CROWN DEPTH OF RADIATA PINE IN RELATION TO STAND DENSITY AND HEIGHT

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SYNOPSIS

An analysis of crown depth data from permanent sample plots showed that the increase in crown depth with lower stocking was linear when plotted over the average spacing between trees. For all data combined, crown depth increased by 1.6 ft for every foot increase in average spacing. This was a great deal less than indicated by previous studies, and shows that earlier predictions of crown depth to be achieved under more drastic thinning regimes may have been over-optimistic.

Site had a significant effect on crown depth, but differences in the rate of increase from close to wide spacing were not significant. There were strong indications, however, that crown depth varies not only with stand density, but also with the height of the stand, particularly in young stands. This would mean that a progressive rise of green crown level in young stands is no guarantee that the stand has reached a maximum crown depth characteristic for a given density.

A number of factors are considered, which may account for this finding. It is concluded that, to obtain a reliable estimate of crown depth under different thinning regimes, both stand density and stand height have to be taken into consideration.

INTRODUCTION

Grade studies carried out in recent years on timber milled from some of the older Corsican and radiata pine stands have focused attention on the high percentage of degrade resulting from the inclusion of bark-encased knots in the timber (Fenton, 1960; Fenton and Familton, 1961; Brown, 1961). This applies not only to the average mill run from stands which were left to grow up virtually untended, but also to the few stands which received fairly intensive thinning and pruning treatment, at least by earlier standards. The grade studies were more particularly concerned with the latter type of stand, and show that these earlier treatments produced no marked improvement in grade recovery, largely because pruning was delayed too long. Most of the branches were dead when pruned and part of the dead branch had become embedded in the outer layers of the wood already formed. Added to this, the late pruning produced a large diameter knotty core, thus restricting clearwood production to the very outside of the log where much of it was lost in slabs.

Bark encasement as a defect is most pronounced in the lower part of the stem where the branches die first as the crown starts to rise off the ground. A major part of the sawn volume derives from this very region and much of it is within reach of normal high-

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pruning operations. This stresses the need for early pruning to as high a level as can be economically justified.

By the time the stand reaches maturity, however, this still leaves a considerable portion of the stem above high-pruning level covered in dead branches. Some of the upper dead branches may not extend very far into the outer layers of the wood, so that most of the wood containing dead knots would come away in the slabs. But lower down bark encasement will become very noticeable. Intergrown knots being preferable to bark encased knots, more drastic thinning has been suggested as a possible means of producing deeper crowns, thereby reducing or perhaps eliminating bark encasement as a defect altogether.

This has resulted in a study of crown depth in relation to stand density. G. S. Brown (1962a) and Whiteside (1962) have determined this relationship for radiata pine, and found a marked increase in crown depth with lower stocking. Whiteside presents a thinning regime, which would enable one to keep the base of the green crown at a height of 32 ft above ground from the time high pruning to that level has been completed until clearfelling takes place at a mean top height of 140 ft. C. H. Brown (1962) formulates a thinning regime on similar lines and indicates the improvement in financial return which could be expected.

As a direct result of these studies, it has now become fairly generally accepted that the attainment of a given green crown depth at certain stages of stand development should be one of the chief criteria in drawing up a thinning regime.

The present paper is concerned with an analysis of crown height data from permanent sample plots controlled by the Forest Research Institute. The analysis supports the general finding that lower stocking produces deeper crowns, but the increase achieved by more drastic thinning appears to be a great deal less than anticipated on the basis of the earlier studies mentioned above. In fact, some of the differences are so small as to question the wisdom of drawing up schedules specially with the object in mind of obtaining deeper crowns. No doubt thinning versus no thinning, or present heavy thinning versus former light thinning, produces a substantial increase in crown depth. But comparing a normal stand well thinned by today's standards with one thinned to a more drastic regime, the differences seem hardly worth while taking into account, unless one is prepared to open up stands to the point where they fail to use the full growth potential of the site and start losing increment.

ORIGIN OF THE DATA AND METHOD OF RECORDING

Since 1956, the measurement of crown height — that is the height from ground level to the base of the green crown — has been standard practice in F.R.I. permanent sample plots concerned with thinning grades and planting espacement. Most of these plots consist of a series of treatments, ranging from light to heavy thinning, with an unthinned sub-plot serving as control.

Measurements in radiata pine plots take place every 2 years, but full measurements incorporating the recording of crown height and a detailed description of crown class and stem form take place whenever the plots are due for thinning, or, if not thinned, at every fourth measurement. On the average this gives a measurement of crown height every 6 years, though in several cases crown heights were recorded at only 2- or 3-year intervals.

Plots are spread on a country-wide basis, representing stands of all ages, but so far few stands have reached maturity. Data from spacing trials, however, are largely confined to the older trials at Kaingaroa (1940 planting), Rotoehu (1942) and Golden Downs Forest (1948) with a few data from younger trials at Ashley (1950) and Eyrewell Forest (1950). These combined include planting espacements ranging from 3×3 to 15×15 ft, as compared with the usual 6×6 and 8×8 ft for most of the thinning grade plots.

In addition, some crown heights were available from fire-regenerated stands in the Taupo area, representing extremely dense unthinned stands side by side with stands which received drastic early thinning and are now little different from the normal type of stand resulting from planting.

Altogether, 273 separate plot assessments of crown height were available from the above sources combined. A few of these refer to successive measurements in the same plot.

The normal procedure in recording crown height for any given plot is to record the crown height of every tree measured for total height. This includes 8 predominants used in the determination of predominant mean height, and 16 sample trees used for purposes of volume estimation. Each predominant is selected as the tallest tree on a 1/40th acre area, using a ½×½ chain grid. In larger stands, as opposed to plots, one selects the tallest tree within a radius of 18.6 ft, locating centres every so many chains or paces apart. Predominant mean height is then computed as the arithmetic mean of the heights of a number of trees selected this way. In sample plots a total of eight trees is considered sufficient to obtain a good estimate for thinning purposes. In larger stands, one could take more heights to reduce the error to any desired level.

