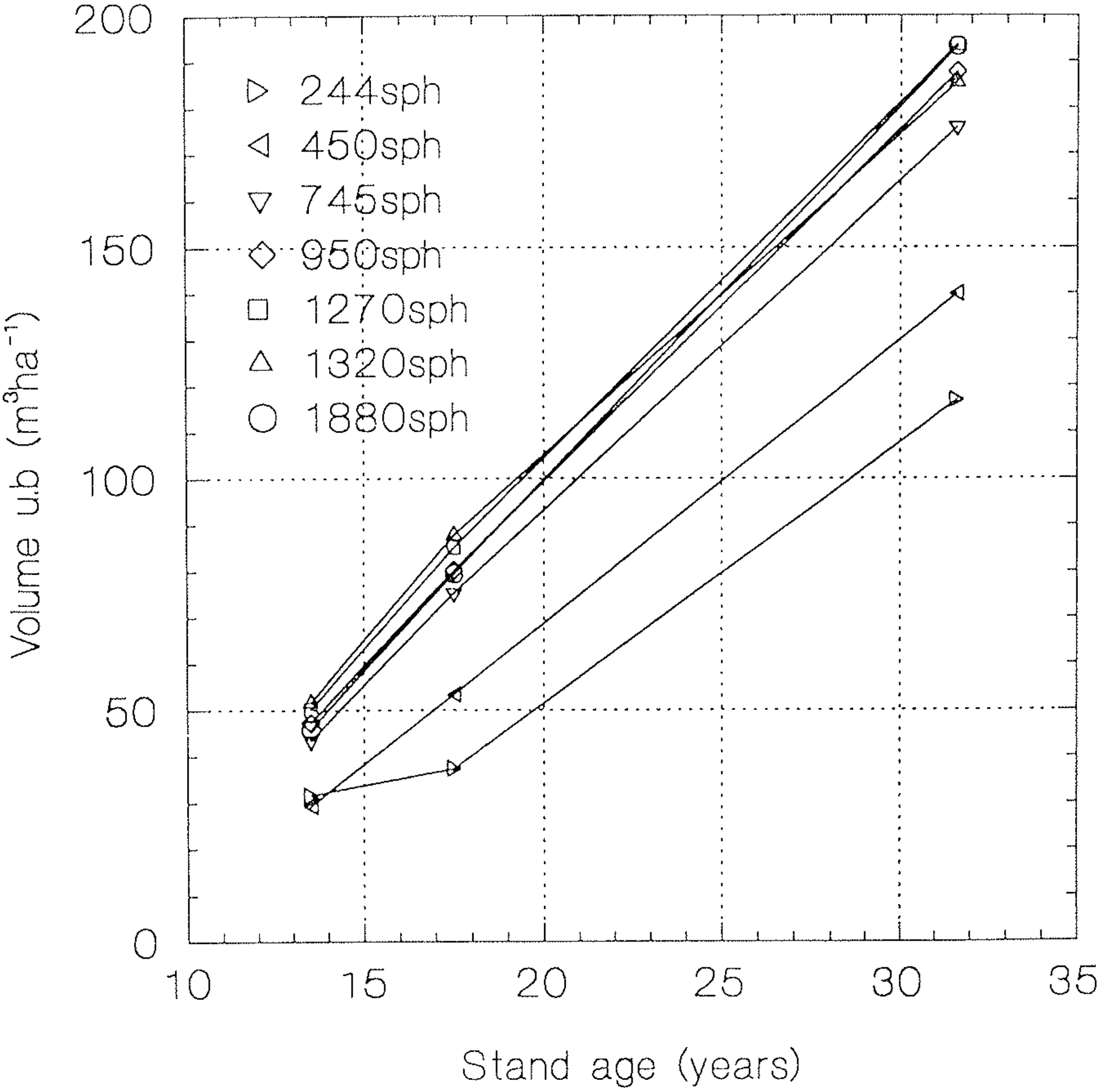

Figure 20.

Plot of volume with age for stocking treatment classes.

$$T7HT = 2.45 - 0.416\ T7S + 1.03\ T7Y + 0.450\ T7Dub$$

Standard deviations of the constants and separate regression coefficients and deviation about the regression line are contained in Table 26.

Table 26. Standard deviations for the coefficients and deviation about the regression lines for multiple regressions for each stocking treatment.

Treat	Standard deviation				s	R^2	n
	Const	Site	Year	Dub			
1	0.227	0.0473	0.1117	0.0297	0.856	95.5	272
2	0.220	0.0411	0.0976	0.0265	0.731	96.4	272
3	0.166	0.0346	0.0886	0.0226	0.646	97.3	272
4	0.213	0.0454	0.1126	0.0266	0.756	96.6	272
5	0.190	0.0399	0.1025	0.0231	0.692	97.1	272
6	0.189	0.0471	0.1140	0.0222	0.737	97.0	264
7	0.155	0.0434	0.1275	0.0220	0.716	97.2	264

All regressions are significantly different.

Volume Growth

Volumes were computed using the volume equation (Sumner, pers. comm.)

Volume under bark (m^3) = 0.445*Dbhub^2 (cm)*Height (m)

The volume equation is developed in the program "pine sp" to use sectional measurements if available and to provide volumes to predetermined stem height or stem diameter limits.

Total stem volume for each subplot was calculated for the 1962, 1967, 1971, 1977 and 1985 measurement for both the whole stand and the final crop portion. Results were expressed as cubic metres per hectare (m^3 ha^{-1}) within the treatment-site classes (Tables 27 and 28).

Stand volume - It has been shown that tree height is independent of stocking and stand density and as volume is calculated as basal area x height x form factor, assuming a constant form factor, stand volume development had the same development trends as those for BAob depicted in Figures 8 to 12.

To obtain homoscedasticity and homogeneity of variance volume data was transformed to natural logarithms for analysis (Tables 6 and 7). The pattern for volume development for the seven stocking treatments is plotted in Figure 20. At ages 13.5, 17.5 and 31.6 years treatment and site effects were highly significant (Table 7). The interaction between site and treatment was also significant in 1985. Up to 32 years of

Table 27: Total stem volume (m^3 ha^{-1}) of the whole stand and final crop at age 32 years

Treatment ($s\ ha^{-1}$)	Site class 1	2	3	4	5	Mean ($m^3\ ha^{-1}$)
			Whole stand			
1 (1880)	295.4	274.3	191.1	162.9	120.4	193.2
2 (1320)	272.5	225.6	203.6	159.6	122.0	185.4
3 (1270)	344.8	247.8	207.8	161.0	122.2	193.6
4 (950)	314.9	216.5	161.3	128.4	104.6	187.7
5 (745)	261.6	213.8	151.8	128.5	93.3	175.7
6 (450)	237.6	161.7	105.1	100.5	81.3	139.9
7 (244)	154.6	103.0	103.6	61.5	42.8	116.9
			Final crop			
1 (1880)	81.0	56.7	42.0	34.2	26.1	44.3
2 (1320)	73.8	55.8	49.8	40.6	30.3	46.8
3 (1270)	81.9	60.0	60.3	40.8	33.9	50.1
4 (950)	102.0	73.3	56.4	42.4	32.9	62.3
5 (745)	106.9	84.6	57.4	47.1	38.7	69.3
6 (450)	141.5	93.7	69.4	56.8	44.3	83.2
7 (244)	154.6	102.9	103.6	61.5	42.8	116.8

Table 28. Mean volumes (m^3 ha^{-1}) for treatment and site classes with progressive measurements. The means have been adjusted by the General Linear Model.

Treatment	Year of measurement 1967	1971	1985
1 (1880)	49.9	86.3	208.9
2 (1320)	55.1	93.9	196.7
3 (1270)	58.0	98.3	216.8
4 (950)	47.1	79.9	185.2
5 (745)	41.7	72.4	169.8
6 (450)	28.8	52.6	137.3
7 (244)	26.5	30.9	97.3
Site class	1967	1971	1985
1	75.5	123.8	271.8
2	49.7	84.6	206.1
3	39.3	67.0	160.6
4	30.2	51.0	128.9
5	24.7	40.8	98.1

```
Stocking   7       6       5       4       3       2       1
(s ha^-1) 244     450     745     950     1270    1320    1880

 1967     ------------    ------------
                                  ---------------------
                          ------------------------------------

 1971     ----    ----    ------------    -------------
                          ------------------------------------

 1985     ----    -----    ------------
                                   ---------------------------

Stocking   7       6       5       4       3       2       1
(s ha^-1) 244     450     745     950     1270    1320    1880
```

Figure 21.

Significance of volume means for the whole stand with variable stocking and stand age. Dashed lines join means which are not significantly different at the 0.05 level of probability on the basis of Bonferroni comparisons.

age the 950, 1270, 1320 and 1880 stocking treatments were not significantly different (Fig. 21) while the 750, 450 and 244 s ha^{-1} treatments were each successively lower in total volume.

Following the rationale of presenting Figure 11 for maximum BAob, in Figure 22, mean volume production of Treatments 1, 2 and 3 aggregated is plotted against age (within site classes) to indicate the maximum stand volume production to be expected on the area. This shows a maximum MAI of 7.9 m^3 ha^{-1} for the 32 years of growth on the best site.

The situation with CAI and MAI volume trends for the stands was similar to those already discussed for BAob in Figure 12.

Wide initial spacings with stockings less than approximately 1000 s ha^{-1} resulted in a significant loss in total volume production up to age 32 years (Table 28, Figs. 20 and 21).

Final crop - Final crop volumes at age 32 years are included in Table 29. The production trends for total stand volume with stocking (Tables 27 and 28) are the reverse of those for the final crop. Final crop volume for 247 s ha^{-1} (T7) stocking was more than twice that in unthinned stands (Table 29).

Table 29. Mean volumes (m^{3}ha^{-1}) for the final crop stand within treatments.

Treatment	Year of measurement				
	1962	1967	1971	1977	1985
1 (1880)	1.75	10.2	17.9	29.3	48.0
2 (1320)	2.55	12.9	22.3	35.9	50.1
3 (1270)	2.51	14.1	24.1	37.8	55.5
4 (950)	2.45	14.7	25.1	40.9	61.5
5 (745)	2.71	16.0	27.6	45.2	67.0
6 (450)	2.35	16.2	30.7	52.6	81.2
7 (244)	2.30	16.0	30.7	60.3	97.3
ALL	2.37	14.3	25.7	43.1	65.8

PAI and MAI values for final crop volumes are plotted against age in Figure 23. The influence of reduced competition in the stand on increment of the dominants was pronounced. PAI peaked for all stocking levels between 18 and 24 years of age. This peak may be independent of the stocking level but the rate of increment increased greatly with decreasing stocking. The PAI's for the 247 and 450 s ha^{-1} (T7 and T6) treatments at the 32 year stand measurement greatly exceeded those achieved by any other treatment.

