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PREDICTION OF  
YIELD AND INCREMENT  
IN  
PINUS RADIATA STANDS  
IN NEW ZEALAND

BY

J. BEEKHUIS

FOREST RESEARCH INSTITUTE  
NEW ZEALAND FOREST SERVICE

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A. L. Poole, Director-General of Forests

NEW ZEALAND FOREST SERVICE  
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## SYNOPSIS

A method of yield prediction is presented which differs from the usual method in that all increments are plotted against height instead of age as the independent variable. Stand height, predominant mean height in this case, proved to be unaffected by thinning treatment and is preferred to age because it allows for the combined effect of age and site. Only at the final stage is the height for any given district or locality translated into age.

It was possible to develop a universal method for the prediction of gross basal area increment based on the increase in stand height between successive thinnings, and on the average height and net basal area of the stand during this interval. In conformity with this prediction method, the percentage of stems removed in thinning is converted to a percentage basal area cut, and the residual basal area thus derived is used to calculate the basal area before the next thinning. In this way one can predict the yield under a wide variety of thinning regimes instead of being restricted to a limited number of often vaguely defined thinning grades, as is the case with the more conventional method.

Volume predictions are based on a linear relationship between total stand volume per square foot of basal area and the height of the stand. This regression, which becomes linear from a stand height of about 35 ft upwards, proved to be largely unaffected by thinning treatment or locality, thus permitting the use of the same formula throughout. Total volume is converted to merchantable volume by applying a direct percentage reduction based on the mean diameter of the stand.

To predict the losses in stems per acre due to natural mortality under normal conditions, the average distance between trees is expressed as a percentage of stand height to indicate the degree of crowding. From observations in pure even-aged stands of other coniferous species it appears that, after a period of rapid decrease in young crops, this "relative spacing" tends to approach a minimum value which remains virtually unaltered with further development of the stand, indicating maximum density. Mortality trends for *P. radiata* are assumed to follow the same pattern.

It is shown how yields can be predicted step by step for a number of thinning regimes drawn up to show the effect of (a) maintaining a high or a low stocking per acre, (b) a few heavy thinnings at long intervals or many light thinnings at short intervals, and (c) widely spaced planting or close planting.

Finally, a combined stand table is drawn up for thinnings and for the stand immediately before thinning, showing the distribution of diameter about the mean and providing a means of deriving the mean diameter of the 100 largest stems per acre.

## INTRODUCTION

Yield tables drawn up for *Pinus radiata* in past years have been for unthinned stands only. Lewis (1954) published a yield table based on a series of alignment charts for predicting future height and future basal area from present height and present basal area, a separate index being used for each of these measures. The progress of mean stand diameter with age is predicted in

the same way. Total volume per acre can then be derived by multiplying future basal area by the volume per square foot of basal area at any future height, and merchantable volume is expressed as a percentage of total volume at any given mean diameter.

The present analysis of sample-plot data from thinned even-aged stands follows to some extent the same principles, in so far as future growth is predicted from present growth and local tables can be derived from these main trends. The main difference between the present analysis and that of Lewis is the plotting of growth trends against height rather than age, and the use of actual trends from successive measurements in the same plots instead of average trends superimposed on a scatter diagram. As Lewis pointed out, the prediction mechanism of his table could not be adequately checked at the time, because most of his data were derived from temporary plots. The only part that could be checked was the volume prediction for given height and given basal area and, in the case of merchantable volume, for given mean diameter.

Many permanent sample plots now have been remeasured several times since establishment and these measurements give a fairly good picture of actual growth trends during the greater part of the rotation. As stands reach maturity, these trends can be perfected. This paper summarises the present findings concerning the basic growth relationships, and the method of applying these findings to specific thinning regimes in a particular area.

# ORIGIN OF THE DATA

The analysis is based on data from permanent sample plots established from 1948 onwards in ordinary stands planted mostly at 6 × 6 ft and 8 × 8 ft spacings. Table 1 shows the distribution of plots by conservancies and by treatments.

TABLE 1: DISTRIBUTION OF PLOTS BY CONSERVANCIES AND TREATMENTS

Conservancy	Number of Plot Series	Number of Plots				
		Un-thinned Controls	Light Thinning	Medium Thinning	Heavy Thinning	Total
Auckland	7	6	6	9	5	26
Rotorua	9	8	9	11	9	37
Wellington	2	2	1	3	2	8
Nelson	3	3	3	3	2	11
Canterbury	7	6	5	6	6	23
Southland	5	3	5	4	3	15
Total	33	28	29	36	27	120

“Light thinning” refers to plots kept at a mean relative spacing\* of 18% or less, “medium thinning” from 19% to 22%, and “heavy thinning” 23% and over.

\* The term “relative spacing” is explained on p. 13.

The age classes covered by the measurements in these 33 series of plots are shown in table 2. It is clear that the bulk of the data are taken from stands between 10 and 25 years of age.

TABLE 2: AGE CLASSES COVERED BY SAMPLE PLOTS

Age Class	Percentage
0-5	0
6-10	13
11-15	33
16-20	30
21-25	17
26-30	7
Over 30	0
	<hr/>
	100

Individual plots have been measured over periods varying from three to 11 years, but the great majority have been measured for eight to nine years. In the past, plots were measured every three years and, more recently, every two years, giving an average of three or four measurements per plot. Admittedly this is a very short span for deriving satisfactory growth trends, but if the information from several plots is combined such trends become more dependable and may be extended over a longer period or a wider range of conditions with a fair amount of confidence. But more data are required from stands younger than 10 years and older than 25 years. The data for very young stands are especially important, because it is not yet possible to obtain a clear picture of the change from free growth before canopy closure to restricted growth after canopy closure; such data are essential for predicting growth up to the time when the first thinning falls due.

The procedure used in obtaining the sample-plot data has been uniform as regards diameter, basal area, and, to a lesser extent, height determination. Methods of volume estimation, however, have varied a great deal over the years and include the direct method based on felled sample trees, two-way volume tables, the volume line (i.e., sample tree volume plotted against sample tree basal area), and form-class volume tables. The use of punch cards has now enforced the reintroduction of the two-way volume table in formula form as a temporary measure. Before the change to punch cards, most of the earlier measurements were checked and recomputed by as uniform a method as possible throughout. It is difficult to say how closely these estimated volumes approach the actual volume, but the increments derived from them should be sufficiently accurate.

It should be noted also that the volumes used here are unadjusted volumes based on trees of normal form, i.e., trees to which ordinary volume tables apply.

## THE USE OF HEIGHT AS A BASIS FOR CORRELATING GROWTH TRENDS

The usual method of comparing the growth and yield from different plots is to plot height, diameter, basal area, etc., over age. In any subsequent analysis, this method requires grouping of the data in a number of rather vaguely defined site classes on the basis of height. Height growth in a given locality does not necessarily conform to the trend adopted for such site classes, but will often cross over from one site class to the next. Thus height curves from different localities will not harmonise in trend as they are supposed to do under the site-class concept.

The solution to this problem is to plot all trends over height and to leave the translation from height to age to the very last, thus allowing the use of the local height-over-age curve for a given forest site or region in preparing the final yield table.

The advantage of height as a basis for the study of growth trends and for yield-table construction is not only that it tends to allow for the effect of site, but also that most other growth factors for a given stand density seem to be directly correlated with height.

The mean height of the stand is not a suitable measure for this purpose because this measure is itself affected by changes in stand density. Stands that suffer severe natural mortality in the lower crown classes, or in which these classes are removed by thinning will have a greater mean height than stands that remain dense. Yet the upper level of the canopy, composed of dominants and codominants, may be the same in both stands. The increase in mean height cannot be identified with the actual height growth of a given number of trees or a definite section of the stand. Low thinning itself causes a computational rise in mean height, so mean height becomes a rather artificial value.

A more appropriate height measure is one based on the larger, more dominant trees in the stand. Both the mean height of the 100 largest-diameter stems per acre (mean top height) and the arithmetic mean height of the 40 tallest trees per acre, selected one in each  $\frac{1}{40}$  acre (predominant mean height), have this advantage. The former is still a computed value derived through basal area, but as it is based on the largest-diameter trees it remains practically unaffected by thinning. A disadvantage is that it has to be read from the height-d.b.h. curve, which in general is very ill defined and subjective. It is no exaggeration to say that height-d.b.h. curves have in past years been one of the biggest stumbling blocks in sample-plot work, needing endless adjustment. A further disadvantage of mean top height is that, by definition, it cannot be determined in stands of less than 100 stems per acre. Moreover, if instead of selecting the 100 largest stems per 1.00 acre we select, say, the 25 largest per 0.25 acre, there is less chance of including exceptionally large trees, growing either singly or in clumps; the mean diameter so determined will therefore be slightly lower than the diameter determined on a full acre.