The sample trees are trees of normal form — that is, free from forking or excessive crookedness — and selected to cover the full diameter range. The application of form-class volume tables necessitates climbing these trees to half height, using ladders; when within reach crown heights are recorded or checked at the same time. In all other cases, crown heights are measured from the ground, using the same instruments and the same procedure as in measuring total height.

In general, crown height may be said to refer to the distance from ground level to the base of the green crown, measured at the point where the branches join the main stem. When the crown is quite regular, so that from a certain node upwards all whorls are fully green while no living branches survive lower down, then crown height is quite clearly defined this way. But in most trees, as a result of irregular spacing and the differences in size of neighbouring trees, crowns descend deeper on one side of the stem than on the other. Consequently, the base of the green crown is not easy to define. One method is to use the point midway between the first green branch and the first green whorl. The difficulty with this method is that the first green whorl is not always taken to mean the first fully green whorl. Sometimes it is the first predominantly green whorl or the first whorl with green branches to all sides, irrespective of some dead branches which may occur interspersed between the living ones. Moreover, the method assumes more or less, that the portion of the stem between the first green branch and the first green whorl carries dead and living branches in about equal proportions, so that the base of the green crown can be taken as midway between these points. In many cases this gives an entirely false picture of crown height, more especially in relating crown height to bark encasement, since the combined effect of all dead branches, or the proportion of the stem affected by them, is not very well described.

For instance, a tree may have fully green whorls from 40 ft height upwards, but with a solitary green branch surviving at 20 ft above ground. Just because of this one branch, one cannot very well say that crown height is at 30 ft. The moment that branch dies, crown height jumps to 40 ft. Putting crown height at, say, 39 ft would be more realistic and would agree better with the proportion of the total stem surface which carries dead branches. On the other hand, a tree may have fully green whorls from 40 ft height upwards, the same as before, but with the lower whorls from 40 ft down to 20 ft also green except for a narrow strip of dead branches all the way down one side of the stem. In this case crown height should be set at little over 20 ft.

Therefore, the procedure adopted for obtaining an appropriate measure of crown height in sample plots was to visualize any irregular crown transformed into a regular shaped crown of the same effective size, that is, by balancing out all sides and completing partly green whorls at the top, as it were, with green branches taken from lower down the stem.

This method has been found less time-consuming than other methods and has produced consistent data.

DERIVATION OF CROWN DEPTH AND AVERAGE SPACING

Comparing the average crown height of the predominants with the average crown height of the sample trees, it was found that there was no marked difference one way or another; both seem to indicate the same level. For this reason, all crown height measurements were combined to give an average figure for the entire plot at each remeasurement. While crown height increases as a stand grows taller, the depth of green canopy tends to remain very nearly the same once full canopy closure has been reached, provided stocking does not change. For this reason, the crown height derived from predominants and sample trees combined was subtracted from the predominant mean height of the stand to give crown depth. This crown depth does not represent the average depth of green canopy for all trees in the stand but more nearly approximates the maximum depth of green canopy.

The reason for adopting this measure, rather than the average crown depth for predominants and sample trees combined, is that the mean total height of such a sample does not necessarily coincide with the mean total height of the stand. Trees would have to be selected in the right proportion from each height class. There is the further difficulty of applying such crown depth values to any of the present thinning regimes, which are based on mean top height and predominant mean height.

Stand density in terms of stems per acre was readily available from the plot records. If thinned at the time of measurement, the stocking before thinning was taken, because this represents the stocking to which crown height has become adapted. By plotting crown depth over stems per acre, a curvilinear relationship results, as shown by Brown (1962a) and Whiteside (1962). This regression becomes linear, however, if the crown depth is plotted not over stems per acre, but over the average distance between trees, assuming all trees to be evenly spaced. In this case triangular spacing has been used, a regular pattern in which each tree is equidistant from its nearest six neighbours instead of the nearest four as in square spacing. Thus, if there are N trees per acre one finds:

$$\text{Triangular spacing} = 224.27/\sqrt{N}$$
$$\text{Square spacing} = 208.83/\sqrt{N}$$
$$\text{or Triangular spacing} = 1.074 \times \text{Square spacing.}$$

Of course, no stand will conform to such regular spacing, but this is no objection; the spacing is just another way of expressing stocking per acre or the average area available per tree.

Of the two measures, triangular spacing and square spacing, the former has been chosen because it is based on a more ideal pattern of distribution and because it is the better guide in marking a stand for thinning. Also, expressed as a percentage of predominant mean height, it is the standard used for regulating stand density in experimental thinning grades.

THE REGRESSION OF CROWN DEPTH ON TRIANGULAR SPACING

Figure 1 shows crown depth plotted over spacing for all stands combined, thinned and unthinned. The crosses indicate the averages for each spacing class, using classes 4.9 ft and under, 5.0 to 6.9 ft, 7.0 to 8.9 ft., etc. The number of stands included in each class average is shown in parentheses. Altogether 224 stands have been used. This excludes all measurements from thinned stands taken less than 5 years after thinning. Successive crown height measurements taken in the same stands seem to confirm that this period of 5 years provides ample time for the depth of canopy to become fully adjusted to the new stocking as demonstrated by the rise in crown levels. In conformity with earlier work, it is assumed here that, when green crown level starts to rise, crown depth has reached a maximum value characteristic for any given stocking. The correctness of this assumption will be tested later.

From the plotted averages it will be seen that the regression of crown depth on spacing is strongly linear and, using the least squares solution, one finds:

$$\text{Crown depth in feet} = 1.60 \times \text{Triangular spacing} + 24.0$$
$$(\text{S.E. of estimate} = \pm\ 5.0\,\text{ft})$$

Points for control plots and for all grades of thinning are fairly evenly scattered about the regression line, showing that treatment has no significant effect on the relationship other than that caused by differences in stocking.