The advantage of reduced stand competition on the final crop volume is also clearly defined by the MAI curves (Fig. 23) where the mean growth rate for the 247 and 450 s ha^{-1} treatments was still increasing at age 32 while it has

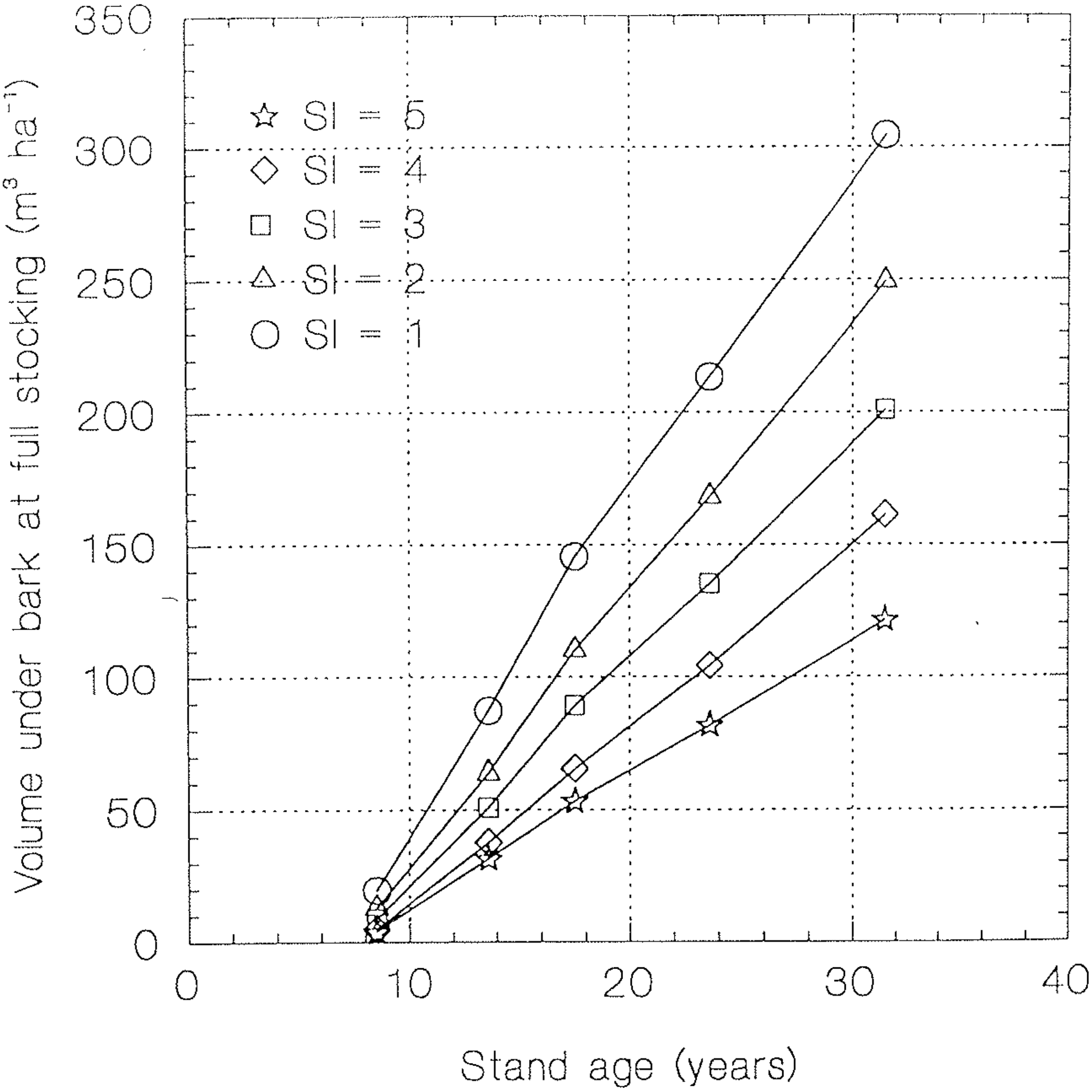

Figure 22.

Maximum volume production for site classes with increasing stand age.

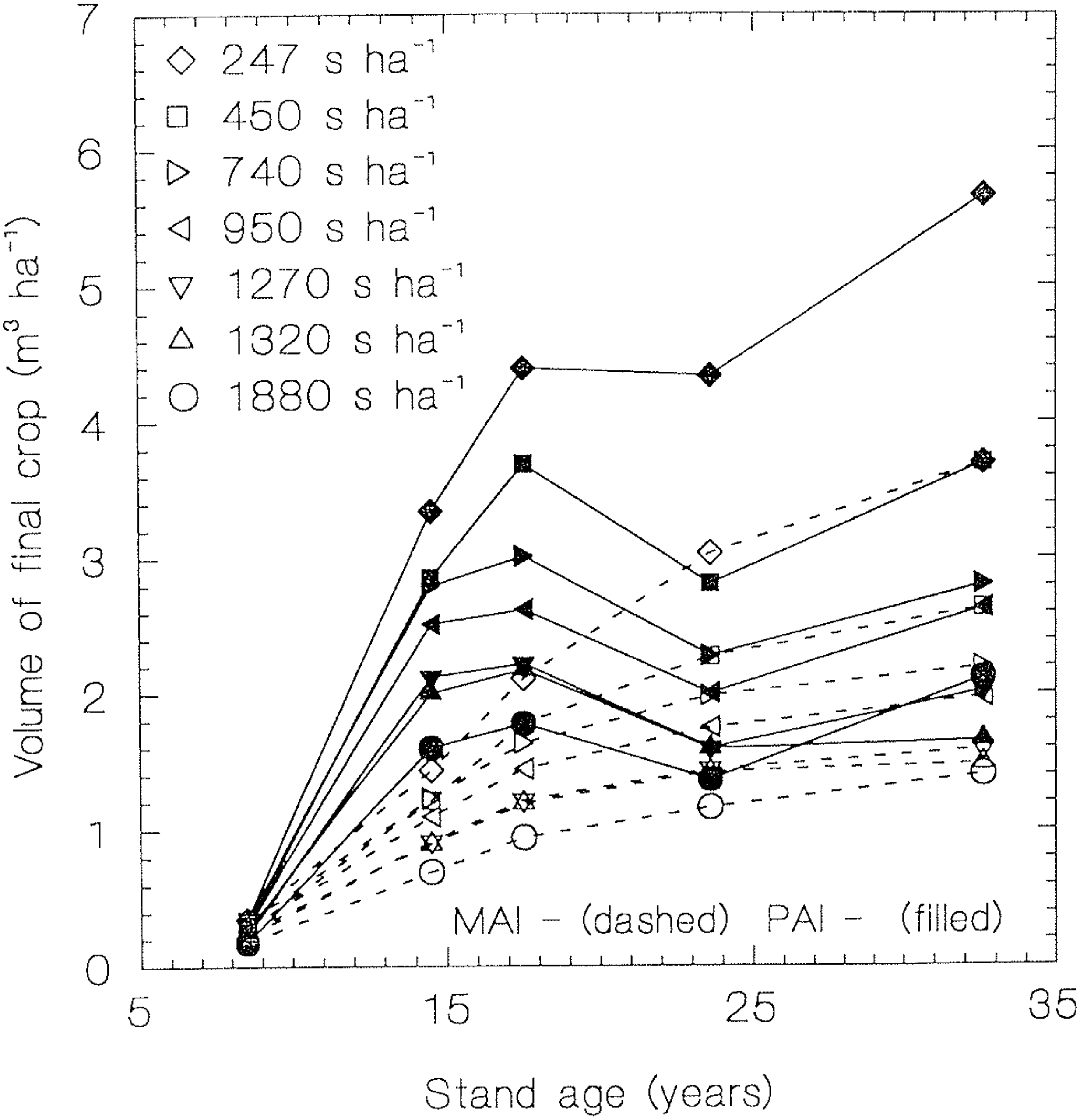

Figure 23.

MAI and CAI for final crop volumes.

culminated for the heaviest stockings. The slope of the curves indicates that these high MAI's could continue for at least a further 10 years of growth. This represents an MAI of 4.9 m^3 ha^{-1} on Site Class 1 areas thinned to ensure minimum stand competition up to age 17 years (Table 29).

Increment - In the trial total volume was not consistently assessed and as height increment is independent of stocking or stand density, total BAob increments within this study are available to examine volume increment trends. Plotting the current annual increment (CAI) in stand basal area against stand age for each stocking treatment (Fig. 12) revealed that stand production is actually very sensitive to stocking (or actual stand density) over the limits of the trial. Table 30 and Figure 24 show the association of increment with decreasing stem numbers and decreasing stand density over the trial time period.

Table 30: Current Annual Increment (m^2 ha^{-1}) for basal area over bark development at breast height for treatments over measurement intervals. Values in brackets are Current Annual Increment in BAob expressed as a percentage of the unthinned control for measurement intervals.

Treatment	Mean CAI BAob for increment period (m^2 ha^{-1})			
(s ha^{-1})	1962-67	1967-71	1971-77	1977-85
1 (1880)	2.36 (100)	1.80 (100)	1.34 (100)	.91 (100)
2 (1320)	2.36 (102)	1.76 (98)	1.25 (93)	.79 (87)
3 (1270)	2.51 (108)	1.70 (94)	1.29 (97)	.89 (97)
4 (950)	2.09 (90)	1.46 (84)	1.17 (88)	.83 (91)
5 (745)	1.85 (80)	1.33 (74)	1.06 (79)	.76 (83)
6 (450)	N/A (-)	1.07 (59)	.95 (71)	.77 (84)
7 (244)	N/A (-)	N/A (-)	.76 (57)	.59 (65)

In Figure 24 BAob increment for each treatment is expressed as a percentage of the maximum achievable for the period (T1) and stocking and density are expressed as a per cent of the control value to compare increment trends for the different measurement periods. For stocking, approximately 22 per cent of the stems produced 65 per cent of the total increment at stand age 18 years (1971). This tended to increase with stand age to 75 per cent increment achieved by approximately 13 per cent of the stocking at age 32 years (1985). Stand density was more proportionate to increment achieved but there still was a tendency for 50 per cent of maximum density to produce 70 to 80 per cent of maximum increment in the older stands (1977, 1985). Both relationships (Fig. 24) indicate that reduction in stand stocking, or density, is not directly proportional to a reduction in BAob (or volume) increment.

Repeated Measures Analysis.