These difficulties are overcome by using predominant mean height, a measure first advocated by Hart (1928). In practice very few stands will ever be reduced to a stocking of less than 40 stems per acre, and the selection of one tree from



every  $\frac{1}{40}$  acre ensures an even distribution. Also, the same procedure can be used on both large and small areas, and no diameter classification or height-diameter curve is required for its determination, the height being the arithmetic mean of the trees as measured. For this reason it was decided to use this height measure rather than mean top height as a basis for growth correlation. (The determination of predominant mean height as a basis for preparing height-over-age curves is dealt with in the Appendix.)

To allow for conversion of predominant mean height to mean top height, the two measures were plotted one against the other for all available data. It was found that the two height measures did not differ markedly. The linear regression equation derived from this correlation can be written as:

$$\text{Predominant mean height} = 0.673 + 1.013 \times \text{mean top height}$$

This gives a difference of:

1.3 ft at 50 ft mean top height

2.0 ft at 100 ft mean top height

2.6 ft at 150 ft mean top height

Thus the differences are of little practical importance; for most purposes predominant mean height\* may be considered synonymous with mean top height.

## THE EFFECT OF THINNING ON HEIGHT GROWTH

Since site has a major effect on height growth, it is not possible to combine plots that have undergone the same treatment in order to compare their average height growth with that of plots of a different treatment or with that of unthinned controls.

To overcome this difficulty all light thinning grades, i.e., 18% mean relative spacing and under, were compared with their respective control plots in the same series and the differences in height plotted as plus or minus deviations from a common zero-deviation line, height of the control plot being used as the independent variable. The same procedure was followed for the medium grades of 19% to 22% mean relative spacing, and for the heavy grades of 23% relative spacing and over.

Examination of the graph (fig. 1) shows an even scatter of points for all three groups about the zero-deviation line, and it would appear that, within the limits of the data, thinning has no effect on the height of the stand or, more precisely, no effect of any practical significance. It will be seen that the scatter about the zero line increases in direct proportion to the height of the stand. This would seem a logical consequence of slight differences in site at the time of establishment between plots in the same series. Any difference in height at establishment would increase steadily over the years; the same would be true of diameter and other stand measures. It demonstrates the shortcomings of age as a basis for comparison in growth studies. By using height instead of

\*In the remainder of this paper, predominant mean height will simply be referred to as stand height.

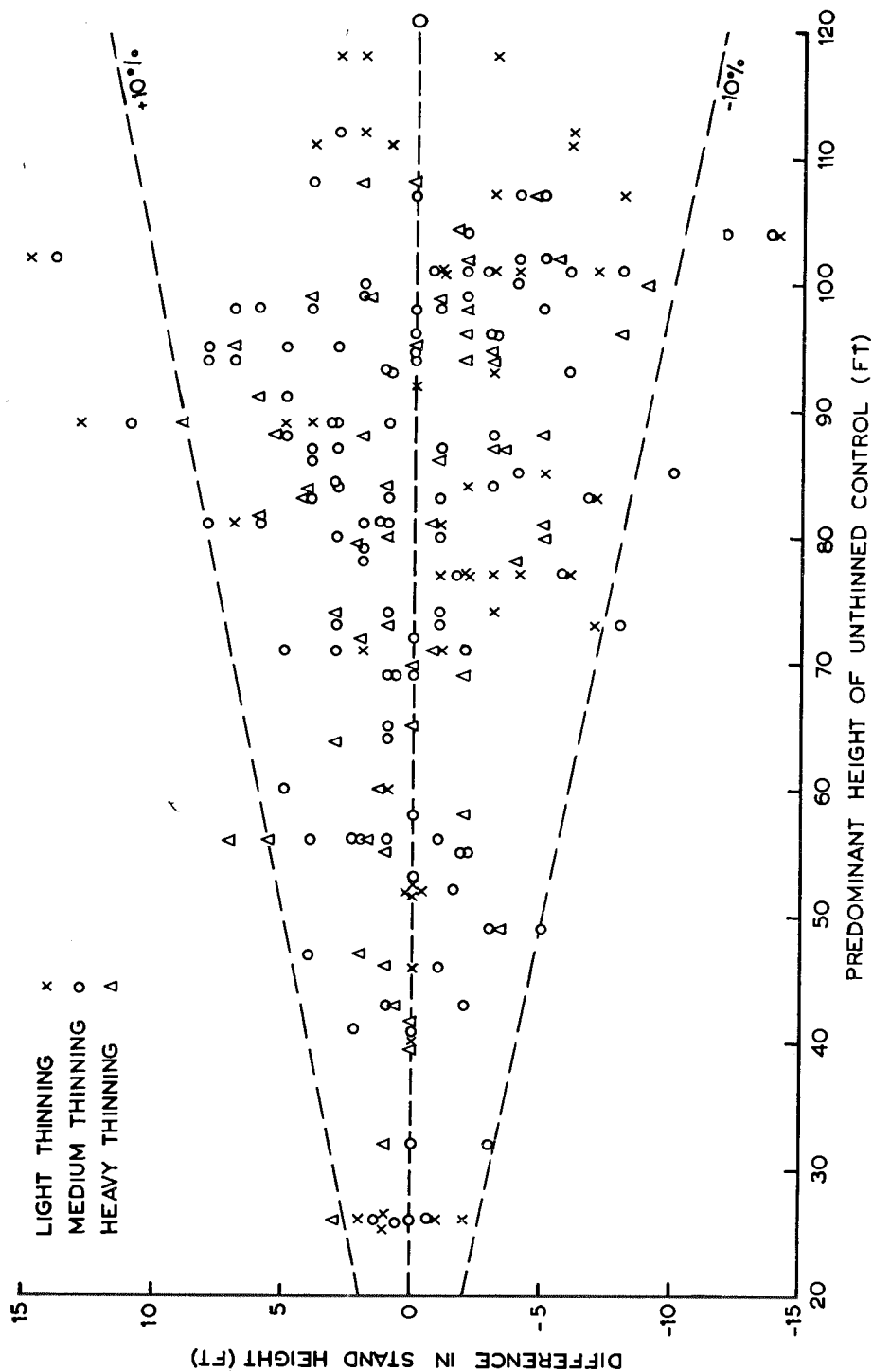


Fig. 1. Height differences between thinned and unthinned stands of the same series.

age one allows for these differences and, as will be shown, most other measures commonly used in describing the growth of a stand can be correlated with height growth. It would seem that this approach will largely overcome the difficulties encountered in establishing the effect of a particular treatment in plots that show slight differences in site, either at establishment or in later years.

In the three different grades of thinning studied here, the differences in height show a scatter within 10% of the control-plot height for all but a few plottings. In other words, at 30 ft stand height one could expect a maximum difference of  $\pm 3$  ft; at 60 ft height this would increase to  $\pm 6$  ft, and so on. Of course it should be realised that this does not represent the true maximum difference, since it incorporates the percentage error (maximum in this case) involved in height measurement.

The finding that thinning treatment has no marked effect on height growth cannot be extended to include the extreme cases. For instance, in dense fire-regenerated stands in the Taupo region it was found that in the untreated controls (which were extremely dense, carrying 2,000–4,000 stems per acre at 13 years) heights were definitely lower than in the thinned plots. This presumably shows the harmful effect of continuous stagnation in the unthinned stands. (Initial density, assessed at three years of age, was close to 1,000,000 s.p.a.!) In contrast with this, stands planted at very wide spacing (10 ft or more) will often be less tall than stands planted at close spacing. But this is before the stagnation effect makes itself felt in the closer spacings. The differences are generally small, and are probably connected with the fact that trees at closer spacings soon shelter one another from wind. They seem to disappear as the wider spacings close canopy, possibly as a result of gradual stagnation setting in in the closer spacings, and competition for dominance making itself felt in the wider spacings. Thus optimum height would be found in progressively wider spacings. In *Pinus radiata* stands, mortality will no doubt tend to upset these trends; Corsican pine would probably be a better species for a study of such relationships.