Also shown on the same graph are the regressions after Brown and Whiteside, converted from stems per acre to triangular spacing. Both these regressions prove to be linear when plotted this way. Brown's regression is based on the formula:

Crown depth $= 834.84/\sqrt{N}$ where N = number of stems per acre.

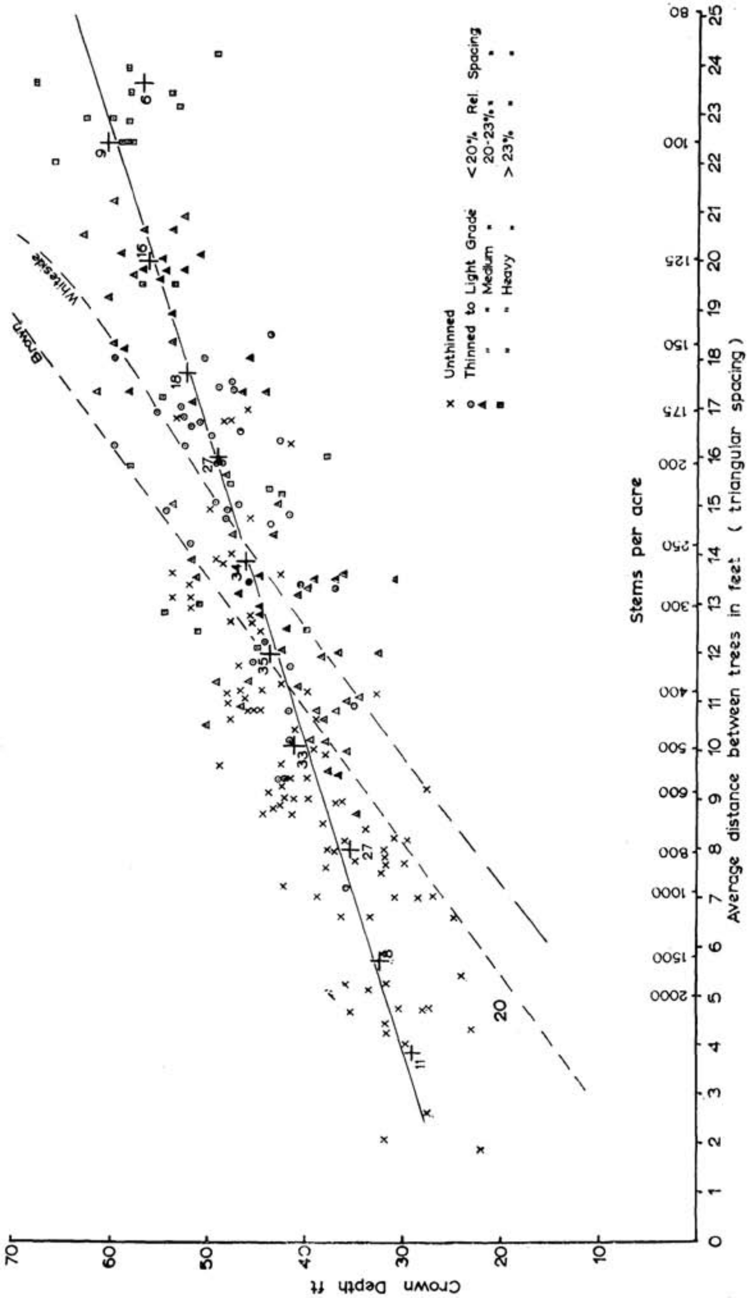

Fig. 1: Green crown depth over average spacing for all data combined.

Expressed in terms of triangular spacing one obtains:

Crown depth = 3.72 × Triangular spacing

which represents a straight line through the origin. Whiteside's regression line gives a negative regression constant, while at spacings over 20 ft the regression is no longer linear but shows a sharp rise in crown depth. This is probably because at this extremity he had very few data to go by and because, in drawing the curve of crown depth over stems per acre, one tends to flatten the curve in this region.

Both Brown's and Whiteside's regressions show about the same rate of increase in crown depth with wider spacing, amounting to about 3.7 ft for every foot increase in spacing, as against 1.6 ft for the sample plot data. This is a marked difference, which at first seems hard to explain. Brown determined his crown depth as the average of a number of trees selected to represent a given stocking per acre. Crown depth derived this way will be less than by using predominant height as the top level of the canopy. Most of the data for stands of low stocking, however, were obtained from "thinned" stands. Since in these stands most of the lower crown classes would have been removed in thinning, the crown depth would be more nearly the same by both methods. The overall effect would be a slightly steeper curve in following Brown's method.

Whiteside's crown depth, however, was based on the average crown depth of 10 dominants per stand. This should show very little difference with the method followed here.

As will be shown in a later section, it seems more likely that the differences are due to the effect of age or stand height on the relationship. In collecting data over a wide range of stocking the left-hand side of the regression becomes predominantly based on data from young unthinned stands, with crowns just starting to rise after canopy closure, while the right-hand side is based on data from more mature thinned stands. In the case of the sample plot data, the inclusion of many old stands of close spacing as well as young stands of wide spacing has to some extent counteracted this effect of age and this may explain the flatter trend obtained.

Turning to the regressions for the different conservancies (Fig. 2), there proved to be no significant difference in slope, but a highly significant difference in the actual position of the line. Highest values are shown by Nelson and lowest by Canterbury Conservancy. The steeper trend of the Nelson regression line proved to be non-significant when compared with the other conservancies combined. On the other hand, the difference in crown depth between Auckland and Rotorua, though only small, proved to be highly significant.

Unfortunately, data for Wellington and Southland Conservancies were insufficient to make a separate analysis.