Data for height, diameter, BAob and volume were analysed by repeated measures techniques with site classes clustered

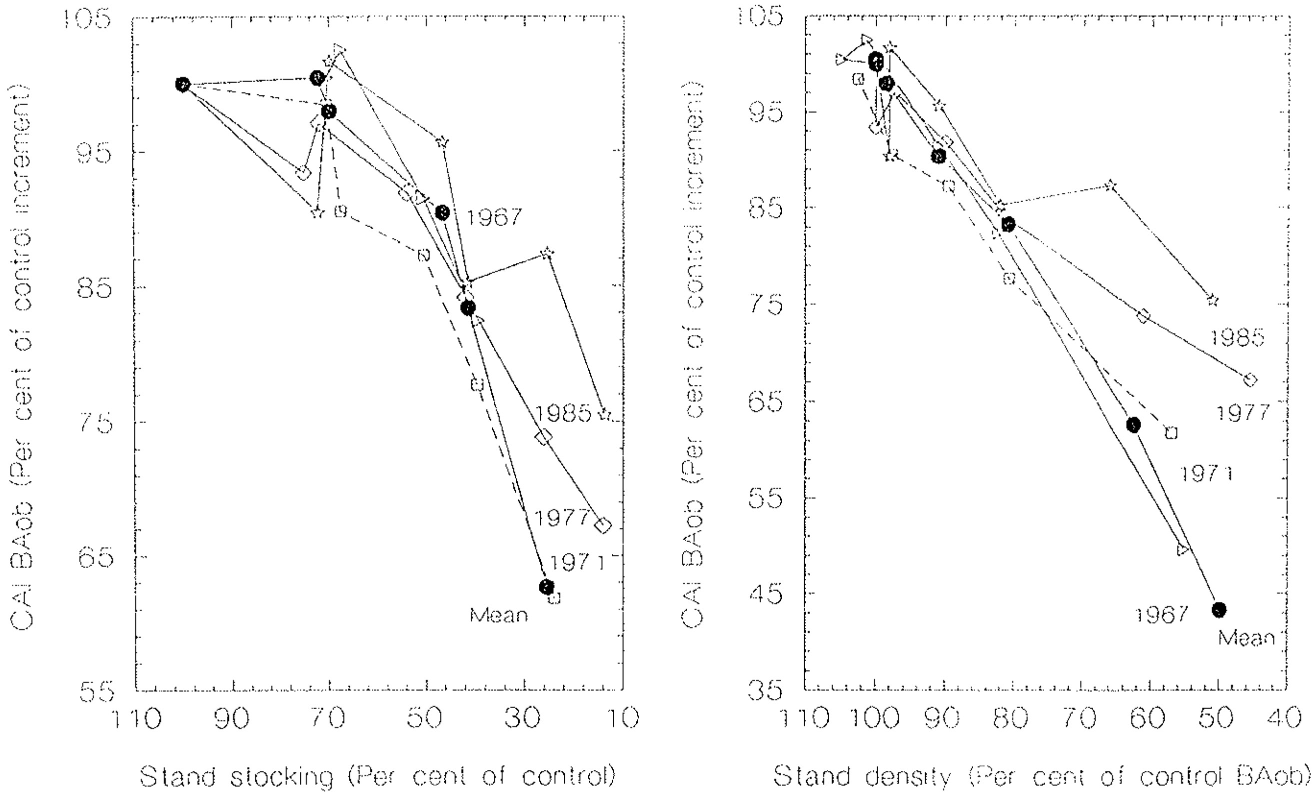

Figure 24.

CAI for BAob plotted against stocking and stand density. Increment, stocking and density are expressed as a percentage of the relevant value for the control treatment (T1).

within measurement years. The object was to see if progressive measurement (development) was associated with trends not apparent in the consideration of separate data sets. The ANOVA (Table 31) provided no further useful information on significance of main effects and interactions. Significant interactions between measurement years and treatments preclude any simplification of comparison of main effect means for the whole trial.

Table 31. Analysis of variance with the General Linear Model for repeated measures analysis of complete data sets. Site is clustered within years. Values are the probability that the F term obtained would be exceeded by chance.

	Height		Dub		H/D		logBA		sqrtVOL	
Source	DF	p	DF	p	DF	p	DF	p	DF	p
Treat	6	0.000	6	0.000	6	0.000	6	0.000	6	0.000
Year	3	0.000	3	0.000	3	0.000	4	0.000	2	0.000
Site(Y)	16	0.000	16	0.000	16	0.000	20	0.000	12	0.000
T*Y	18	0.226	18	0.000	18	0.000	24	0.000	12	0.000
Error	1848		1848		1848		2214		1389	
Total	1891		1891		1891		2268		1421	

Foliar analysis - Foliar sampling was not complete within the 8 blocks used to randomise the 7 stocking treatments (Fig. 1). For analysis the two blocks within each compartment were combined to set 4 blocks from east to west (separated by fire breaks in Fig. 1) The adjacent unfertilised control plots were placed in block 5 and relate to stands to the north and south of the trial. The coverage of each sampling over stocking levels and blocks is shown in Table 32.

Table 32. Number of plots sampled for foliar analysis within stocking and site blocks.

	Blocks																	
	1			2			3			4			5			ALL		
Stock-ing	70	71	72	70	71	72	70	71	72	70	71	72	70	71	72	70	71	72
1880	1	1	0	1	1	2	0	1	0	1	2	0	3	8	2	6	13	4
1320	1	2	0	2	2	2	1	2	0	1	1	0	0	0	0	5	7	2
1270	2	2	0	2	2	0	2	2	1	1	2	1	0	0	0	7	8	2
950	1	2	2	1	1	0	0	1	0	1	1	0	0	0	0	3	5	2
745	1	2	2	2	2	0	1	1	0	2	2	0	0	0	0	6	7	2
450	1	1	0	0	0	0	2	2	0	0	1	2	0	0	0	3	4	2
244	2	2	0	0	1	0	0	1	1	0	1	1	0	0	0	2	5	2
ALL	9	12	4	8	9	4	6	10	2	6	10	4	3	8	2	32	49	16

For the February 1970 measurement, six months after fertiliser addition, differences for blocks for P levels were highly significant with blocks 1 and 2 only showing an effect of added fertiliser (Table 32). Stocking levels for P and K and block levels for N and K were not significantly different. The stocking level for N was significant at the .03 level.

In the 1971 sampling stocking levels were not significantly different for either P or K but block differences for both P(.030) and K (.008) differed significantly (Table 33). For P there was no difference between fertilised blocks and significance was due to levels in the trial being higher than the unfertilised control. The K significance was associated with a high value obtained for block 1.

Table 33. Mean values for stocking treatments and site blocks for per cent foliar composition of N, P and K sampled in 1970, 1971 and 1972.

	N70	P70	K70	P71	K71	N72	P72	K72
Block								
1	0.725	0.101	0.439	0.095	0.553	0.732	0.076	0.498
2	0.668	0.096	0.411	0.092	0.392	0.653	0.074	0.496
3	0.700	0.066	0.388	0.101	0.333	0.814	0.119	0.783
4	0.679	0.065	0.477	0.098	0.389	0.793	0.102	0.590
5	0.672	0.060	0.451	0.068	0.402	0.636	0.042	0.737
Stocking								
1	0.647	0.077	0.452	0.086	0.461	0.781	0.057	0.572
2	0.739	0.080	0.480	0.101	0.429	0.831	0.076	0.585
3	0.672	0.075	0.420	0.086	0.447	0.667	0.109	0.474
4	0.769	0.078	0.416	0.088	0.334	0.728	0.067	0.487
5	0.701	0.083	0.462	0.087	0.522	0.746	0.084	0.509
6	0.666	0.077	0.437	0.097	0.359	0.754	0.112	0.735
7	0.627	0.075	0.367	0.090	0.345	0.637	0.103	0.754

Sampling in 1972 showed no differences in nutrient levels due to stocking treatments but significance for differences between blocks for N (.018) and P (.003) (Table 33). The differences in both N and P levels were associated with higher values retained in blocks 3 and 4, while levels in blocks 1 and 2 had returned to the equivalent of the unfertilised control block 5.

DISCUSSION

Site Productivity

Major emphases on investigations into the potential of sites for pine production in Western Australia was placed on two aspects. The initial requirement was to ensure that, for afforestation, only those sites containing native vegetation or cleared for agriculture which could produce a satisfactory stand of pine were selected. For this purpose local rainfall records, soil types, topography and native vegetative characteristics are considered. In some cases, advance trial plots of pines or tree arboreta were available to indicate the potential of specific types for tree growth (Havel 1968).

The second requirement was to stratify or divide the developing pine crop into a range of stem quality and volume production zones to efficiently plan cultivation, pruning, thinning, fertilising and harvesting requirements. Usually this is associated with a site index system for the species concerned (Clutter et al 1983). Theoretically it is desirable to use the initial ecological system for both purposes as the natural factors, soil depth, chemical content, wetness, exposure could be used to analyse the potential for fertiliser additions, and the initial stocking required. The application of the vegetation classification system to the trial area in 1969 allowed these possibilities to be considered.

Topographic relationships - Height growth decreased with increasing elevation above the base level of the land surface and decline was progressive up to a surface rise of approximately 7 m (Fig. 2). Pine height was uniform and relatively poor for elevations 7 m to 12 m above the base level and then showed an abrupt increase in the final 3 m of elevation on the site.

The site improvement within the highest contour intervals on the trial area was observable in the field. It was restricted to a narrow fringe of pine near the top of the highest dunes. The reason for this was associated with the presence of a yellow sand (more fertile) subsoil within the surface 1 m of soil profile on these restricted sites. They represent part of the younger, Spearwood Dune system to the west and define the trial area as a true transition between the two Dune Systems and soil types. The soil type was tested extensively by gravimetric sampling for soil moisture variation in the trial area. The significant subsoil was not present, within a 3 m sampling depth, outside the contour height intervals of 140-155 feet (Table 3).

The height-soil association provided a direct lead to the factors important in site quality determination. Its influence demonstrated that site factors associated with good pine growth in the area need not be restricted to the lower topographic situations. The fact that contour height provided a strong general correlation with pine quality (height growth) for much of the trial area has limited value for specific site classification. Variation of the height means is not shown but it may be excessive. In associated studies on the flatter areas of the Bassendean Dunes system in South Lane Poole Block variation from the best to poorest pine growth was measured along the same contours and within distances of 20 m or less. Again, this variation was associated with presence or absence of substantial subsoil horizons resulting from past drainage patterns or dune movements. Topography per se was thus ruled out as a useful tool for defining precise site types in the region and within the Free Growth Study.

Table 34: Relationship between vegetative site classes and pine height development at age 32 years.

Vegetative site class	Number sub plots	Top height (m)			
		Minimum	Maximum	Mean	95% error
1	48	13.9	23.0	18.4	4.0
2	76	15.9	21.4	18.5	2.5
3	114	11.0	21.9	15.7	3.6
4	131	11.8	18.5	14.2	2.7
5	62	13.2	19.2	15.8	2.7
6	36	14.1	19.8	16.3	2.4
7	8	18.6	20.7	19.8	1.6

Vegetation classification - In Tables 34 and 35 the subplots identified in the 1985 measurement have been grouped within the 7 vegetation types of the 1969 survey (Table 4) to provide subplot frequency, height, basal area and volume data associated with each type. Table 33 provides Top heights for all subplots but Table 34 only refers to subplots in the control Treatment 1.

Table 35. Vegetative types and associated volume and basal area of the unthinned pine crop (Treatment 1) at age 32 years

Vegetative site class	Number of subplots	BAob (m^2 ha^{-1})		Volume u.b.(m^3 ha^{-1})	
		Mean	95% error	Mean	95% error
1	7	40.7	11.0	183	80
2	12	51.9	6.7	277	51
3	17	34.7	4.6	132	21
4	17	32.8	4.2	117	24
5	9	37.0	6.8	155	66
6	7	43.5	6.9	185	40
7	-	-	-	-	-

For the 7 types the Top heights overlap extensively and most include an extremely wide range of height classes (Table 34). Type 3, for instance, ranges from Top height 11.0 to 21.9 m, the full range recorded for the area in Figure 3. As such the vegetative typing has limited value for site differentiation. Results are similar for volume and basal area (Table 35).

By far the best vegetative site mean was Type 7 which included only 8 subplots ranging from 18.6 to 20.7 Top height. This mean was better than that obtained for any other class yet lower Types 1, 2 and 3 contain subplots with greater Top heights than 7. No vegetative types identified were mutually exclusive in pine height classes.

Types 1 and 2 averaged the second highest productivity for the area and were inseparable on the basis of height, basal area or volume growth of the pine crop. The ranges of the two types vary, Type 2 being the more specific.

Types 5 and 6 were next in order of productivity and also inseparable on pine growth parameters. Again the ranges of each type were considerable including poor pine height classes (Fig. 3) as well as average classes. Type 3 was only slightly less than these two and inseparable from Type 5 on mean values. As mentioned above it is non-specific in range, containing poorer and better subplots than Types 5 and 6.