#### THE EFFECT OF THINNING ON BASAL AREA INCREMENT

Spurr (1962) has shown the great value of gross basal area as a basis for assessing maximum productivity of a given site and for making a true comparison between thinned and unthinned stands. Similarly Møller (1954) has shown the surprising uniformity of all types of thinning in terms of total basal area and total volume produced. Since he refers to European practice, which would normally allow very little growth to be lost as a result of mortality between thinnings, Møller's finding is really no different from Spurr's.

Basal area is no doubt the most accurate single measure of stand growth used in volume estimation and yield production. To obtain gross basal area increment over a period of years, it is necessary to include the basal area of stems which have died during that period. With this object in mind, an accurate record has been kept of all mortality losses in sample plots from 1956

onwards. Before that date the records of dead trees are not always reliable, and in the first measurement, at plot establishment, there are none at all. Further, many of the earlier plots were established at a fairly late stage in stand development, when the accumulated losses due to mortality must have been considerable. This means that it is not possible to fix upon a reliable starting point for the cumulative gross basal area curve.

To overcome this difficulty, the gross basal area increment during a given measurement period was expressed as the increment per 10 ft height increase of the stand. For instance, if basal area in a certain period increased from 85 sq. ft. to 126 sq. ft. per acre with a mortality loss of 4 sq. ft., while height increased from 58 ft to 73 ft, then the gross basal area increment was 45 sq. ft. for a 15 ft increase in height, or  $45 \times 10/15 = 30$  sq. ft. for every 10 ft increase in stand height. Next, this increase was plotted on a graph showing basal area along the vertical axis and height along the horizontal. From the point corresponding to the net basal area and height for the middle of the growth period, a line was drawn representing the increase in gross basal area over a 10 ft height interval, 5 ft to each side of this point. Thus, for instance, the 30 sq. ft. increase in the above example would be plotted with its centre at a point indicating a net basal area of 105.5 sq. ft. and a height of 65.5 ft. One can thus produce a set of gross basal area trends covering various combinations of stand basal area and height. These are the two measures one would expect to have most effect on basal area increment, the first because it is a measure of the stem area on which the increment is produced and accumulates; the second because it incorporates the effect of age, which could have an effect on basal area increment different from its effect on height growth.

Gross basal area increment, plotted in this way against net stand basal area and height at the middle of the growth period, gave a series of almost parallel linear trends for both thinned stands and controls. Nor were there any notable differences between the data from the various conservancies. However, close examination of these trends, especially where the data cover a wide range, shows a slight but consistent decrease in increment with increasing height for the same basal area, or with decreasing basal area for the same height. On the whole, the trends were found to radiate from a common centre, which may be set at a point well outside the graph (at height — 50 ft, basal area — 270 sq. ft.). With a ruler held against this point one can make an accurate prediction of gross basal area increment within the range covered by the data, i.e., for stands between 35 ft and 110 ft stand height derived from  $6 \times 6$  ft and  $8 \times 8$  ft spacing. These trends may be represented in a single graph, as shown in fig. 2.

It is difficult to say down to what basal areas these trends are valid, but as a rough guide they should not be relied upon if the basal area in square feet is less than the height of the stand in feet. For example, a stand 60 ft in height should have a basal area of 60 sq. ft. or more, a stand 100 ft in height should have a basal area of 100 sq. ft. or more, and so on. This corresponds roughly with the basal area left after the most drastic thinnings carried out in the sample plots included in this study. At basal areas below these limits (indicated by the broken lines) the trends are not reliable and would no doubt give over-estimates if stands were seriously understocked for long periods.

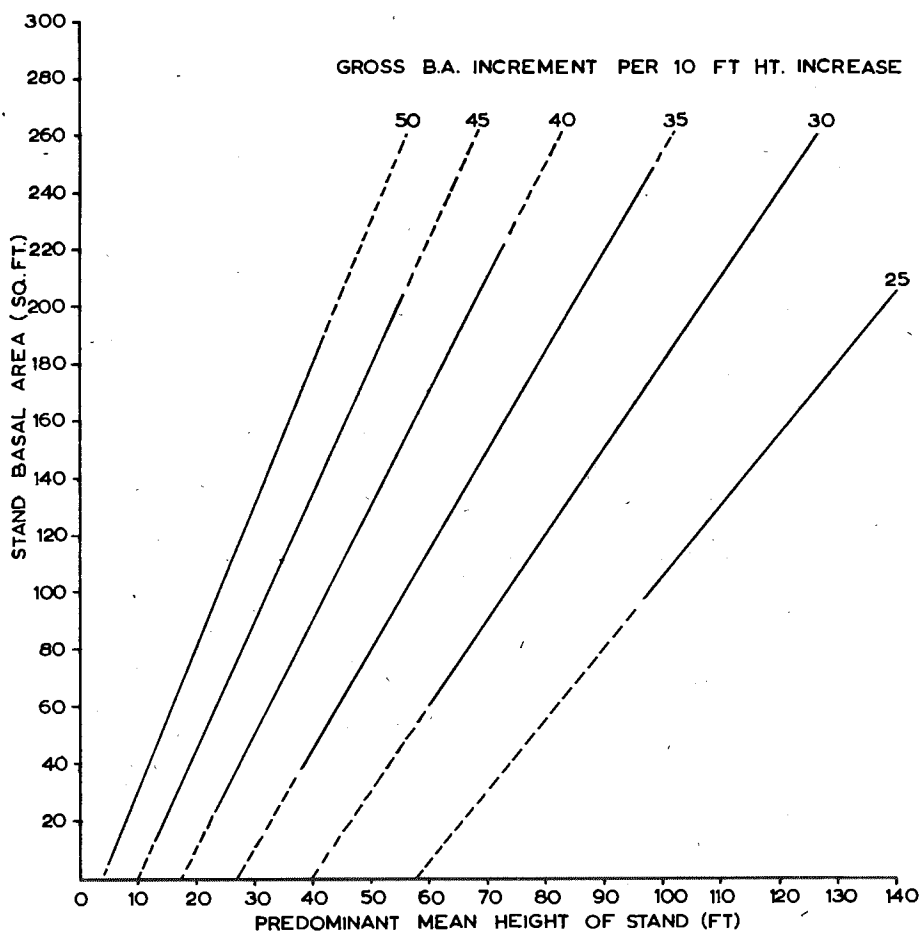


Fig. 2. Gross basal area increment at given stand height and stand basal area.

At the other extreme, where we are dealing with stands of high basal area and greater height, there does not appear to be any limit. For instance, in some Southland plots with basal areas reaching 360 sq. ft. or even 400 sq. ft. at heights of 100 ft and over, the gross basal area increment still conformed to these trends. In most localities, of course, net basal area increment approaches zero at this point or even at much lower basal areas. But normally the basal area in thinned stands will be kept below 200 sq. ft., so that losses due to mortality should be negligible. Of all the thinned plots included in this study, only 20 had basal areas rising above 200 sq. ft., and of these only three, in Southland, which did not receive first thinning until stand height had reached 70 ft or more, had basal areas exceeding 220 sq. ft.

Fig. 2 may therefore be used with some confidence in predicting the progress of net basal area in thinned stands in normal years, i.e., in the absence of droughts, floods, insect epidemics, and similar unusual conditions. To derive trends intermediate between those shown in fig. 2, the graph may be pasted

on a larger sheet of paper with the pivot centre (height — 50 ft, basal area — 270 sq. ft.) marked.

Another way of obtaining the increment is to use the following formula:

$$I_b = I_h \times (B + 270)/(H + 50) \quad \frac{\Delta B}{\Delta H} = \frac{B + 62.0}{H + 15.2} \quad (\text{metric})$$

where  $I_b$  = increment in stand basal area  
 $I_h$  = increment in stand height (i.e., predominant mean height)  
 $B$  = basal area at beginning of period  
 $H$  = stand height at beginning of period.

This formula shows that the higher the basal area at any given height, the higher the basal area increment. For instance, if a stand is thinned to a basal area of 90 sq. ft. at 40 ft height, the basal area increment per 10 ft increase in stand height works out thus:

$$I_b = 10 \times (90 + 270)/(40 + 50) \text{ sq. ft.} = 40 \text{ sq. ft.}$$

If instead the basal area is reduced to 45 sq. ft. at 40 ft height, the increment works out at 35 sq. ft., or 12½% lower. It should be noted, however, that the basal area increment derived here is gross increment, and that allowance has to be made for mortality, especially where stand basal areas are kept at a high level. To reap the benefit of greater increments at higher basal areas requires frequent thinning to offset mortality losses.