The regressions for the different conservancies, with the standard error of the estimate in parentheses, are as follows:

Auckland: Crown depth $= 1.67\,S + 24.9\ (\pm 4.8)$ ft
Rotorua: Crown depth $= 1.56\,S + 24.5\ (\pm 3.9)$ ft
Nelson: Crown depth $= 2.21\,S + 22.5\ (\pm 3.1)$ ft
Canterbury: Crown depth $= 1.57\,S + 19.7\ (\pm 4.7)$ ft
Overall: Crown depth $= 1.60\,S + 24.0\ (\pm 5.0)$ ft

where S = Triangular spacing.

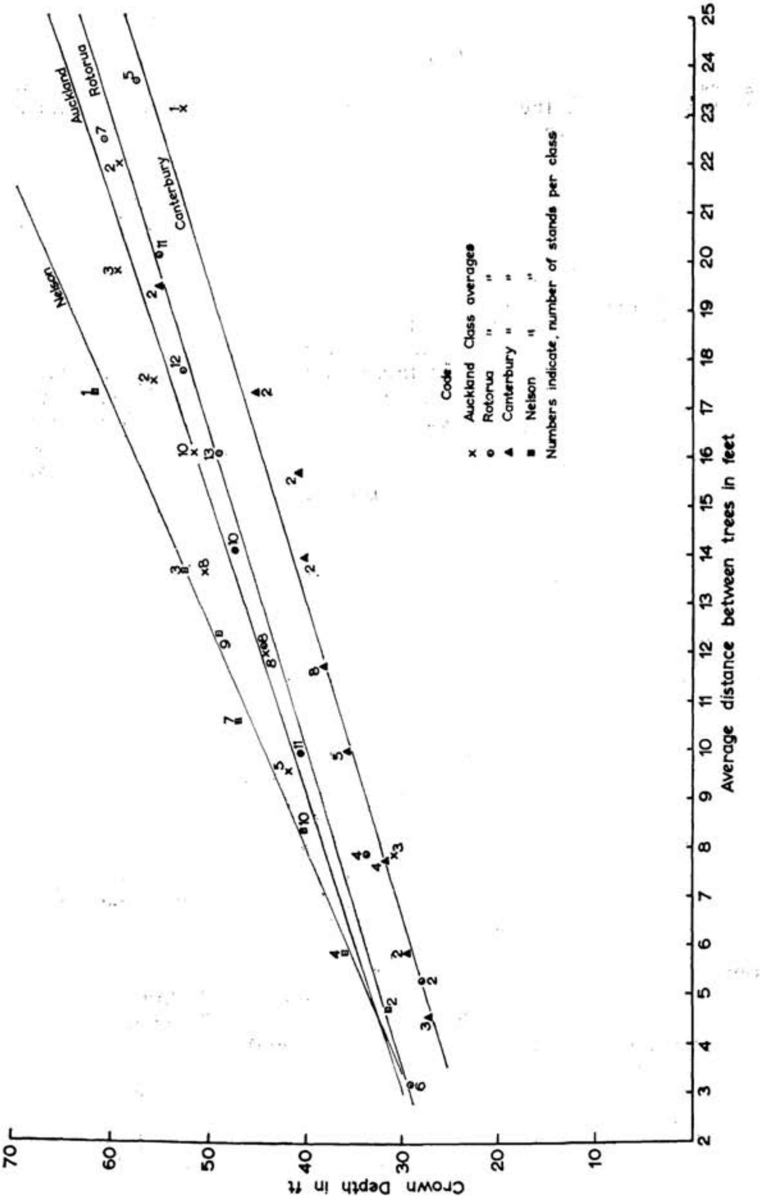

Fig. 2: Green crown depth over average spacing for different conservancies.

CROWN DEPTH UNDER DIFFERENT THINNING REGIMES

If three thinning grades are selected (light, medium and heavy), the green crown level at any stage can be predicted by using the above regressions. This will demonstrate the rise in crown level with advancing age or height of the stand. To do this it will be easier if each regression is expressed directly in terms of stems per acre. Since:

Triangular spacing $= S = 224.27/\sqrt{N}$, it is found:

Auckland: Crown depth $= 374.53/\sqrt{N} + 24.9$ ft
Rotorua: Crown depth $= 349.86/\sqrt{N} + 24.5$ ft
Nelson: Crown depth $= 495.64/\sqrt{N} + 22.5$ ft
Canterbury: Crown depth $= 352.10/\sqrt{N} + 19.7$ ft
Overall: Crown depth $= 358.83/\sqrt{N} + 24.0$ ft

Assuming that stands have an initial stocking of, say, 800 stems per acre and that there will be three thinnings with clearfelling at 140 ft predominant mean height (P.M. ht.), then Table 1 sets out the reduction in stocking for each of three grades and the derived green crown depth and green crown level according to the Rotorua regression.

TABLE 1: REDUCTION IN STOCKING AND DERIVED GREEN CROWN DEPTH AND LEVEL

P.M. ht.	*Light Thinning 15%*	*Medium Thinning 19%*	*Heavy Thinning 23%*
35	800–457	800–285	800–194
	36.9/0	36.9/0	36.9/0
70	457–203	285–127	194–86
	40.9/29.1	45.2/24.8	49.6/20.4
105	203–114	127– 71	86–49
	49.1/55.9	55.5/49.5	62.2/42.8
140	114–0	71–0	49–0
	57.3/82.7	66.0/74.0	74.5/65.5

The percentages for the different grades of thinning refer to the spacing/height ratio immediately before each thinning. The notation for crown depth and green crown level is shown underneath the figures for stems per acre. For instance, at 70 ft height in the light grade, the crown depth corresponding to the before-thinning stocking of 457 stems per acre works out at 40.9 ft. Subtracting this figure from 70 ft gives a green crown level of 29.1 ft.

These derived crown levels have been used in Fig. 3 to demonstrate the rise of the green crown for each of the three grades.