Type 4 is the most prevalent on the area (131 out of 472 subplots) and, on the average, is the poorest. It is inferior to all other types but still included plots with Top height up to 18.5 m. Again, from Figure 3, it will be seen that these are better than the average.

For establishment purposes it would have been advantageous if Type 4 (29 per cent of the area) had been excluded from planting. This is equivalent to the Havel Type G (Havel 1968). Type 5 (13 per cent of the area) is also of the Havel Type G which represents deep, dry, pale grey sands, strongly leached and occurring on lower slopes in the transitional soil zone and slopes and dune crests within the Bassendean Dunes System. It can be identified quite readily in Figures 2 and 1.

These unfavourable types are most easily identified within the understorey species by the absence of *Xanthorrhoea preissii*. The old foresters of the area identified the 'good' pine sites on the Bassendean sands as containing tall blackboy (*Xanthorrhoea preissii*) and or the eucalypt jarrah (*Euc. marginata*).

Using the vegetation, topography and colour of soil it would be possible to exclude Types 4 and 5 from planting and remove the 40 per cent of the plantation carrying the majority of the poor sites.

Type 3 is the second most common in the area (24 per cent). It is equivalent to Havel Type H and is characteristic of deep, pale grey sands, dry at the surface, moist at depth, strongly leached throughout and occurring on subflats and around swamps in the transition zone and within the Bassendean Dune System. Association with adjacent favourable or unfavourable areas would have to constitute the reason for inclusion or exclusion from planting. The type is non-specific for pine growth and has limited diagnostic value. Total exclusion (with Types 4 and 5) would leave too little (35 per cent) and too dissected an area on which to base a plantation.

The vegetative type system with local knowledge of unfavourable topographic and soil characteristics provides an effective means for planting the area which will contain the majority of the good pine sites. The area planted will however, still contain a broad spectrum of pine quality ranging from poor to good.

Pine Height Classes - The 1 metre height classes separated on the bases of Top height at age 32 years (Fig. 3) may be grouped to provide site classes which are unique and identifiable to age 9 years, at least (Figs. 4, 5 and 6). These can be separated by height intercept measurements in young stands, direct measurement or remote sensing to provide a basis for silvicultural planning and yield monitoring. In Table 36, mean heights, basal areas and volumes for the 1 metre classes at stand age 32 are presented. The data are for Treatment 1, the unthinned stands only. Volume and basal area estimates for variable stocking in developing stands within 1 metre Predominant height classes are contained in Appendix 1.

Table 36: Top heights and volume and basal area for unthinned stands (Treatment 1) within site classes.

Site class	Top height (m)		BAob (m^3 ha^{-1})		Volume u.b. (m^3 ha^{-1})		Number of subplots
	Mean	95% error	Mean	95% error	Mean	95% error	
1	18.7	1.2	46.3	10.2	243	65	11
2	17.3	1.2	46.0	2.8	249	57	9
3	15.9	0.7	38.5	3.3	146	15	17
4	13.5	0.7	34.8	5.2	135	23	12
5	13.2	1.6	29.0	3.3	102	19	20

The height-age relationship will vary with the fertiliser regime which may be imposed. It will also vary with the degree of genetic improvement which has been provided to the seed source.

Height Relationships

The pattern of height development for treatments within each site class was consistent with age (Tables 9 and 10). Dominance was expressed at an early age in the species and maintained under a wide range of stand densities.

Data in Figures 4 and 5 and Table 7 confirm that the height indexation procedure used for subplots is applicable to all stand ages and practically independent of thinning influences.

Stocking (and stand density) had no practical influence on height growth. This is usually assumed and is the basis of the use of index height for practical definition of site quality (Carmean, 1975). The current data (Table 9) covering such a range of sites, stand densities and a thirty-two year growing period (which included the most severe drought in history) establishes the independence of *Pinus pinaster* height growth from stand density under these conditions.

The practical independence of height growth on spacing within the range of plantation stockings used in the trial (Table 9) was established for *Pinus patula* and *Pinus elliottii* by Marsh (1957) from free growth trials in South Africa. This situation is generally accepted for most species and Lanner (1985) has discussed the physiological reasons for the insensitivity of height growth of trees to spacing. He notes the exception to the general rule in the inhibiting effects of very close spacing (as in natural seed regeneration) on height growth, especially on dry sites or poor soils. In Queensland, Johnston (1975) recorded depressions of height growth in Cypress pine, apparently associated with dense spacing, dry climate and mixed aged stands. Vanclay and Henry (1988) accepted this association in developing a model for volume production of the species on the basis that the H/D ratio is insensitive to variable spacing. Hopkins (pers comm) has also measured significant differences in Top height increment associated with variable stand density, during brief period of extreme drought, on certain sites within Western Australian *Pinus pinaster* plantations.

For plantation populations however, the lack of significance of the effects of a wide range of spacing on height growth is strongly supported on the evidence of the controlled and conclusive data of free growth trials.

Height/Age - The regressions for site index (Table 13, Fig. 7) were used to predict height values at age 19 years and a further set of curves were compiled to compare with height-age curves for site index at age 19 years available for the Basal Area thinning series at Gnangara and Yanchep.

The regression equation for Site Index at 19 years of age was

$$\mathrm{LogTHt} = 2.87 + 0.0272\ \mathrm{SITHt19} - 26.0\ 1/\mathrm{Age} + 1.02\ \mathrm{SI19/Age}$$

$$s = 0.08668 \qquad R^2(\mathrm{adj}) = 96.5\%$$

Comparisons of the height relationships obtained for Top height with those of the Basal Area trials and Havel's site index curves are provided in Figure 25.

For development after 14 years (Fig. 26) height and stand age relationships are similar to those published for the area by Havel (1968). Plots of the two data sets using log height against the reciprocal of age indicates that there is no significance in the apparent differences. Agreement of the trends prior to age 14 is however, poor.

The more rapid height growth to age 14 in the Havel data can only be related to superior site types. It is unexpected, as stands in both sets of data were of similar seed source and had identical establishment procedures. The trial, in fact, received an additional fertiliser application at age 9 not provided to the earlier stands included in Havel's data. One would have expected comparable or faster early growth from the trial areas. The fertiliser however, may have provided for longer optimum height extension on sites which were initially poorer (Figure 25). The comparison with the BAob Control Series shows the Control curves to continue to increase over

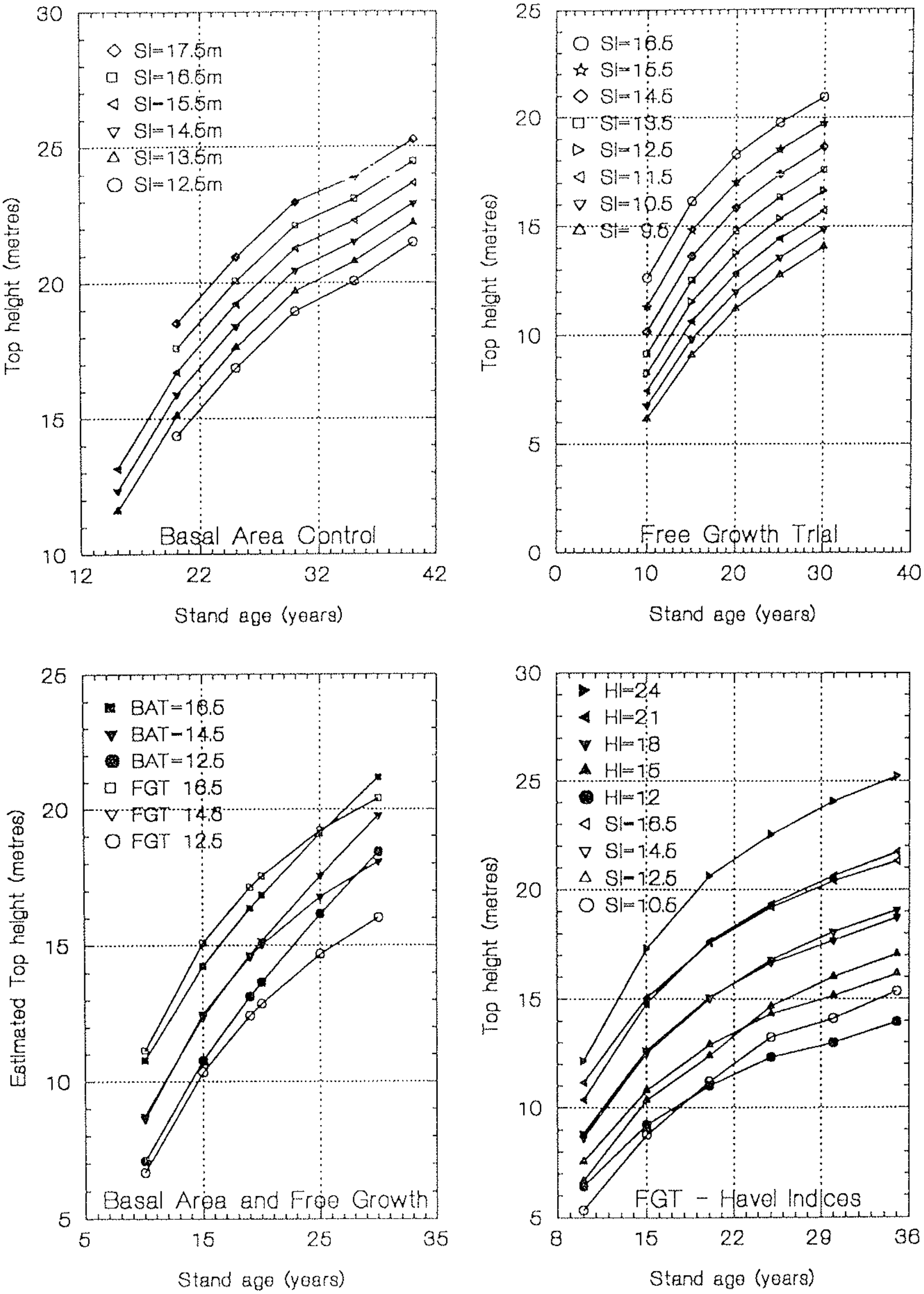

Figure 25.

Site index curves for the Basal Area Control trial(top left), the Free Growth trial (top right) and comparisons of Free Growth data with the Basal Area Control data (bottom left) and Havel site index estimates (bottom right).

the Free Growth curves with time, reflecting the continued application of fertiliser with time to the former stands. This situation needs further definition in the field.

Height/Diameter - As height development is not influenced by stocking and Dub is very sensitive to competition (Fig. 15) it is to be expected that H/D ratios would be sensitive to competition.

Considerable interest has been directed to height and diameter relationships for stand modelling (Curtis 1967, Stout et. al. 1982, Buford 1986, Vanclay and Henry 1988). Most workers accept that the function is dependent on spacing and relate their models to unthinned stands or mixed species stands of multiple age classes.

From a Free Growth study in South Africa Marsh (Marsh 1957) found that for the height-diameter relationship (Fig. 18) there is a base curve common to all stand densities from which each density deviates in turn as competition sets in. The common base curve represents the relation between height and diameter in which trees are not under competition (Free grown). The current trial clearly demonstrate that the common height-diameter base is present for both stand density and site classes until competition sets in when unique, significantly different curves separate for stand density classes and site classes (Figs. 18 and 19, Tables 7, 23, 24 and 25). The height-diameter association was significantly different for stand ages (Table 7, Fig. 16) with a tendency to stabilise with increasing age. Slopes of the height-diameter relationship were parallel with stand age (Fig. 19).