Little can be said regarding the continuation of these trends beyond the range of the present data, that is, at heights of 110 ft and over. Wherever vigorous height growth is maintained up to the end of the rotation, trends may be expected to deviate little from those indicated here. But if the rotation is extended to a point at which height growth diminishes rapidly while diameter growth continues at a comparatively fast rate, then gross basal area trends may be expected to rise sharply; in other words extrapolation of the present trends would cause an underestimate towards the end of the rotation. This would call for an adjustment depending on the height development in a given locality towards the end of the rotation.

## NORMAL MORTALITY TRENDS

To gain some idea of the mortality which may be expected in various areas, the losses in basal area increment between measurements were expressed per 10 ft increase in stand height and were plotted against the basal area and height at the middle of the growth period, by the method used for calculating gross basal area increment. These graphs did not permit any definite conclusions to be drawn. As was to be expected, the highest mortality rates occurred in some of the plots in the pumice region soon after *Sirex noctilio* became established. Hinds (1955) states that, before the appearance of *Sirex*, stands of the 21–25-year age class in these areas carried basal areas of more than 250 sq. ft. per acre, whereas after 1950, by which time the insect had become well established, basal areas in stands of this age had fallen to about 200 sq. ft. In recent years, however, basal areas in these regions have been rising again to very high levels, reaching 400 sq. ft. in some 50-year-old stands (Rotorua Conservancy reports on Kaingaroa mortality plots). It is possible that, now that there are parasites to control *Sirex*, mortality will never again be as severe

as in the initial outbreak. It is largely because of these sudden and very local outbreaks of *Sirex* and other pests that it is impossible to obtain meaningful trends. Some plots suffered severe mortality in years and localities when and where pests were prevalent; others escaped. One simply cannot allow for these spasmodic outbreaks.

If we confine ourselves to the study of mortality under average climatic conditions and in the absence of insect epidemics, etc., we can obtain more definite trends. Probably the most promising method for study of such trends is the use of relative spacing as a measure of density (see Hart, 1928). Relative spacing refers to the average distance between trees expressed as a percentage of the predominant mean height of the stand, or:

$$S_r = 100S/H \text{ per cent}$$

where  $S_r$  = relative spacing  
 $S$  = triangular spacing  
 $= 1.074 \times \text{square spacing}$   
 $H$  = predominant mean height.

The higher the stocking at a given height, the lower is the relative spacing. If stocking remains constant while height increases, relative spacing decreases. But soon after canopy closure, some trees will die, and as crowding becomes more and more acute through the years with increase in tree size, the mortality rate will increase until the stand approaches a maximum density or, to express it in another way, a minimum relative spacing. With further height growth this minimum value tends to remain unaltered. This fact was first observed by Ferguson (1950), who found that unthinned even-aged stands of *Pinus merkusii* in Indonesia attained a minimum relative spacing of about 19%, and that mortality first became noticeable at a relative spacing of about 30%. This tendency is also very marked in the oldest unthinned sample plots in *P. ponderosa* and *P. strobus* at Waitapu Forest, details of which follow:

*P.S. Plot R. 7, P. ponderosa.* Planted 1903 at 4 × 4 ft spacing. From 1928 (top height 55 ft) until the last measurement in 1963 (top height 120 ft), i.e., for 35 years, the relative spacing of the stand remained virtually unaltered at 12% (min. 11.3, max. 12.5). During this period stocking decreased from 1,328 to 228 stems per acre.

*P.S. Plot R. 8, P. ponderosa.* Planted 1903 at 4 × 4 ft spacing. From 1925 (top height 50 ft) until 1959 (top height 121 ft), i.e., for 34 years, the relative spacing of this stand remained at about 12% (min. 11.2, max. 13.1). During this time stocking decreased from 1,436 to 208 stems per acre.

*P.S. Plot R. 6, P. strobus.* Planted in 1905 at 4 × 4 ft. From 1937 (top height 65 ft) until the last measurement in 1962 (top height 102 ft), i.e., for the last 25 years, the relative spacing remained virtually unchanged at 8% (min. 7.6, max. 8.8). During this time stocking fell from 1,540 to 720 stems per acre.

These percentages seem to be characteristic of each species and locality, and it is unlikely that *Pinus radiata* would form an exception to these findings. Unfortunately, none of the plots included in this study have yet reached the stage at which they maintain a constant maximum density, but as far as can be judged the trends point to a minimum relative spacing somewhere between 10% and 12%. A tentative average value for the whole country would be 11%.

Mortality seems to show up first when relative spacing has fallen to about 30%, as in the case of *P. merkusii*. From these two percentages one can now derive a set of mortality trends such as that shown in fig. 3. (The lines shown in this graph for 16%, 19%, and 22% relative spacing will be discussed in a later section.)

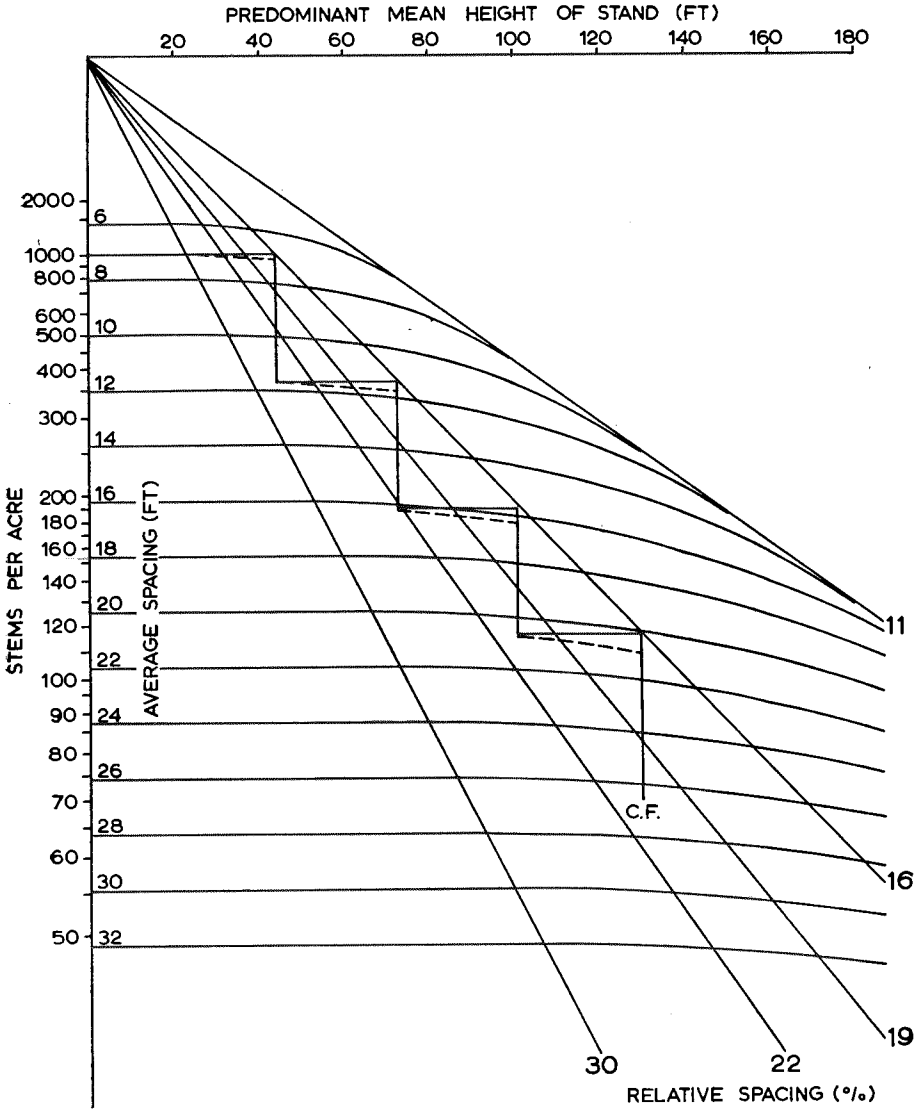


Fig. 3. Normal mortality trends. C.F. = clear felling.



The following example illustrates the use of this graph. Assuming that after planting and blanking one is left with a stocking of 800 stems per acre, then mortality will start when stand density reaches a relative spacing of 30% at a height of about 26 ft. By the time stand height has reached 60 ft, stocking will have fallen to just under 700 stems per acre, at 76 ft height to 600 stems per acre, and so on. At about 100 ft height the stand will have reached maximum density and from then on the lowering in stocking can be read directly from the 11% line.