It should be noted that these grades cover a wide range. While the 19% grade compares closely with present normal thinning standards, the 15% is very light and the 23% extremely heavy. In the light grade, mortality is bound to show up between thinnings, while in the heavy grade the trees will not fully occupy the site for some years after each thinning. Yet it will be seen that the final difference in crown depth between the medium and the heavy thinning amounts to only 9 ft at the most.

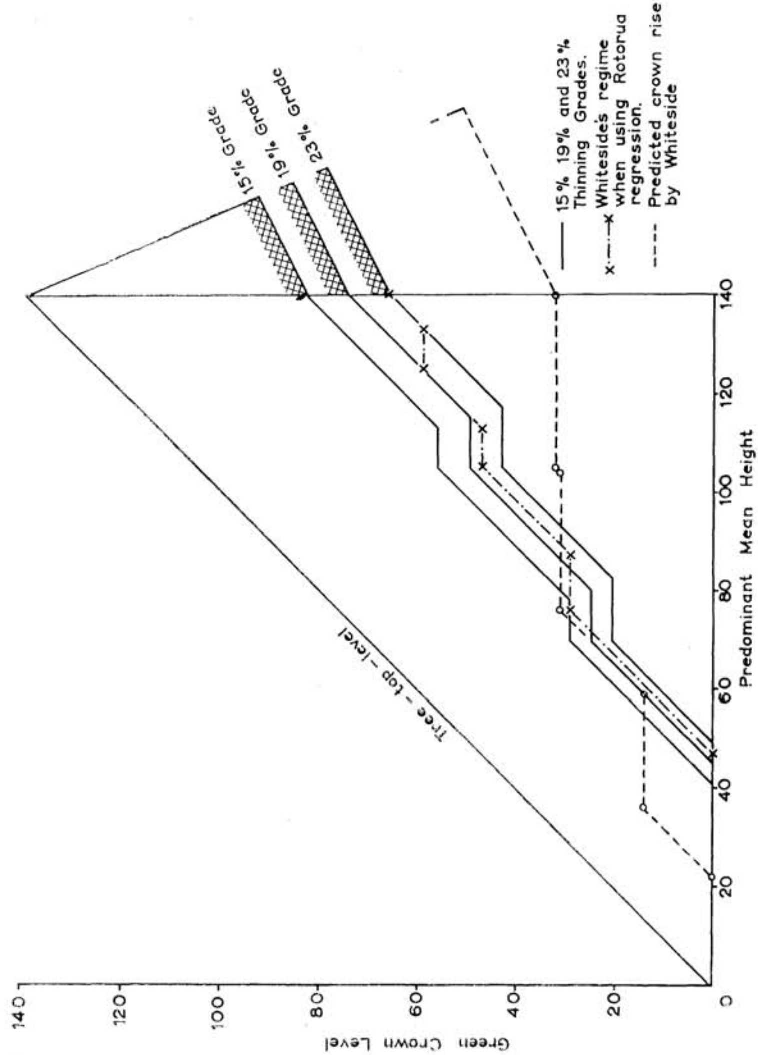

Fig. 3: Predicted rise of green crown level for certain thinning regimes.

As mentioned earlier, Whiteside has derived a thinning regime which, on the basis of his data, is expected to retain green crown level at 32 ft above ground. Table 2 shows his thinning regime with his predicted crown depths (CD) and green crown levels (CL). For comparison, the last column shows the crown depth and crown level computed from the Rotorua regression.

TABLE 2: COMPARISON OF WHITESIDE AND ROTORUA PREDICTED GREEN CROWN DEPTHS AND LEVELS

Mean Top Height	*Thin to*	*Whiteside CD/CL*	*Rotorua Regression CD/CL*
	900 (planted)		
36	250	22/14	36/0
76	110	45/31	47/29
105	70	73/32	58/47
125	50	93/32	66/59
140	Clear fell	108/32	74/66

The crown depth figures given here relate to the stocking left after the previous thinning. For instance, Whiteside gives a crown depth of 45 ft at 76 ft mean top height. This is the crown depth which corresponds to 250 stems per acre and the green crown level derived from this is 31 ft.

This comparison clearly brings out the large differences involved. According to the Rotorua regression, one ends up with a crown level more than twice as high as that predicted by Whiteside. The rise of the green crown level with increasing height of the stand is shown graphically in Fig. 3 (broken lines). Of course, strictly speaking, the Rotorua regression should not be applied to the Southland data on which Whiteside based his figures, but this should only cause minor differences.

THE EFFECT OF STAND HEIGHT ON THE RELATIONSHIP BETWEEN CROWN DEPTH AND STAND DENSITY

In order to account for the large differences involved, it is necessary to look more closely at the assumption that maximum crown depth for any given stocking is reached when green crown level is no longer stationary but starts to rise. This has so far been accepted as the stage when crown depth has become fully adapted to any particular stocking. A further analysis of the sample plot data shows that this may be a false assumption.

A thing that strikes one as odd in the previous section, for instance, is that crown depth for 900 stems per acre, according to the Rotorua regression, works out at 36 ft. This means that in a young stand crowns would not start to lift off the ground until predominant mean height had reached 36 ft or more. In young stands of about this stocking, however, it will be found that crowns start to lift when predominant mean height is about 20 to 25 ft, which is the height shown by Whiteside. (According to Brown's formula it would start rising at 28 ft stand height or over.)