The free growth approach is ideal for studying such relationships. It shows that under commercial plantation conditions, H/D is extremely sensitive to stocking and sensitive to site.

Marsh suggested that H/D was relatively insensitive to small changes in site quality. Significant influences of site potential on the H/D relationship were found at 9, 14 (.01 level) and 32 (.002 level) years of age in the present trial (Table 7). Figures 16 and 17 and Table 23 however, reveal no significant differences between site classes 1 and 2 and 4 and 5 and support Marsh's suggestion of insensitivity to small changes of site. However, very real differences for H/D were observed over the range of sites tested in the trial (Table 7, Fig. 19). Values established within the trial (Table 23) may be of use in setting broad levels for the impact of thinning on H/D ratios in stand modelling.

Curtis presents a wide range of models relating height to diameter and height to diameter and age (Curtis 1967). For the current data the range of possibilities were examined (Table 25). No advantage was achieved by replacing height by square root or natural log transforms. Ninety per cent of variation in height for all treatments, site classes and age classes was explained by Dub and 92.7 per cent by Dub and Age. Equations incorporating treatment by site or treatment by age interactions explain 95.0 per cent of height variation with a standard deviation about the regression of 1.0 m. The minimum reduction in standard deviation about the regression was obtained by the regression

```
Height = 0.195 + 0.338 Dub + 0.553 SqrtDub + 2.50 Age
         - 0.0923 Treatment*Age + 0.188 Site*Age

Predictor        Coef        Stdev     t-ratio        p
Constant       0.1948       0.2360        0.83    0.409
Dub           0.33817       0.0254       13.31    0.000
SqrtDub        0.5530       0.1506        3.67    0.000
Age           2.49836       0.0481       51.88    0.000
T*Age       -0.092310       0.0038      -23.70    0.000
S*Age       -0.187997       0.0060      -31.32    0.000

s = 0.7426       R^2 = 96.7%       R^2(adj) = 96.7%

Analysis of Variance

SOURCE         DF          SS           MS          F          p
Regression      5     30442.2       6088.4   11042.15      0.000
Error        1886      1039.9          0.6
Total        1891     31482.1

SOURCE         DF      SEQ SS
Dub             1     28212.2
SQRTDub         1        72.1
Age             1      1063.8
T*Age           1       553.4
S*Age           1       540.7
```

Although the current data only covers part of the potential site range for the species in the area they consist of regular measurements of the same trees and stands over a period commencing at 9 years and progressing to 32 years of age. The weight of this data must be considered if a basic height-age-diameter model is required for the species. Further modelling was not continued on the understanding that data to be made available from the basal area trials will compliment the current base to provide the full range required for the species in the area. Analysis of the basal area trials will also provide information on the impact of fertiliser addition on the height-age relationship.

Variable use of fertilisers and the gradual introduction of genetically improved seed to plantations, limit the use of the classical site index system. Buford and Burkhart (1987) have shown that for *Pinus taeda* the shape of the curves remains constant irrespective of genetic source and by measuring the actual dominant height at any age, the stand can be related to standard height-age curves for the species. Similarly it is suggested (Buford 1986, Buford and Burkhart 1987) that the shape of height-diameter relationships is not influenced by genotype. It is possible therefore that standard height-age and height-diameter data can be used for modelling future stands employing improved seed.

Whether the consistent height-age and height - diameter shape relationships continue to exist with fertiliser response should be assessable on analysis of the basal area trials.

Competition and Diameter

The timing used to establish the range of stockings in a free growing condition was based on data provided by Marsh for *Pinus patula* and *Pinus longifolia* in South Africa. The success of this judgement cannot be ascertained within the trial design. It can be shown however, that for the conditions, competition is present within a stand at the following stockings and ages -

by 9 years for 1880 s ha^{-1} or more
by 14 years for 950 s ha^{-1} or more
by 18 years for 745 s ha^{-1} or more
by 24 years for 450 s ha^{-1} or more.

This record can be refined by further analysis of the interim measurements at ages 12, 16 and 22 years (Table 2) if required. It would not however, assist in indicating the performance of more rapid thinning and further reduced stockings which are relevant to current plantation practice. The above results provide upper limits to delaying thinnings if diameter development of a final crop is to be maximised. They illustrate a principle of increasing competition with increasing stand density at an early age that is not often clear from field trials. The results had, until recently, little application to practice as previous plantation regimes were well adjusted within the limits established. A current emphasis on particle board yields should favour more conservative stocking levels and may again require careful consideration of stand diameter (piece size) development.

From the data, there is no evidence to suggest that the time of onset of competition varies with site quality. Data in Table 22 shows that the ratio of diameter measured to that at age 31.5 years was constant for all sites. Craib (1947) claimed that in South Africa, competition in a given density commenced at the same age, irrespective of site. Marsh (1957) indicated that for very poor sites there may be a two year delay in competition at a given density, compared to that on a good site. For practical purposes however, it can be considered that the onset of competition at a fixed stocking is independent of site.

The H/D ratios obtained for the whole stand in the higher stockings (T1 to T4) exceed those obtained for the dominant portion of the final crop at least to stand age 18 years (Table 23). This difference also applied to all treatments in the 1962 measurement when thinning was only partially complete. The 1985 measurement must be excluded from this comparison as only the final crop heights were measured at that time: all other stand heights required for volume assessment were derived from the H/D ratio calculated for the final crop.

The difference in ratios between the whole stand and the dominant stand could indicate that competition has a relatively greater suppressing effect on the diameter of the dominated and suppressed portion of the stand. If this is the case competition can be considered to be present in all treatments at age 9 years but is not detectable in the dominant stems of all but the unthinned treatment (Fig. 16). The response of *Pinus pinaster* to competition with increasing stand density would therefore be more similar to the *Pinus patula* data in South Africa in which competition had set in within stockings of 247 s ha^{-1} at age 10 years.

The dramatic effect of density on diameters of the dominant stand in (Figure 15) has also been shown for the total stands by Butcher and Havel (1976) for the basal area trials.

Stand Density and Increment

Marsh (1957) used early results from free growth trials in South Africa to clarify some previous European ideas concerning stocking and stand increment. Moller is associated with the theory that within certain wide limits, the volume increment of a forest stand is not influenced by density of stocking (Heiberg 1954). Consideration of the physiological potential of a stand has also restated the theory to mean that the average increment over long periods is not affected by the degree of thinning within wide limits.

Volumes referred to in these instances obviously meant total volumes and European measurements relating to small sizes and branch wood which, these days, could theoretically be used as pulp yields.

Marsh found the free growth series were ideal to consider these propositions for the species and conditions concerned. He showed that the theory only related to the sparser stockings of 740 s ha^{-1} and less which produced well below the maximum total volume production of the heavier stockings on the site.

In the present trial, using total BAob to represent total volume, data presented will be conservative for volumes at the highest stockings (i.e. with the highest value for form factor) in the densest stands (Marsh 1957). It is clear from Figure 12 and Table 11 that CAI total volume is very sensitive to changes in stand density. The plateau of no increment loss associated with the Moller theory is for Treatments 1, 2 and 3 only; a very restricted degree of thinning. Differences in CAI associated with decreasing stocking and stand density are illustrated within increment periods in Table 30.

The Moller theory has little application to total volume production for *Pinus pinaster* under plantation conditions at Gnangara. Butcher and Havel (1976) suggested however, that further north, in dry years and on certain drought prone sites, volume production is largely independent of density within a wide range of basal areas. Further analysis of the developing trials concerned show that such influences are of very short duration and unimportant in total stand development.

It is also obvious from Figures 14 and 23 that it is the final crop volume or merchantable volume with which we are practically concerned and it is value rather than volume which is important (Harvey 1983). There are however, three aspects of increment and density which arise from the present results which may explain some of the misunderstandings attached to the Moller theory.

Degree of thinning - Increments associated with stand decreases from 1880 to 1320 to 1270 s ha^{-1} have little influence on basal area and volume increment (Figs. 9, 13, Table 30). Reductions in stand density of the order of 20 per cent (i.e. T1 to T4, T4 to T6, T6 to T7), with thinning favouring the remaining dominants, are required to provide significant changes in BAob and total volume increment (Table 30). Although the stocking reduction from 1880 to 1270 s ha^{-1} (T1 to T3) at age 5 years represents a reduction in stem numbers of 32 per cent, removal of the poorest stems in the stands leads to a stand density (and growth potential) reduction that was not detectable at the first measurement, four years after thinning. Such relatively light thinnings (mainly from below) which perhaps were once common in well stocked naturally regenerated stands have relatively little impact on volume production. Density reductions of some 25 per cent or more directed at the dominant stand are required for a realistic stand response.

Thinning interval - With time, the stand density of the dominant portion of the crop in thinned stands will increase more rapidly than that in unthinned stands (Fig. 23). Also, at high stockings, decreases in stand density due to mortality will also become relevant (Table 15) with respect to increment, with age. Hence, over any time period, standing density and CAI could tend to approach that of the site maximum (Figs. 11 and 22). It should be noted however, that in the trial, CAI of Treatment 7 is still 65 per cent of T1 and T4 is still 91 per cent of the control (Table 30), twenty five years after treatment. In the meantime continued loss in total volume production has resulted due to the reduced potential of the stand due to thinning.

For reasonable plantation rotations of 30 to 60 years, reducing stand density to produce a more favourable commercial crop will be associated with decrease in total volume production.

Stand efficiency - Moller supported his theory on the belief that stands at lower stockings will develop to fully utilise the available growing space. The extent that this occurs in shown in Figure 24 in which up to 80 per cent of the maximum CAI is achieved by about 13 per cent of the stem numbers by age 32 years. Two major processes favour this efficiency at reduced density.

Table 37: Height (m) to the first branch carrying live crown for final crop trees at age 32 years.

Treatment (s ha^{-1})	Site class 1	2	3	4	5	Mean
1 (1880)	9.0	8.3	8.3	7.1	7.1	8.0
2 (1320)	10.9	9.6	8.4	7.8	7.2	8.7
3 (1270)	9.7	9.2	8.4	7.6	7.0	8.4
4 (950)	10.4	8.0	7.7	7.3	6.3	7.9
5 (745)	10.5	8.5	6.9	7.5	6.4	7.9
6 (450)	9.6	7.6	6.4	6.1	5.3	7.0
7 (244)	8.1	6.4	5.7	5.1	5.1	6.1
Mean	9.7	8.2	7.4	6.9	6.3	

Thinning provides for a new form of crown development not available in denser stands. As well as being able to increase in crown width, residual trees increase crown volume by increasing the depth of the live crown on the stem. Variation in crown depth with stocking is shown for the 1985 measurement in Table 37. Final crop trees in the lowest stand density carried 15 per cent more of the stem in live crown than the lightly thinned stands.

This factor imposes disadvantages to wood production as well as advantages. It increases branch size and the number of green knots in the merchantable timber. Extreme spacings for rapid growth with *P. pinaster* must be accompanied by green pruning to provide quality sawlogs. These operations and results need to be evaluated against reduced interest charges due to shortening the rotation to produce optimum log sizes.

A second factor associated with the relatively high efficiency of selectively thinned stands is that the weaker, less competitive trees are culled to favour the dominant and most efficient genotype. Previous use of imported, unimproved seed of *P. pinaster* required initial stockings of 2,500 s ha^{-1} to produce 250 suitable vigorous and straight trees ha^{-1} for a final crop. Tree improvement has greatly reduced the proportion of defective, non-vigorous genotypes in seed available for future stands and currently the order of 1 000 s ha^{-1} planting will give a good final crop selection (Butcher and Hopkins 1993).