With an initial stocking of 500 stems per acre, mortality would first appear at stand height 33 ft and maximum density would be reached at about 125 ft. Thus the graph makes it possible to decide when a stand should be thinned to prevent severe mortality, and how many stems per acre should be left to prevent severe mortality before the next thinning.

It must be stressed again that this graph shows mortality under normal conditions, and that relative spacing expresses stand density in terms of height, not age. If age is used, one gets the impression that stands on the better sites show higher mortality, because of their greater heights at the same age. Also, it should be noted that these mortality trends refer to stands planted at  $6 \times 6$  ft and  $8 \times 8$  ft. There are indications that stands resulting from dense natural regeneration after fire or after clear felling will close up to a lower relative spacing than 11% if left unthinned. This is probably a result of the greater variation in tree size. Many of the smaller trees can be classed as "non-effective", in that they have little or no effect on the development of the stand.

To allow for the conversion of normal mortality losses in terms of stems per acre to losses expressed in square feet of basal area per acre, an analysis was made of all losses recorded in past measurements, i.e., at regular intervals of two or three years. To express the relationship between the stems-per-acre loss and the corresponding basal area loss, several variables were tested, such as height and diameter of stand at the beginning of the period, mean diameter in combination with relative spacing, and square of mean diameter. It was found that the last gave the best estimate. The formula derived was:

$$B = 0.004158 D^2 N \pm 0.000270 \text{ (5\% probability level)}$$

where B = basal area loss in square feet per acre

D = mean d.b.h. of stand at beginning of period in inches

N = losses in stems per acre.

Fig. 4 is an alignment chart based on this formula.

$$\frac{\Delta B}{B} \approx 0.7624 \frac{\Delta N}{N} \text{ (metric)}$$

To estimate the basal area loss over a period of more than three years or over an increase in stand height of, say, 12 ft or more, it would be necessary to work in short stages, each time computing the gross basal area increment and subtracting the mortality losses to arrive at the stocking, basal area, and mean diameter of the stand at the beginning of the next period. The most suitable period to choose would be one representing an increase of 10 ft in stand height. For less detailed estimation, or where mortality losses are expected to be very low, it may suffice to raise the mean diameter at the beginning of the period slightly to allow for a period with an increase in stand height of more than 12 ft.

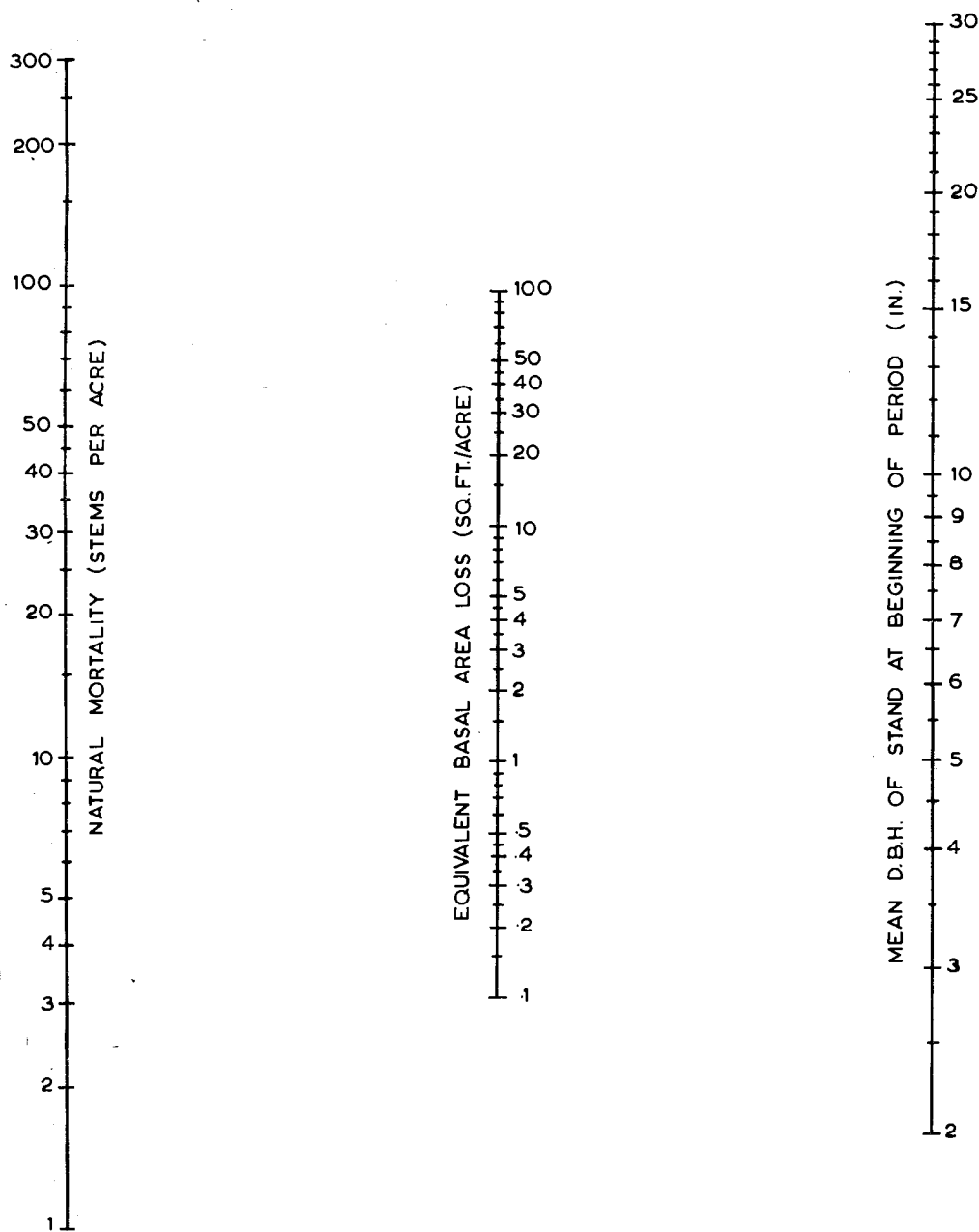


Fig. 4. Alignment chart for reading the basal area loss in square feet per acre corresponding to a given stems-per-acre loss in a stand of given mean diameter.

## TOTAL VOLUME PER SQUARE FOOT OF BASAL AREA IN THINNED STANDS AS A FUNCTION OF PREDOMINANT MEAN HEIGHT

Lewis (1954), in producing his yield data for unthinned stands, divided his total volume per plot by the basal area and plotted the resulting value, which represents the volume per square foot of basal area, over mean top height of the stand. The points thus plotted produced an almost perfect straight line. Lewis makes no reference to this rather surprising fact, beyond stating that "It appears that the stand volume table (i.e., the direct relation between mean top height and the volume per square foot of basal area as derived from the graph) will give satisfactory results in varying conditions of site, density, and age throughout the country". Though the deviations from a straight line are minute, Lewis makes no attempt to pass a straight line through his plottings, but uses a very weak S-shaped curve.

On fitting a straight line to his plottings as shown on this graph, one derives the relationship:

$$V/B = 3 + 0.3H$$

where V = total stem volume per acre in cubic feet

B = basal area per acre in square feet

H = mean top height in feet.

Cromer (1961) finds a similar straight-line relationship over mean top height for *Pinus radiata* stands in Australia. He also gives a regression coefficient of 0.3, but his regression passes through the origin in most cases. He remarks that this relationship holds for all regions and for different densities. It is of interest to record that the same relationship applies to the growth of single trees. A number of predominants felled at Kaingaroa some years ago for stem analysis show a perfect linear trend when total volume i.b. per square foot of basal area i.b. is plotted over total height. Below a height of 35 ft, the line curves steeply upwards to reach infinity at 4 ft 6 in. height, as a result of basal area becoming zero while volume is still greater than zero. The same upward trend occurs in plotting the volume per square foot of basal area for all trees in a stand, which follows logically from the above result for single trees.