When crown depths recorded at successive measurements in the same plots are compared, it is found that almost invariably crown depth increases at a much faster rate than that shown by the regression line; that is, after allowing for the drop in stocking due to natural mortality between measurements. In Fig. 4 this tendency is shown very clearly for a number of young plots. Unfortunately, very few successive measurements are available at this stage and some of the plottings shown here were taken less than 5 years after thinning. However this does not affect the unthinned controls, and in all the light-, and most of the medium-, thinning plots one

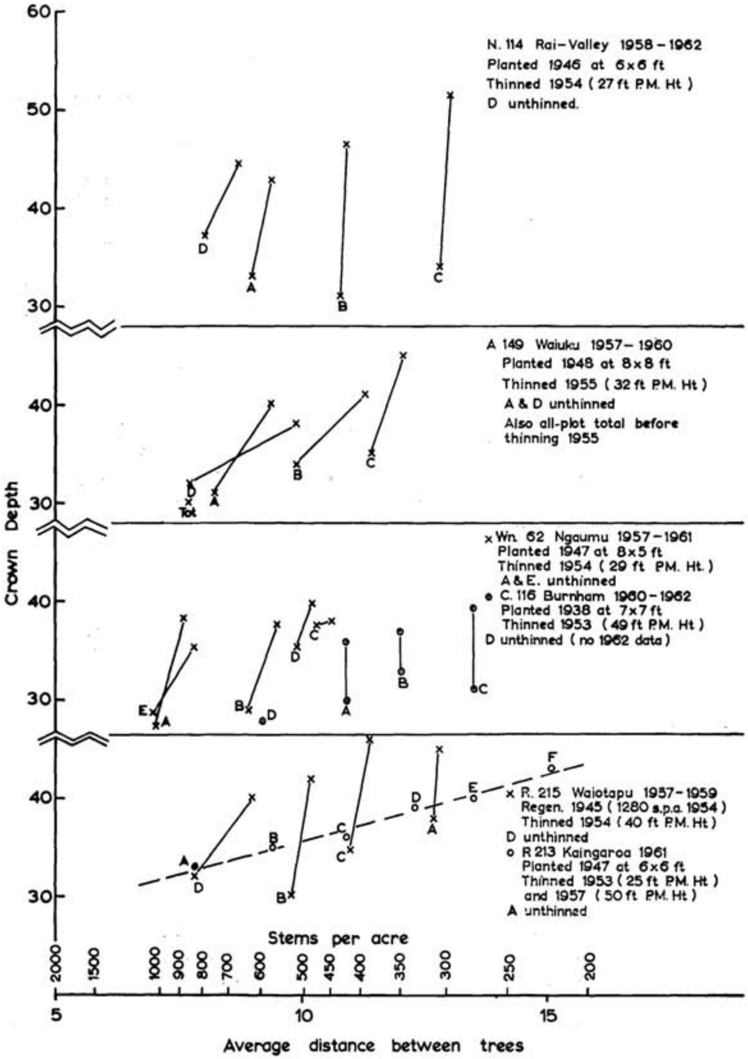

Fig. 4: Successive measurements of green crown depth in the same plot series, over average spacing.

may assume that canopy closure was reached in less than 5 years after thinning. On the whole, therefore, these plottings give a fairly true picture of what is happening.

Also shown on the same graph is a series of crown depth plottings for plot R.213 at Kaingaroa Forest. These were all taken in the same year in plots which received only light thinning, so that all treatments had closed canopy in 1961 when the measurements were taken. The plottings produce an almost perfect straight line — slightly flatter in trend than the Rotorua regression (regression coefficient 1.37 instead of 1.56) — but still well below it.

A similar trend is evident in Fig. 5, which shows crown depth data, recorded in the Kaingaroa and Rotoehu spacing trials, plotted over average spacing. Both trials were 19 years old when these measurements were taken, but owing to a difference in site the average predominant height at Kaingaroa was 83 ft as against 97 ft at Rotoehu. It will be seen, however, that this difference in height has had no definite effect on crown depth. Plottings from both trials correspond very closely, as is evident from the following regressions:

Kaingaroa:	Crown depth $= 1.28S + 30.04$
Rotoehu:	Crown depth $= 1.24S + 29.77$
All data combined:	Crown depth $= 1.23S + 30.43$

The regression for all data combined is the one plotted in Fig. 5.

It should be noted that the Kaingaroa crown depths were measured 3 years after the last thinning. This could affect the crown depth in the heavily thinned plots with stockings of 120 stems per acre or less. (Triangular spacing 20.5 ft and over.) Judging from the plottings, however, this does not appear to be so. The Rotoehu plottings in this upper range, which were taken 6 years after thinning, show very much the same crown depth.

The regression coefficient of 1.23 probably gives the best estimate so far of the differences in crown depth under light, medium and heavy thinning. Taking the example in the previous section, where stands are thinned to final stockings of 114, 71 and 49 stems per acre for the 15%, 19% and 23% grades, respectively, the green crown depths would work out at 56, 63 and 70 ft instead of 57, 66 and 75 ft. In other words, very heavy thinning would increase crown depth by about 7 ft when compared with medium thinning. This is not much of a difference to aim for in radiata pine at a height of 70 ft above ground, where, in the absence of bark encasement, much of the timber would be degraded on account of cone-stem holes.

The above trends clearly show the effect of stand height on crown depth in young stands. Successive measurements in older stands, however, do not show this variation so clearly, and conform more to the general trend.

As a final check, all data for thinned and unthinned stands were sorted into different density classes on the basis of triangular spacing. The following classes were used:

Spacing class	Under 8.0	8.0–11.9	12.0–15.9	16.0–19.9	20.0 and over
Corresponding s.p.a.	Over 785	785–351	350–196	195–126	125 or less