Misinterpretation of the Moller theory has perhaps led to misunderstanding on the effect of stand density on certain forest influences such as interception, transpiration and run-off. The efficiency of the reduced stand density in Figure 24 is due to the effective use of the stand environment by the residual stand. Increment is only partly reduced and so are transpiration and interception only partly reduced. Worley et. al. (1971) have shown that stream flow increases from West Virginian stands were only minor until the order of 80 per cent of the stand volume had been removed. Butcher (1976) has also shown that within the local basal area thinning series for *P. Pinaster*, reduction in stand density from 25 m^2 ha^{-1} to 7 m^2 ha^{-1} (i.e. by 72 per cent) increased the effective rainfall by only 15 per cent.

Fertiliser effects

Fertiliser addition at ages 8 and 16 years was evenly over the trial and diferential effects within the trial can not be assessed. The addition in 1969 was followed by foliar sampling for N, P and K content and associated with adjacent non-fertilised plots. The February 1970 sampling, 6 months after fertiliser application showed comparable levels of K and N for each site sampling block and the unfertilised controls (Table 33, Fig. 26). P levels for blocks 1 and 2 registered full response to fertiliser addition and were significantly higher than those of blocks 3 and 4 and the control block 5 (Fig. 26). The reason why the P response was complete and prior to that on the better sites in blocks 3 and 4 cannot be explained. The significant N response received at the .03 level for N for stocking treatments results from high levels in the 600, 400 and 300 s ha^{-1}levels. This result is not consistent with the treatment progression, the absence of stocking effects on nutrient contents measured in 1971 and 1972 and in foliar sampling of the Basal Area Thinning Series. With the non-significance of stocking effects for these later measurements it is concluded that the wide range of stocking levels did not influence the foliar content of N, P and K in the canopy.

The 1971 sampling was 18 months after fertiliser addition and foliar P levels throughout the trial were in the vicinity of 0.1 per cent which is near maximum for foliar P for the species. Means for blocks 1 to 4 were significantly higher than the unfertilised control which remained at the level of the previous year (Fig. 26). The K levels were significantly different (.008) due to an unexplainable high value in block 1 and a low value in block 3. This cannot be related to fertiliser or stocking influences. Sampling in 1972 was more restricted but confirmed the absence of significant differences between N, P and K levels within the stocking range. A residual effect of applied P was observable 30 months after fertiliser application. The level in the unfertilised control had decreased to .04 per cent which is recognisably deficient to growth on these sands. The highest levels of residual P were in the western blocks 3 and 4 which were identified with the yellow subsoil and the highest pine site qualities. Similarly the significantly highest N levels in this sampling were associated with the better quality, blocks 3 and 4 (Fig. 26).

The foliar sampling confirmed a lack of P for optimum growth on these sites and at least 2.5 years significant improvement in foliar levels following fertiliser application. Stocking had no effect on foliar levels of N, P and K.

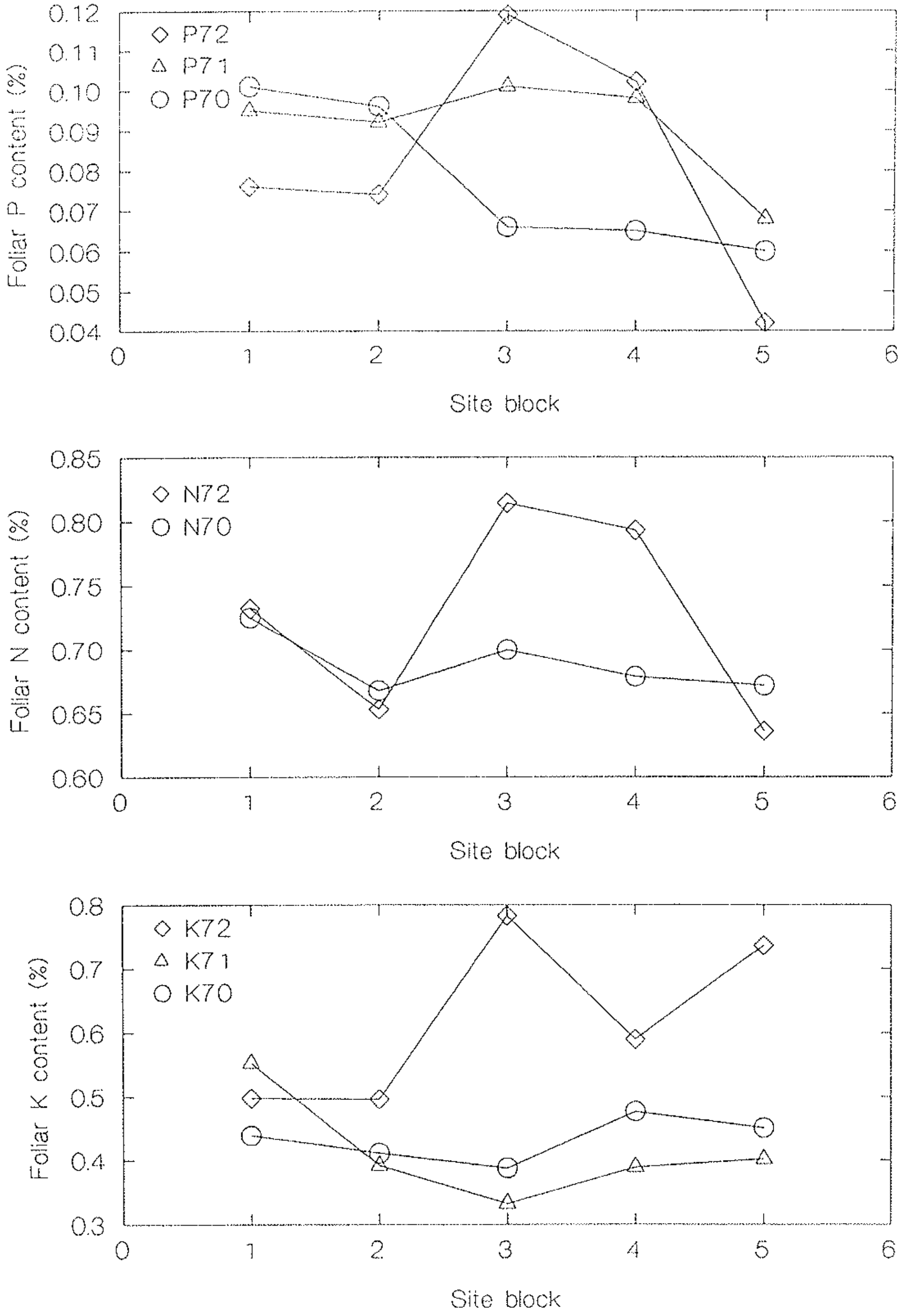

Figure 26.

Means for N, P and K levels of uniformity blocks (1 to 4) and the unfertilised control (block 5) from foliar sampling in February 1970, 1971 and 1972.

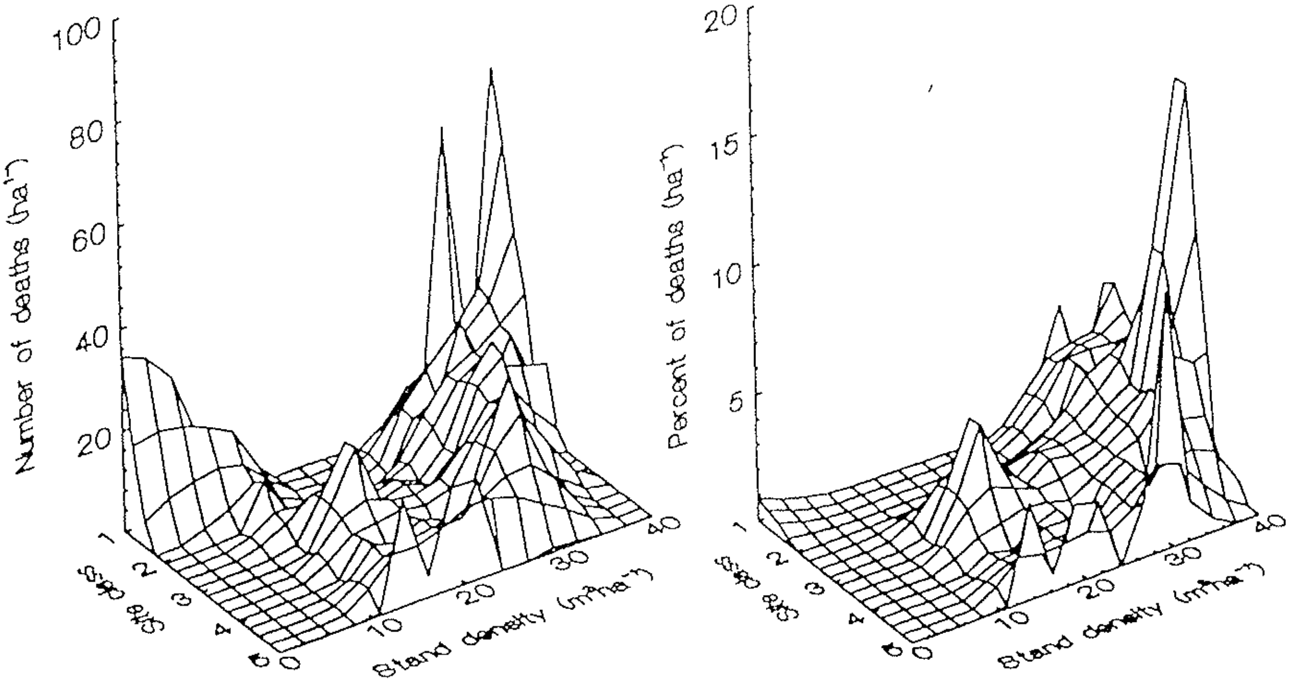

Figure 27.

Plots to show the pattern of drought mortalities with site class and stand density.

Drought Effects

Several droughts influenced stand development in the trial and stem mortalities associated with drought were recorded in the 1977 and 1985 measurements (Table 15). It is also probable that relatively high CAI values for T6 and T7 in the 1977-85 period (Table 30) include a favourable advantage for dominant growth of the wider spacings in the dry period.

The major factor associated with drought mortality was stand stocking (Tables 15 and 16). Mortalities in the 1880 s ha^{-1} treatment exceeded those in any other treatment by at least three times. This association remained when percentage mortality was compared to compensate for the greater number of stems in the unthinned treatment. Drought deaths were also concentrated in the superior site class where numbers of deaths in Site 1 were almost double those of any other site class (Tables 15 and 16).

An attempt to relate the extent of mortality to the stand density (BAob) in 1977 (Tables 38 and 39) was partly effective as only about 28 per cent of the variation in mortalities could be explained by a model. Certainly most stands with the highest stand density suffered drought mortality but some (T3 SC3, Table 15) were unaffected while certain low density stands (T6 SC5 and T6 SC2, Table 15) had relatively high mortality. Figure 27 while showing these trends, also indicates the interaction effect between site and stocking.