To find out whether thinning has any effect on this relationship between the volume per square foot of basal area and stand height, the grades of thinning were grouped as before into light, medium, and heavy thinnings. For each conservancy and for each of the above groups a graph was prepared, before-thinning volumes and before-thinning basal areas being used throughout. This gave three graphs for thinned stands and one for control plots in each conservancy. It was found that wherever sufficient data were available, the regressions for controls, light thinnings, medium thinnings, and heavy thinnings in the same conservancy were almost identical. Thus the Rotorua data, processed by the least-square method, gave the following regressions:

Controls	$V/B = 3.40 + 0.30H$
Light thinnings	$V/B = 3.25 + 0.30H$
Medium thinnings	$V/B = 2.69 + 0.31H$
Heavy thinnings	$V/B = 2.97 + 0.30H$
All plots combined	$V/B = 3.20 + 0.30H$

where V = total volume per acre in cubic feet

B = basal area per acre in square feet

H = predominant mean height in feet.

A similar overlapping of trends for the different treatments was obtained for the other conservancies, and it can only be concluded that differences in stand density, either natural or artificial, have no effect on the relationship. When all plottings for a conservancy were combined, irrespective of treatment, the following regressions were computed, the standard error of the estimate being shown in parentheses:

Auckland	$V/B = 3.67 + 0.30H (\pm 1.1)$
Rotorua	$V/B = 3.20 + 0.30H (\pm 2.0)$
Wellington and Nelson	$V/B = 2.36 + 0.32H (\pm 2.3)$
Canterbury	$V/B = 1.51 + 0.31H (\pm 1.0)$
Southland	$V/B = 3.72 + 0.30H (\pm 1.0)$

The similarity of these regressions shows that there is also a very close correspondence between conservancies. It is unlikely that the slight differences in trend shown here are of any real significance, since the data cover a very narrow range except in Auckland and Rotorua. In the absence of more data to prove that such differences are real, it would seem sufficiently accurate to adopt the same regression for all data combined, which for simplicity may be written as  $V/B = 3 + 0.3H$ . A more detailed statistical test embracing all conservancies will be carried out when more data are available.

Additional data from spacing trials at Kaingaroa and Rotoehu Forests were examined and were found to fit in well with this formula. It was suspected that the agreement between stands of different density was due in some measure to the application of the same volume tables, so a further test was carried out. An 18-year-old fire-regenerated stand at Waitapu Forest was selected, part of which had received drastic early thinning. Accurate sectional measurement of 23 sample trees in the thinned stand and 30 in the unthinned stand gave the data shown in table 3.

TABLE 3: DATA FROM 18-YEAR-OLD NATURAL REGENERATION IN  
WAITAPU FOREST

	Thinned Stand	Unthinned Stand
Stems per acre	174	670
Basal area per acre (sq. ft.)	161	171
Mean d.b.h. (in.)	13.0	6.8
Mean top height (ft)	94	88
Mean top d.b.h. (in.)	14.8	11.5
Total stem volume per acre (cu. ft.)	5,320	5,354
Total vol./b.a. (cu. ft.)	33.0	31.3
$V/B = 3 + 0.3H$	31.2	29.4
Difference	1.8	1.9

As can be seen, the volume per square foot of basal area estimated from the formula in both cases is slightly lower than the actual, but the plottings for the two stands are parallel to the regression line, which seems to indicate that there is no basic difference between the two stands, but only a difference due to the method of volume estimation or to the use of mean top height instead of predominant mean height.

It may be of interest here to mention that it had been intended to apply Gray's taper-line method in determining the volumes of the sample trees. However, the stem profiles obtained by plotting sectional area under bark against height above ground were seldom straight over any great length, and the method was not considered sufficiently accurate for the purpose. In almost all cases there was a sudden change in stem taper from the base of the green crown upwards. It would appear from this that the average green-crown level in a stand might be a useful measure to incorporate in normal two-way stand-volume tables, thus producing a form-class tariff table. If crown level can be related in a satisfactory way to stand density and stand height, it would not even be necessary to measure green-crown level for this purpose. Average crown level would be a great deal simpler to measure than a variable such as the diameter at half height used in present form-class volume tables.

It has been pointed out that the formula  $V/B = 3 + 0.3H$  was derived from measurements taken before thinning. After thinning there is a slight rise in the volume per square foot of basal area because of the greater average height of the trees left, while for the trees taken out in thinning this volume is lower. When the total volume per square foot of basal area of the thinnings was plotted against the total volume per square foot of basal area of the stand before thinning, it was found that for most thinnings the difference can be taken at  $2\frac{1}{2}\%$ , i.e.:

$$V/B \text{ for thinnings} = 0.975 \times V/B \text{ for stand before thinning}$$

#### DERIVATION OF RESIDUAL BASAL AREA AFTER THINNING FROM THE PERCENTAGE OF STEMS REMOVED IN THINNING

Because thinning regimes are generally expressed in terms of stems per acre instead of basal area, it becomes necessary to convert such specifications into basal area. Various methods may be used to determine the percentage of basal area removed for any percentage of stems removed in thinning. One can never expect a very precise answer to this question, because the relationship between these two measures varies with type of thinning, the person marking the thinning, amount of malformation, size-class distribution, risk of wind damage (in so far as it affects the type of thinning), and so on. As far as the data in this study are concerned, the analysis has been confined to low thinning in stands planted originally at  $6 \times 6$  ft and  $8 \times 8$  ft. Since in low thinning one aims at removing the lower crown classes and retaining the trees of better form in the upper crown classes, the percentage of basal area removed is always less than the percentage of stems removed. As the percentage of stems cut out approaches 100, the percentage of basal area cut also approaches 100. Similarly

at the other extreme, as the percentage of stems removed approaches 0, the percentage of basal area removed also approaches 0. This gives two fixed points to be used in plotting the curvilinear trend of one percentage against the other.

The method which gave the best correlation was to group all thinnings into three categories, viz, first thinnings, second thinnings, and third and later thinnings. Next, these thinnings were grouped according to the height of the stand when thinned. The height classes used were 26-50 ft, 51-75 ft, and 76 ft and over.

Average trends fitted to the data in each group gave the percentages shown in table 4. These percentages are a fairly close approximation to the actual data except perhaps those for first thinnings in the 26-50 ft height class. Further work is being done to discover better means of conversion.

TABLE 4: PERCENTAGE OF BASAL AREA REMOVED IN THINNING

Percentage s.p.a. Cut $p_B \approx 1 - (1 - p_n)^c$	Predominant Mean Height of Stand in Feet				
	26-50 ft	51-75 ft		76 ft and Over	
	1st Thinning Only	1st Thinning	2nd and Later	2nd Thinning	3rd and Later
20	..	..	13	13	14
25	..	13	17	16	18
30	22	17	22	20	22
35	26	20	26	24	27
40	30	24	31	28	32
45	35	29	36	33	37
50	39	34	41	39	42
55	44	39	47	44	47
60	49	45	52	49	(52)
65	54	51	(58)	(55)	(58)
70	60	(58)	(63)	(61)	..
75	66	(64)	..	..	..
80	72	..	..	..	..

Figures in parentheses were obtained by extrapolation.

### DIRECT ESTIMATION OF VOLUME INCREMENT

With gross basal area increment given by the formula:

$$I_b = I_n(B + 270)/(H + 50),$$

and the volume per square foot basal area by:

$$V/B = 3 + 0.3H,$$

it is possible to derive a formula for the gross volume increment over any given period in terms of the volume and stand height at the beginning of the period and the increase in stand height during that period.

If  $f = V/B$  at stand height  $H$  at the beginning of the period,  
 $f' = V'/B'$  at stand height  $H'$  at the end of the period,  
 $I_h = H' - H$  = the increase in stand height over the period,  
 $I_b = B' - B$  = the increase in basal area over the period,  
 $I_v = V' - V$  = the increase in total volume over the period,  
then  $I_v = f'B' - fB$

$$= f'(B' - B) + B(f' - f)$$

$$= f'I_b + B(f' - f).$$

$$\text{Now } f' = 3 + 0.3H'$$

$$= 3 + 0.3(H + I_h), \text{ while from } V/B = 3 + 0.3H \text{ we derive}$$

$$B = 10V/3(H + 10). \text{ This value, substituted in the formula}$$

$$I_b = I_h(B + 270)/(H + 50), \text{ gives:}$$

$$I_b = I_h[10V + 3 \times 270(H + 10)]/3(H + 10)(H + 50).$$

$$\text{Finally: } f' - f = (3 + 0.3H') - (3 + 0.3H)$$

$$= 0.3(H' - H)$$

$$= 0.3I_h$$

Substituting these values for  $f'$ ,  $I_b$ ,  $B$ , and  $f' - f$  in the above formula for  $I_v$ , one derives:

$$I_v = \frac{[3 + 0.3(H + I_h)] \times I_h(10V + 810H + 8,100)}{3(H + 10)(H + 50)} + \frac{V \times I_h}{H + 10}$$

which can be simplified to:

$$I_v = I_h[V(2H + I_h + 60)/(H + 10)(H + 50) + 81(H + I_h + 10)/(H + 50)]$$

For example, if a stand is thinned at a height of 40 ft, leaving 1,000 cu. ft. total volume per acre, and it is intended to carry out a second thinning at a stand height of 70 ft, then:

$$I_v = 30[1,000(80 + 30 + 60)/(50 \times 90) + 81(40 + 30 + 10)/90]$$

$$= 3,293 \text{ cu. ft.,}$$

so that the total volume of the stand will have reached 4,293 cu. ft. at height 70 ft, provided that no mortality has occurred during this period.