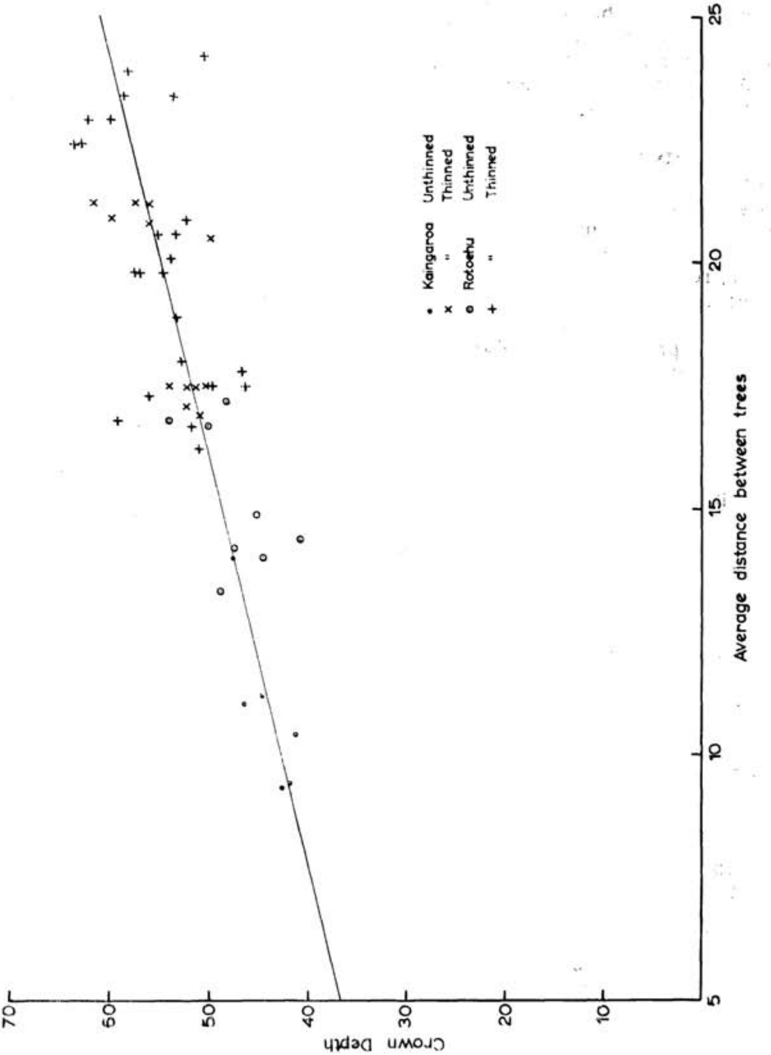

Fig. 5: Regression of green crown depth over average spacing for two sites at 19 years old.

For each of these classes crown depth was plotted over stand predominant mean height and a freehand curve drawn through the data. The plottings for any given class produced a wide scatter, largely because data from all conservancies had to be pooled to obtain an adequate range of stand heights. However, by observing the trend for the plottings from each conservancy in turn, the same increase in crown depth in the early stages of stand development could be detected. After harmonizing the freehand curves, the graph shown in Fig. 6 resulted. It shows that, for a given number of stems per acre, crown depth of a stand tends to increase as height increases. The rate of increase is fairly rapid at first (3 to 4 ft for every 10 ft increase in height), but after reaching a predominant height of about 80 ft, crown depth becomes more stable. The graph also shows the stand height at which crown level would start to rise for any given spacing.

When the curves are compared at a given height, one finds a constant increase of about 4½ ft in crown depth for every 4 ft increase in spacing (*i.e.*, difference between classes). This would indicate a regression coefficient as low as 1.12 when crown depth is plotted over triangular spacing for stands of the same height. Whether this increase is really the same at all heights, as shown by these curves, must remain doubtful at the moment owing to the variable nature of the data included in this analysis. The only way to perfect such a set of curves would be to collect sufficient data from the same locality at successive measurements in stands of different spacing. To ensure a wide range, spacing trials would be most suitable for this purpose. There is no doubt that, on the basis of the present data, such curves are essential for an accurate prediction of crown depth and crown level in stands of different height and spacing. Apart from stand density and stand height, there may be other factors involved, but from the present analysis it seems unlikely that such factors will cause differences of practical significance (see also Fairburn, 1958; Warren, 1958).

DISCUSSION

If crown depth varies not only with stand density but also with stand height, then the regression of crown depth over average spacing alone is no longer a sound basis for comparison. This could well account for the differences obtained with Brown's and Whiteside's data. If crown depth for high stocking is measured in young unthinned stands of normal 6×6 and 8×8 ft spacing, soon after crowns have started to die off near ground level, then a steep regression will result — showing a rapid increase in crown depth with lower stocking. If, by the inclusion of data from spacing trials and similar stands of extreme density, the data are more evenly spread out over older stands of dense stocking and younger stands of low stocking, then the trend will already be a great deal flatter. Finally, the regression will become least steep when all data are obtained in stands of the same height. Such trends based on stocking alone are therefore totally unreliable for predictive purposes.

It remains to consider what factors could cause crown depth to vary with stand height after green crown level has started to rise. Assuming that light is the limiting factor, then in any given stand green crown level will start to rise when the light penetrating