Table 38: Stand density (BAob. m^2 ha^{-1}) of the trial at the time of the drought. Stand age 24 years

Treatment	Site class				
(s ha^{-1})	1	2	3	4	5
1 (1880)	40.3	36.4	30.2	27.8	23.4
2 (1320)	39.0	32.9	34.5	27.7	23.6
3 (1270)	43.4	37.3	30.3	26.1	23.5
4 (950)	40.2	28.7	25.5	22.2	20.0
5 (745)	32.8	28.5	22.4	20.7	16.6
6 (450)	26.1	20.6	15.1	16.0	14.9
7 (244)	18.8	12.5	13.4	9.2	7.4

Mortality tended to be high at stand densities above 30 m^2 ha^{-1} basal area over bark, medium at densities of 25 - 30 m^2 ha^{-1}, low at densities of 20 - 25 m^2 ha^{-1} and absent below 20 m^2 ha^{-1} (Table 15).

Butcher (1979) described the drought history of the region and also records pine mortalities in plots on the northern coastal plan. As in the current trial he was unable to relate drought deaths to any critical basal area: site water availability was the dominant influence. He also found that most deaths were related to dense stands and fertilised stands.

Table 39. Best subsets regression showing degree of variation in number of drought deaths accounted for by regression models of attributes measured.

Response is DROUGHT DEATHS

Vars	R^2	Adj. R^2	C-p	s	Treat	Site	BA77	BA71	PDHT77	PDHT71
1	16.1	15.9	96.1	91.25				X		
1	10.7	10.6	132.0	94.09			X			
2	27.7	27.4	19.6	84.77			X	X		
2	16.8	16.5	92.9	90.92	X			X		
3	28.7	28.2	15.0	84.28	X		X	X		
3	28.3	27.8	17.5	84.51			X	X		X
4	29.4	28.8	11.9	83.93		X	X	X		X
4	29.4	28.8	12.1	83.94			X	X	X	X
5	30.2	29.4	9.0	83.59	X		X	X	X	X
5	30.1	29.3	9.7	83.65	X	X	X	X		X
6	30.8	29.9	7.0	83.32	X	X	X	X	X	X

Measurement data from the basal area thinning series at Gnangara and on the limestone soils to the north (Butcher and Havel 1976, Butcher 1977a) also shows loss of volume increment with reduced stand density at Gnangara and on most sites at Yanchep. For Yanchep however, it was possible to show that in a drought period, volume increment on the heaviest thinned stands (7 m^2 ha^{-1}) was comparable to that on the densest (25 m^2 ha^{-1}) stand. Butcher and Havel concluded that on sites where water availability was critical to stand development, volume production was largely independent of density within a very wide range of basal area levels. Recent analyses of the trials involved show that comparisons of merchantable volume (to a fixed top diameter) are biased towards thinned stands, at least in early stand development. Comparisons of total volumes and longer development periods favoured increasing volume production with increased stand density. This is important if pulpwood and or particle board markets are available. Experience with plantations in Western Australia over the past decade make it essential that allowance for drought is a major factor in planning and management.

Marketability.

Although fundamental interests will continue to concentrate on maximum biomass production in ecosystem research, for commercial forestry the key factor is increment to produce piece sizes and wood qualities that can be harvested and marketed economically. The greatest costs incurred in wood plantation enterprises are usually associated with harvest, transport and conversion of stem material. Hence, to the market, increment to produce specific product sizes and quality is more relevant than total volume. For pulp markets the key may be in reducing the content of short fibred wood, for sawlogs it may be the log diameter, or number and sizes of knots per unit area. Spacing has more impact on these key aspects of wood production (Figs. 14, 23), relevant to commercial interests, than has the consideration of total production alone (Butcher, 1977).

Data Models.

Site index models were developed from progressive height data to explain the range of site classes covered and the pattern of development (Figs. 7 and 25). Similar summary models were examined for basal area and volume development.

For BAob 90 per cent of the variation in basal area data was explained by Predominant height and stand age (Table 40). The log transform provided most satisfactory homoscedasticity.

Table 40. Best subsets regression to show association between logBAob and stand parameters

Response is LogBAob

2366 cases used 4 cases contain missing values.

Vars	R^2	Adj. R^2	C-p	s	Treatmen	Site	Trees	PDHt	Age	1/Age	PDHT/Age
1	71.0	71.0	5368.7	0.521				X			
1	67.5	67.5	6298.4	0.551						X	
2	81.9	81.9	2459.2	0.411			X	X			
2	80.4	80.4	2861.3	0.428	X			X			
3	90.0	90.0	316.5	0.307			X			X	X
3	87.8	87.8	891.0	0.338	X					X	X
4	90.9	90.8	80.3	0.293			X		X	X	X
4	90.2	90.2	245.3	0.302			X	X		X	X
5	91.1	91.0	30.3	0.290			X	X	X	X	X
5	91.0	91.0	53.5	0.291	X		X		X	X	X
6	91.2	91.1	6.3	0.288	X		X	X	X	X	X
6	91.1	91.0	32.3	0.290		X	X	X	X	X	X
7	91.2	91.1	8.0	0.288	X	X	X	X	X	X	X

The regression equation is

LogBAob = 2.25 +0.000548 Trees - 30.4 1/Age + 2.94 PDHt/Age

Predictor	Coef	Stdev	t-ratio	p
Constant	2.25059	0.03080	73.07	0.000

Trees	0.00054751	0.00001062	51.58	0.000
1/AGE	-30.3805	0.2016	-150.71	0.000
PDHT/AGE	2.93844	0.04767	61.64	0.000

s = 0.2810 R^2 = 91.3% R^2(adj) = 91.3% n = 2365

For BAob the equation is

BAob = - 21.1 + 0.00945 Trees + 2.78 PDHt

s = 5.152 R^2 = 83.8% R^2(adj) = 83.8%

The regression equation for non-transformed data is presented to indicate the order of standard error involved in prediction.

For volume data 98 per cent of variation was explained by BAob*PDHt (Table 41).

Table 41: Best subsets regressions for volume and stand parameters.

Response is VOLUME

Vars	Adj. R^2	R^2	C-p	s	TREAT	SITE	AGE	STEMS	PDHT	BAOB	1/AGE	PDHT/AGE	BA*HT
1	98.2	98.2	587.5	9.701									X
1	90.0	90.0	1E+04	22.63						X			
2	98.4	98.4	282.5	9.074				X					X
2	98.4	98.4	302.8	9.117	X								X
3	98.5	98.5	143.6	8.773				X			X		X
3	98.5	98.5	196.9	8.889	X						X		X
4	98.6	98.6	67.8	8.603			X	X			X		X
4	98.5	98.5	101.7	8.678		X		X	X				X
5	98.6	98.6	52.5	8.566		X		X			X	X	X
5	98.6	98.6	53.1	8.568		X	X	X			X		X
6	98.6	98.6	25.9	8.504		X	X	X			X	X	X
6	98.6	98.6	29.0	8.511		X	X	X	X		X		X
7	98.6	98.6	17.2	8.482		X	X	X		X	X	X	X
7	98.6	98.6	21.0	8.491	X	X	X	X			X	X	X
8	98.6	98.6	11.5	8.467	X	X	X	X		X	X	X	X
8	98.6	98.6	15.9	8.477		X	X	X	X	X	X	X	X
9	98.6	98.6	10.0	8.461	X	X	X	X	X	X	X	X	X

The regression equation is

VOLUME = - 1.49 + 0.341 BAob*PDHT

Predictor	Coef	Stdev	t-ratio	p
Constant	-1.4889	0.3853	-3.86	0.000
BA*HT	0.3406	0.0011	315.63	0.000

$s = 9.701$ $R^2 = 98.2\%$ $R^2(\text{adj}) = 98.2\%$ $n = 1863$

This model is referred to as the Australian volume Equation (Spurr 1952). The most satisfactory association for homoscedasticity was obtained using the square-root transform with BAob and Predominant height.

The regression equation is

SQRTVolume = - 0.195 + 0.216 BAob + 0.389 PDHt

Predictor	Coef	Stdev	t-ratio	p
Constant	-0.19526	0.04389	-4.45	0.000
BA0b	0.215848	0.001278	168.85	0.000
PDHt	0.389062	0.004740	82.09	0.000

$s = 0.4462$ $R^2 = 98.3\%$ $R^2(\text{adj}) = 98.3\%$ $n = 1863$

A model stand for BAob and volume development is constructed as Appendix 1 for stand ages 10, 15, 20, 25 and 30 years, Predominant heights from 3 to 21 metres and stockings of 250, 500, 1000 and 1500 s ha^{-1}.

Silvicultural Implications

The `Free Growth Trial' was installed as a precursor to fixed density (rather than fixed stocking) trials established in 1965 and 1966 (Hopkins 1971; Butcher and Havel 1976). The objective was to promote thinning in plantation practice in the area, particularly to demonstrate practical procedures for, and results of, early thinning and green pruning. The trial was also used as a sounding ground to assist in determining procedures to account for site variation and in developing methods which were acceptable for studying silvicultural procedures in *Pinus pinaster*. Up to the time of the trial, previous thinning studies had proved unsuccessful due to treatment complexity and site variation.

Table 42: Requirements for stocking and age relationships in *Pinus pinaster* plantations on the Swan Coastal Plain in the 1980's.

Stand Age	Stand Density
0	1000 s ha^{-1}
7	800 s ha^{-1} Low prune 800 s ha^{-1} to 2 m and cull.
12	800 s ha^{-1} Lift pruning on 250 s ha^{-1} to 5 m.
15	250 s ha^{-1} Lift pruning on 100 s ha^{-1} to 7.5 m. Residual BAob of 7 m^2 ha^{-1}.
18	Lift pruning on 50 s ha^{-1} to 10 m.
22	100 ha^{-1}. Residual BAob of 7 m^2 ha^{-1}.
30	50 ha^{-1}. Residual BAob of 8 m^2 ha^{-1}.
42	Clear-fell. Final BAob 16.5 m^2 ha^{-1}.

Silvicultural impact - The demonstration of the low cost, early cleaning (thinning) by the gangs used to set up the trial greatly influenced the acceptance of the value of culling, thinning, pruning and fertiliser application for effective stand development. As a result of this and the basal area trials, a general concept for management in the 1970's and 1980's was as shown in Table 42 (Butcher, pers. com.).

The development of genetically improved stock had sufficient improvement and uniformity in tree vigour and straightness to provide an excellent final crop selection of 50 to 100 s ha^{-1} from an initial planting of 1000 s ha^{-1} (Butcher and Hopkins 1993) while providing the option of full stocking and maximum volume production on the site. Proven inter-row cultivation techniques and green pruning allowed this spacing and subsequent heavy thinning to be practised without problems from weed growth and excessive branch size on the prime bole log.

With the current market for particle board logs in the region and a lack of favour for pruning, use of full stocking until a particle board thinning is practicable will reduce branch stub size, provide a good final crop selection and maximise early financial returns from the plantation. Hence culling and pruning would be excluded from the regime in Table 41 and 1000 s ha^{-1} would be carried to age 15-18 until the particle board harvest. Drought problems will occur in certain drought years prior to the first commercial thinning. There is no reason to clean to avoid the build up of stand density levels within the anticipation of a market for small logs. Where drought deaths occur they provide a spacing stimulus for diameter increment of the remaining stand. The maximum volume possible will still be available for a first commercial thinning.

Emphasis on earliest development of a high quality final crop sawlog yield is not as real now as when the trial started but still is important. The market for clear wood has not materialised as expected and price premiums for large diameter logs cease at a relatively low cut off point. It is probable that both a maximum particle board cut and final crop sawlogs to meet current quality can both be achieved by favouring full stocking up to the time of the first commercial thinning. Reduction of stand density to below 20 m^2 ha^{-1} at this stage will reduce risks from drought damage to the final crop.