It will be seen from the formula that, for any given initial volume and height, the volume increment for a given period is not directly proportional to the height increase during that period. Thus in the foregoing example, one cannot conclude that if height increased by 15 ft instead of 30 ft the volume would increase by  $3,293 \div 2 = 1,647$  cu. ft., producing a total volume of 2,647 cu. ft. at a stand height of 55 ft. The correct calculation gives a total volume of 2,394 cu. ft.

## CONVERSION OF TOTAL STEM VOLUME TO MERCHANTABLE VOLUME

The best means of converting total volume to merchantable volume proved to be the method followed by Lewis, who used mean diameter of the stand as the independent variable and plotted merchantable volume as a percentage of total volume. Separate graphs were plotted for control plots, light-thinning plots, medium-thinning plots, and heavy-thinning plots. In each case exactly

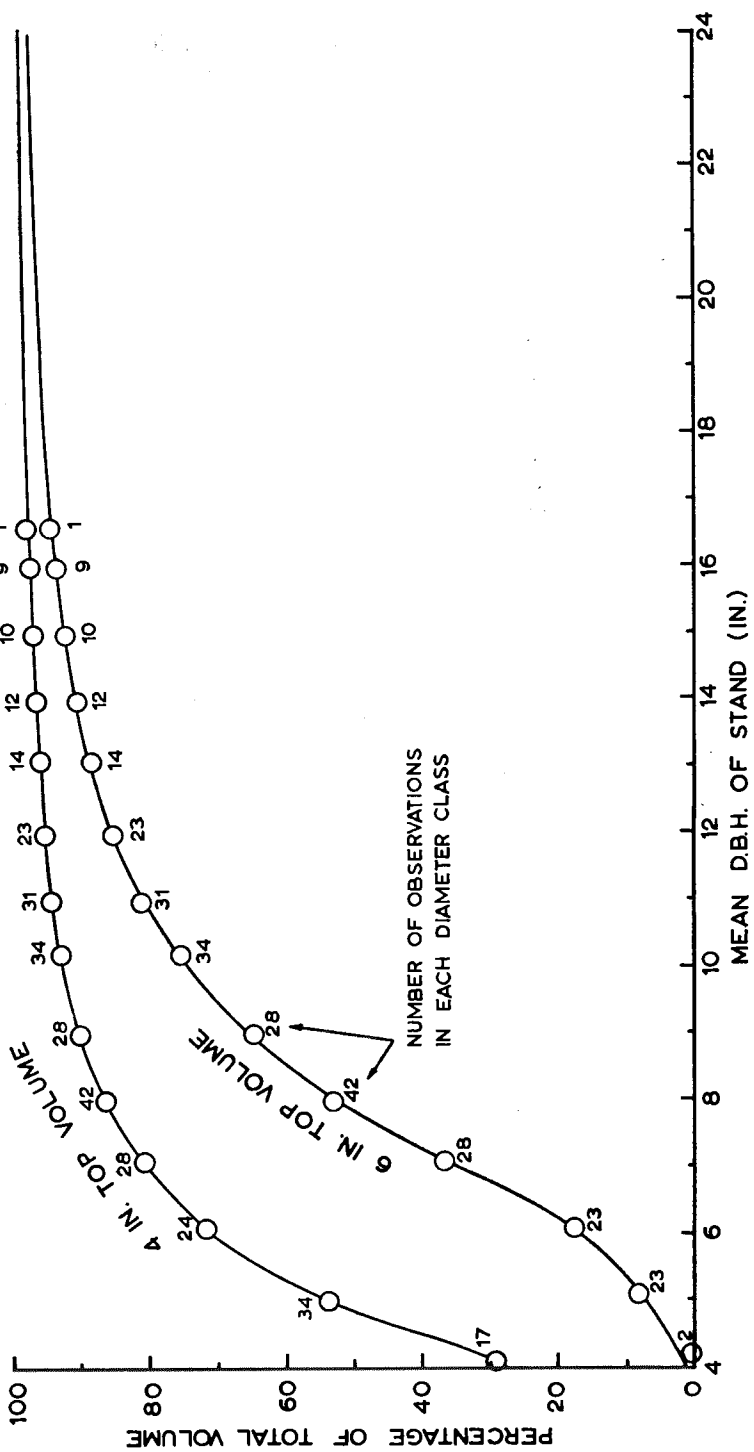


Fig. 5. Stand volume to 4 in. and 6 in. top diameter i.b. as percentages of total stand volume i.b.



the same regression resulted, showing that thinning has no effect whatsoever on this relationship apart from the effect incorporated in the mean diameter of the stand. Fig. 5 and table 5 show the 4 in. and the 6 in. top volume as percentages of total volume.

TABLE 5: STAND VOLUME TO 4 IN. AND 6 IN. TOP DIAMETER I.B.  
AS PERCENTAGES OF TOTAL STAND VOLUME I.B.

Stand Mean d.b.h.	Percentage of Total Volume		Stand Mean d.b.h.	Percentage of Total Volume	
	4 in. top	6 in. top		4 in. top	6 in. top
4	27.2	1.4	15	97.0	92.3
5	53.5	7.1	16	97.4	93.6
6	70.3	16.8	17	97.7	94.7
7	80.0	34.5	18	98.0	95.3
8	86.4	52.5	19	98.2	95.9
9	90.2	65.2	20	98.4	96.4
10	92.7	74.2	21	98.6	96.8
11	94.1	80.8	22	98.8	97.0
12	95.1	85.3	23	98.9	97.3
13	95.9	88.5	24	99.0	97.7
14	96.5	90.8	25	99.0	97.9

$P \approx 100(1 - 0.917^{12.5})$

## PREDICTION OF INCREMENT AND YIELD UNDER VARIOUS THINNING REGIMES

The growth relationships derived so far provide a means of predicting increment and yield under various thinning regimes. It is assumed in the following examples that we are dealing with normal 6 × 6 ft, 8 × 6 ft, and 8 × 8 ft plantings; initial stocking for the 6 × 6 ft spacing will be set at 1,000 s.p.a., which represents 83% survival. Adopting the same survival percentage for the other spacings, we get initial stockings of 750 s.p.a. for the 8 × 6 ft planting and 560 s.p.a. for the 8 × 8 ft planting.

Three different comparisons will be made: (1) a comparison of three different grades of thinning, maintaining the stand at close (16%), medium (19%), and wide (22%) spacing on the basis of the relative spacing percentage maintained before thinning; (2) a comparison of thinning frequencies, applying respectively two, three, and four thinnings to the same rotation and the same grade; (3) a comparison of stands derived from close and from wider plantings, using 1,000 s.p.a., 750 s.p.a., and 560 s.p.a. as indicated, and using the same rotation and the same grade as in (2) above. In the first two comparisons the initial stocking is set at 1,000 s.p.a.; the clear-felling height in all three comparisons is assumed to be 130 ft. Table 6 shows the schedules used. At the top