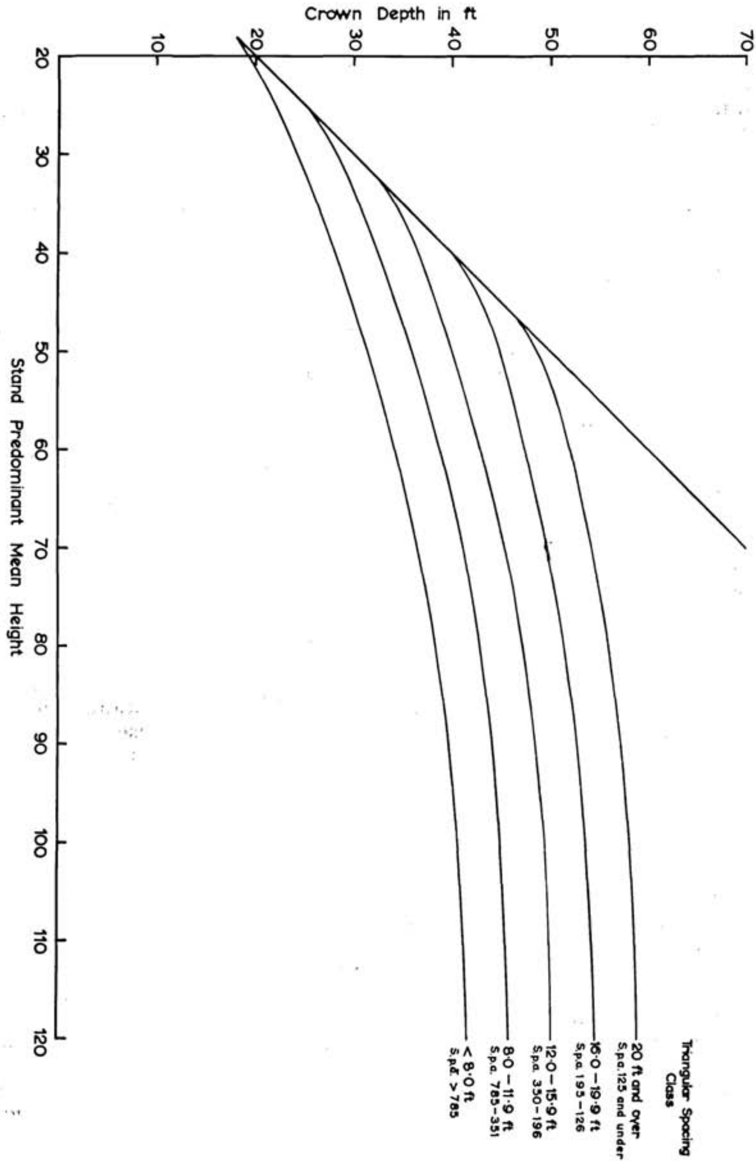

Fig. 6: Regressions of green crown depth over stand predominant mean height for certain stocking classes.

through the upper canopy to the lower branches of the living crown falls below a certain critical level for survival of the needles. However, this is no sudden process. At first only a few trees will be affected and the general green crown level will rise very slowly, much more slowly than the height of the stand. As more trees become involved, this rise will accelerate, until all gaps are filled and the canopy as a whole is one green mass of foliage using the available sunlight in the most effective way. This stage may be defined as full canopy closure and green crown level will be rising at the same rate as stand height, thus maintaining a constant maximum crown depth for a given stocking.

At the same time, the lower laterals will tend to curve upwards at their tips, as soon as neighbouring crowns start touching, and this will accentuate the increase in crown depth because crown depth is measured to the base of the green crown where the branches join the main stem and not to the underside of the green needles of the canopy.

This process of filling the gaps and adapting themselves to neighbouring trees may take several years and in a species like radiata pine, which is reputed to thin itself, the adaptation of crown depth to altered spacing may go on indefinitely. In Corsican pine, which is much less affected by mortality and in which height growth levels off towards much lower final values, crown depth may be expected to remain much more stable once full canopy closure has been reached. Recent work by Fairburn (1962) and Brown (1962b) on Corsican pine seems to confirm this point.

In older stands, which have been thinned, one would expect the same gradual process of stand closure to manifest itself, that is, after green crown level has started to rise again. However, the few successive measurements so far available from older thinned stands do not show a very pronounced increase, nor do the curves in Fig. 6, which tend to level out at greater heights for any given number of stems per acre. This shows that there must be other factors involved. One such factor is windsway. Rawlings (1961) describes the continual clashing together of neighbouring trees, which kills or injures side shoots and growing tips and causes attack by fungi. This natural side pruning tends to keep crowns narrow and leaves considerable gaps in the canopy so that more light will reach the lower levels.

This effect is particularly noticeable in tall radiata pine stands at close spacing. If more widely spaced, the trees grow sturdier, and their crowns will start touching at a lower level where branches are longer and give more readily to the movements of surrounding trees. Therefore, the older, more closely spaced stands will have comparatively deep crowns, almost as deep as more widely spaced stands of the same height. But it would also produce a gradual increase in crown depth as a stand of given stocking grows older and the effect of windsway becomes more and more noticeable, particularly so in the case of dense unthinned stands. In stands of lower stocking, however, or in older stands in which height growth starts to fall off, the effect would be less pronounced.

Consideration should also be given to the variations in leaf size and leaf structure with site and age. Trees tend to become less shade-tolerant as they grow older — the crowns become more open as a result of the smaller and more sparsely distributed light-needles, which let in more light to lower levels. Also, stands on favourable sites produce a denser canopy with a larger percentage of shade-needles; the species appears more shade-tolerant on such sites (Büsgen, *et al.*, 1929). Minor changes of the same nature occur on the same site with wet and dry years.

To a large extent, these variations are tied up with differences in uptake of water and mineral nutrients by the roots. In any stand, the roots can only support so much total crown area. If the site is being utilized to the same extent by two stands of different stocking, but of the same age, then, other conditions being equal, one may expect the same total crown area in both stands. It does not matter whether this canopy is supported by a few large diameter stems or by many smaller stems. However, with trees further apart the canopy would have to reach lower down to make up for the lower crown coverage in the top layer. Similarly, if windsway produces gaps in the canopy, this loss may be compensated for by retaining a deeper canopy.

It is very difficult, however, to make any deductions with regard to a possible change of crown depth with age. Though young stands are known to be more shade-tolerant and produce a denser canopy than older stands, there is no information on changes in crown depth. It could well be that the greater profusion of larger, shade-tolerant needles in young stands results in a shallower crown depth for any given stocking. In older stands the needles are smaller and more sparsely distributed. Yet the rate of uptake of water and nutrients by the roots must be equal to, or probably more than, that in a young stand. Thus, to retain the same effective leaf area, crown depth would have to be greater. This assumption would also explain why there is no change in crown depth in older stands after they have been thinned, and after crown level has started to rise again.

CONCLUSION

The present analysis seems to indicate that both site and stand height have to be taken into account when making predictions of crown depth for any given stocking under different thinning regimes. At the same time, it is clear that a great deal more data are required to perfect the trends indicated here for different localities.

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