Site coverage - The restricted site coverage of the trial with respect to the known potential for the species in the area (Fig. 25) was expected by experienced observers. Earlier planting on the southern, flat areas of the Bassendean Sands was of a higher and more uniform quality than those on the transitional soils. The trial sites are however, representative of the soils of Banksia woodland planted since 1953.

Most of the trial includes pine of a site class (growth potential) that is quite inadequate for commercial production. Work carried out during the period of this trial has explored the economics and response of fertiliser addition to upgrade volume production on all sites (Butcher 1979). It is also possible to show from the vegetation site classification incorporated in this trial that a basis for exclusion of most of the unfavourable sites is available. It is extremely doubtful that the site classes 4 and 5 reported in the trial would ever have been planted if this knowledge was then available. For second rotations site index of the current stands provide a precise and certain means to eliminate uneconomical sites from plantation.

Trial design - With hindsight, it is seen as unfortunate that the trial did not cover a range of treatments from 1600 to 800, 400, 200, 100, 50 and 25 s ha^{-1} Useful response requires steps of somewhere in the order of fifty per cent reduction in density. In the current trial the Treatments 1480, 1236, 990 s ha^{-1} (2, 3 and 4) are not sufficiently different from the control to warrant inclusion. On the other hand, the final stocking selected of 247 s ha^{-1} was inadequate to cover the range of thinning responses practicable on the sites for medium and mature aged plantations. These problems were noted and provided for in designing the subsequent basal area control trials in which each treatment was reduced by one third of the previous basal area to a final level of 7 m^2 ha^{-1}. This covers the range required for study for mature aged stands.

Future of the trial - There is little value in continuing to measure the trial in its current form. Recently a large part of the western section of the trial was destroyed by fire. Selective sampling based on Top heights could be of use to provide information on stem taper (form) and branch size, if required. The implications that height-age-diameter relationships obtained from such a comprehensive, basic series is applicable to future crops of improved genotype (Buford and Burkhart 1987) could also relate to site changes due to fertiliser application. If so, or, as the impact of fertilisers must be included in stand modelling, the measurement base provided by the existing trial could provide a ready means to obtain this new information.

The measurement record and results of the basal area thinning trial at Gnangara are currently being documented. It is possible the current free growth data may have further value when compared with and added to, this more practical data set.

REFERENCES

Buford, M.A. (1986). Height - diameter relationships at age 15 in Loblolly pine seed sources. Forest Science, 32(3):812 - 818.

Buford, M.A. and Burkhart, H.E. (1987). Genetic improvement effects on growth and yield of Loblolly pine plantations. Forest Science, 33(3):707 - 724.

Butcher, T.B. (1977). Impact of moisture relationships on the management of *Pinus pinaster* Ait. plantations in Western Australia. Forest Ecology and Management, 1:97 - 107.

Butcher, T.B. (1979). Management of *Pinus pinaster* plantations on the Swan Coastal Plain for timber and water yield. Australian Water Resources Council. Technical Paper 42, Canberra.

Butcher, T.B. and Havel J.J. (1976). Influence of moisture relationships on thinning practice. New Zealand Journal of Forest Science, 6(2):158 - 170.

Butcher, T.B. and Hopkins E.R. (1993). Realised gains from *breeding Pinus pinaster*. Forest Ecology and Management, 58:211-231.

Carmean, W.H. (1975). Forest site quality evaluation in the United States. Advances in Agronomy, 27:209 - 269.

Clutter, J.L., Fortson, J.C., Pienaar, L.V., Brister, G.H., and Bailey, R.C. (19830. Timber management: a quantitative approach. J. Wiley and Sons, New York, pp 332.

Craib, I.J. (1947). The silviculture of exotic conifers in South Africa. British Empire Forestry Conference.

Curtis, R.O. (1967). Height - diameter and height - diameter - age equations for second-growth Douglas Fir. Forest Science, 13(4):365 - 375.

Harvey, A.M. (1983). Growth, volume and value production of Patula pine in a free growth spacing trial. Department of Forestry, Queensland, Technical Paper No 33, pp40..

Havel, J.J. (1968). The potential of the northern Swan Coastal Plain for *Pinus pinaster* Ait. plantations. Forests Department Western Australia, Bulletin 76.

Heiberg, O.S. (1954). Thinning problems and practices in Denmark. State University of New York, College of Forestry at Syracuse, Technical Publication 76.

Hopkins, E.R. (1971). Early responses to thinning in stands of *Pinus pinaster*. Forests Department Western Australia, Research Paper 2.

Johnston, T.N. (1975). Thinning studies in cypress pine in Queensland. Queensland Department of Forestry, Research Paper 7. 87pp.

Lanner, R.M. (1985). On the insensitivity of height growth to spacing. Forest Ecology and Management, 13:143 - 148.

Marsh, E.K. (1957). Some preliminary results from O'Connors Correlated Curve Trend (C.C.T.) experiments of thinnings and espacement and their practical significance. Commonwealth Forestry Conference, Australia and New Zealand.

O'Connor, A.J. (1935). Forest research with special reference to planting distances and thinning. British Empire Forestry Conference, South Africa, 1935.

Spurr, S.T. (1953). Forest Inventory. The Ronald Press Company, New York. pp 476.

Stout, B.B. and Shumway, D.C. (1982). Site quality estimation using height and diameter. Forest Science, 28 (3):639 - 645.

Vanclay, J.K. and Henry, N.B. (1988). Assessing site productivity of indigenous cypress pine forest in southern Queensland. Commonwealth Forestry Review, 67(1):53 - 64.

Worley, D.P. and Patrick, J.H. (1971). Economic evaluation of some watershed management alternatives on forest land in West Virginia. Water Resources Research, August 1971, pp 812 - 818.

APPENDIX

FREE GROWTH TRIAL DEVELOPMENT MODEL

Derived values for BAob (B) in square metres per hectare and total Volume (V) in cubic metres per hectare for Predominant height (m), Stand age (years) and Stocking (250, 500, 1000 and 1500 stems per hectare) levels.

Predom height (m)		10 years					15 years			
		250	500	1000	1500		250	500	1000	1500
3	B	1.2	1.4	1.8	2.4	B	--	--	--	--
	V	1.5	1.6	1.9	2.2	V	--	--	--	--
4	B	1.6	1.9	2.5	3.3	B	--	--	--	--
	V	2.9	3.1	3.6	4.3	V	--	--	--	--
5	B	2.2	2.6	3.4	4.4	B	3.8	4.3	5.7	7.5
	V	5.0	5.3	6.1	7.4	V	6.6	7.2	8.9	11.4
6	B	3.0	3.4	4.5	6.0	B	4.6	5.3	7.0	9.2
	V	7.8	8.3	9.7	11.8	V	9.8	10.8	13.3	17.0
7	B	4.0	4.6	6.1	8.0	B	5.6	6.4	8.5	11.2
	V	11.6	12.5	14.8	18.2	V	14.0	15.4	19.1	24.5
8	B	5.4	6.2	8.2	10.8	B	6.8	7.8	10.3	13.6
	V	16.8	18.2	22.0	27.6	V	19.3	21.3	26.6	34.3
9	B	--	--	--	--	B	8.3	9.6	12.6	16.6
	V	--	--	--	--	V	26.1	28.9	36.3	47.4
10	B	--	--	--	--	B	10.1	11.6	15.3	20.1
	V	--	--	--	--	V	34.7	38.6	49.1	64.9
11	B	--	--	--	--	B	12.3	14.2	18.6	24.5
	V	--	--	--	--	V	45.7	51.1	65.9	88.1
12	B	--	--	--	--	B	15.0	17.2	22.7	29.8
	V	--	--	--	--	V	59.7	67.3	87.9	119.4
13	B	--	--	--	--	B	18.3	21.0	27.6	36.3
	V	--	--	--	--	V	77.8	88.4	117.3	161.5

Predom height (m)		20 years					25 years			
		250	500	1000	1500		250	500	1000	1500
8	B	7.7	8.8	11.6	15.3	B	8.2	9.4	12.4	16.3
	V	21.0	23.3	29.5	38.7	V	22.1	24.6	31.4	41.7
9	B	8.9	10.2	13.4	17.7	B	9.3	10.6	14.0	18.4
	V	27.4	30.4	38.6	50.8	V	28.2	31.4	40.1	53.1
10	B	10.3	11.8	15.6	20.5	B	10.4	11.9	15.7	20.7
	V	35.1	39.1	49.9	66.0	V	35.4	39.5	50.4	66.7
11	B	11.9	13.7	18.0	23.7	B	11.7	13.4	17.7	23.3
	V	44.5	49.7	63.8	85.0	V	43.8	48.9	62.6	83.1
12	B	13.8	15.9	20.9	27.5	B	13.2	15.1	19.9	26.2
	V	55.8	62.6	80.9	108.6	V	53.7	60.0	77.1	102.7
13	B	16.0	18.4	24.2	31.9	B	14.8	17.0	22.4	29.5
	V	69.5	78.2	102.0	138.1	V	65.2	73.0	94.2	126.2
14	B	18.6	21.3	28.1	36.9	B	16.7	19.1	25.2	33.1
	V	86.0	97.3	128.1	175.0	V	78.5	88.2	114.5	154.2
15	B	21.5	24.7	32.5	42.8	B	18.8	21.5	28.3	37.3
	V	106.1	120.6	160.5	221.5	V	94.1	106.1	138.5	187.7
16	B	25.0	28.6	37.7	49.5	B	21.1	24.2	31.9	41.9
	V	130.6	149.3	200.8	280.1	V	112.4	127.0	167.0	227.9
17	B	28.9	33.2	43.6	57.4	B	23.8	27.3	35.9	47.2
	V	160.6	184.7	251.2	354.2	V	133.6	151.7	200.9	276.0
18	B	33.5	38.4	50.5	66.5	B	26.7	30.7	40.3	53.1
	V	197.5	228.5	314.4	448.3	V	158.5	180.6	241.1	334.0
19	B	38.8	44.5	58.5	77.0	B	30.1	34.5	45.4	59.7
	V	243.0	282.9	394.0	568.1	V	187.7	214.8	289.2	403.9
20	B	--	--	--	--	B	33.8	38.8	51.0	67.1
	V	--	--	--	--	V	222.1	255.2	346.7	488.2

Predom height (m)		30 years				
		250	500	1000	1500	
11	B	11.6	13.3	17.5	23.0	B
	V	43.4	48.4	61.8	82.0	V
12	B	12.8	14.6	19.3	25.3	B
	V	52.3	58.4	74.7	99.1	V
13	B	14.1	16.1	21.3	28.0	B
	V	62.6	69.8	89.5	119.0	V
14	B	15.5	17.8	23.4	30.8	B
	V	74.2	82.9	106.6	142.1	V
15	B	17.1	19.7	25.9	34.0	B
	V	87.4	97.9	126.2	168.9	V
16	B	18.9	21.7	28.5	37.5	B
	V	102.4	114.9	148.8	200.0	V
17	B	20.9	23.9	31.5	41.4	B
	V	119.5	134.4	174.8	236.2	V
18	B	23.0	26.4	34.7	45.7	B
	V	138.9	156.6	204.9	278.1	V
19	B	25.4	29.1	38.3	50.4	B
	V	160.9	182.0	239.4	327.0	V
20	B	28.0	32.1	42.2	55.5	B
	V	186.0	211.1	279.4	383.8	V
21	B	30.9	35.4	46.6	61.3	B
	V	214.7	244.4	325.6	450.1	V