TABLE 6: INCREMENT AND YIELD UNDER VARIOUS THINNING REGIMES

Thinning Regime		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Ht. (ft.)	Age (yr)	Stems per Acre				Basal Area and Mean d.b.h. (sq. ft.)		V/sq. ft. of Basal Area		Total Volume (cu. ft.)		Increment (cu. ft.)		Volume to 6 in. Top		Volume to 4 in. Top									
		Tot.	Res.	Cut	%	Tot. d.b.h.	Res.	Cut	d.b.h.	%	Tot.	Res.	Cut	Per.	M.A.C.A.*	%	Cut	%	Cut						
1,000/3/130/16%	44	9	930	370	560	60	160	5.6	82	78	5.0	49	16.2	15.8	2,592	1,360	1,232	288	..	288	7	86	54	665	
	73	14 1/2	344	100	154	45	186	10.0	119	67	8.9	36	24.9	24.3	4,631	3,003	1,628	3,271	404	595	65	1,058	90	1,465	
	101	21	177	115	62	35	202	14.5	147	55	12.7	27	33.3	32.5	6,727	4,939	1,788	3,724	457	573	88	1,573	96	1,716	
	130	31	107	0	107	CF	220	19.4	0	220	19.4	CF	42.0	42.0	9,240	..	9,240	4,301	448	430	96	8,870	98	9,055	
1 000/3/130/19%	37	7 1/2	970	300	670	69	135	5.1	55	80	4.7	59	41.1	13.7	1,904	808	1,096	3,170	376	551	70	1,165	46	504	
	68	13 1/2	291	140	151	52	170	10.3	97	73	9.4	43	23.4	22.8	3,978	2,314	1,664	3,170	376	551	70	1,165	91	1,514	
	99	20 1/2	136	82	54	40	191	16.0	130	161	14.4	32	32.7	31.9	6,246	4,300	1,946	3,932	439	562	92	1,790	97	1,888	
	130	31	80	0	80	CF	210	21.9	0	210	21.9	CF	42.0	42.0	8,820	..	8,820	4,520	436	430	97	8,555	99	8,732	
1,000/3/130/22%	32	7	990	245	745	75	115	4.6	39	76	4.3	66	12.6	12.3	1,449	514	935	3,154	354	526	77	1,208	35	327	
	65	13	243	110	133	55	163	11.1	86	77	10.3	47	22.5	21.9	3,668	1,982	1,686	3,924	426	561	94	1,942	93	1,568	
	97	20	109	61	48	44	184	17.6	118	66	15.9	36	32.1	31.3	5,906	3,840	2,066	3,924	426	561	94	1,942	97	2,004	
	130	31	60	0	60	CF	204	25.0	0	204	25.0	CF	42.0	42.0	8,568	..	8,568	4,728	438	430	97	8,311	99	8,482	
1,000/4/130/19%	37	7 1/2	970	390	580	60	135	5.1	69	66	4.6	49	14.1	13.7	1,904	1,000	904	2,297	350	540	53	652	43	388	
	60	12	378	200	178	47	157	8.7	97	60	7.9	38	21.0	20.5	3,297	2,067	1,230	2,297	350	540	53	652	86	1,058	
	84	17	104	122	72	37	175	12.9	124	51	11.4	24	28.2	27.5	4,935	3,533	1,402	2,868	416	574	83	1,164	95	1,332	
	107	22 1/2	118	82	36	31	189	17.1	146	43	14.8	23	35.1	34.2	6,634	5,163	1,471	3,101	447	539	92	1,353	97	1,472	
1,000/2/130/19%	37	7 1/2	970	200	770	79	135	5.1	39	96	4.8	71	14.1	13.7	1,904	589	1,315	5,192	417	561	88	2,323	49	644	
	84	17	194	82	112	58	205	13.9	109	96	12.5	47	28.2	27.5	5,781	3,141	2,640	5,192	417	561	88	2,323	95	2,508	
	130	31	80	0	80	CF	213	22.1	0	213	22.1	CF	42.0	42.0	8,946	..	8,946	5,805	416	415	97	8,678	99	8,857	
																		12,901	..	..	..	11,001	..	12,009	
750/3/130/19%	43	9	728	270	458	63	135	5.8	65	70	5.3	52	15.9	15.5	2,146	1,061	1,085	3,072	366	585	74	98	60	651	
	72	14 1/2	262	135	127	48	168	10.8	102	66	9.8	39	24.6	24.0	4,133	2,549	1,584	3,072	366	585	74	98	92	1,457	
	101	21	131	82	49	37	188	16.2	133	55	14.3	29	33.3	32.5	6,260	4,472	1,788	3,711	425	550	91	1,627	97	1,734	
	130	31	80	0	80	CF	208	21.8	0	208	21.8	CF	42.0	42.0	8,736	..	8,736	4,264	426	426	97	8,474	99	8,649	
560/3/130/19%	50	10	543	235	308	57	135	6.7	73	62	6.1	46	18.0	17.6	2,430	1,339	1,091	2,941	352	560	19	207	71	775	
	77	15 1/2	228	130	98	43	164	11.5	113	51	9.8	31	26.1	25.4	4,280	2,985	1,295	2,941	352	560	74	958	92	1,191	
	103	21 1/2	126	82	44	35	189	16.6	138	51	14.6	27	33.9	33.1	6,407	4,719	1,688	3,422	404	526	92	1,553	97	1,637	
	130	31	80	0	80	CF	207	21.8	0	207	21.8	CF	42.0	42.0	8,694	..	8,694	3,975	412	430	97	8,433	99	8,607	
																		12,768	..	..	..	11,151	..	12,210	

\* Mean annual increment for period between thinnings.

CF = clear felling.

of the table we find the prescribed heights (column 1) and residual stockings (column 4) for a stand of 1,000 s.p.a. initial stocking, thinned to a grade of 16% relative spacing; with three thinnings before clear felling at 130 ft stand height, i.e., the 1,000/3/130/16% regime. Fig. 3 shows how this regime may be set out step by step on the relative spacing graph (solid line). It should be added here that in this regime, as well as in the others shown in table 6, the increase in stand height between successive thinnings has been kept constant. From fig. 3 we read that a stand of 1,000 s.p.a. will reach a relative spacing of 16% at a stand height of 44 ft. This gives a height increase of  $(130 - 44)/3$ , or 28.7 ft, between thinnings, so that the second thinning will be due at 73 ft height and the third thinning at 101 ft height. The number of stems read from the graph at 73 ft height on the 16% line is 370 per acre, which is the residual stocking prescribed after first thinning (table 6, column 4). By repeating the same procedure, the residual stocking for the remaining two thinnings may be found.

In practice, a stand thinned to say 370 s.p.a. will be reduced to a lesser number by natural mortality before the next thinning is due, particularly in thinning grades which maintain a low relative spacing. On the basis of the normal mortality trends depicted in fig. 3, we may expect residual stocking under the 1,000/3/130/16% regime to follow the course shown in broken lines. It means that the stand does not quite reach the prescribed 16% relative spacing, but is thinned at a slightly higher percentage. This does not greatly matter in so far as the thinning prescriptions are concerned, but for the purpose of yield prediction such losses cannot be entirely ignored. If the loss in stems per acre is determined for any of the mortality trends shown in fig. 3 between the 30% and 16% relative spacing lines, it will be found to remain constant at 7% of initial stocking. Similarly the 19% relative spacing shows a loss of about 3% and the 22% relative spacing a loss of only 1%. These percentages have been used to arrive at the losses between thinnings. For instance, in the 1,000/3/130/16% regime, the number of stems predicted before the first thinning is 1,000 s.p.a. minus 7%, or 930 s.p.a. The 370 s.p.a. left after the first thinning will again suffer 7% mortality, leaving 344 s.p.a. before the second thinning, and so on. (Since relative spacing after thinning does not always reach a value of 30% or more, while that before thinning does not quite reach the percentage prescribed for the grade, there is a slight over-estimate of the losses involved.)

On the whole, the 19% regime conforms closely to present practice in most conservancies, while the 16% and 22% regimes may be said to represent the two extremes of thinning intensity likely to be practised.

To be able to predict increment and yield under any of the above thinning regimes, it is necessary first to ascertain the basal area before the first thinning. This is difficult because the present data give very little information on this point, being mainly derived from older stands that received their first thinning much later than normally practised nowadays. However, by using extra data from spacing trials and by plotting basal area over stand height with the stems-per-acre figure entered against each plotting, the following average basal areas at first thinning were estimated:

TABLE 7: BASAL AREA OF STAND IMMEDIATELY BEFORE  
FIRST THINNING

	Height at First Thinning (ft.)	Basal Area (sq. ft.)
<i>1,000 s.p.a. initial stocking</i>		
16% regime	44	160
19% regime	37	135
22% regime	32	115
<i>750 s.p.a. initial stocking</i>		
19% regime	43	135
<i>560 s.p.a. initial stocking</i>		
19% regime	50	135

Also, an allowance had to be made for the losses in basal area between thinnings due to natural mortality. These losses, expressed as a percentage of the basal area left after the last thinning, were read from the alignment chart in fig. 4 referred to earlier; they averaged 5% between successive thinnings in the 16% regime, 2% in the 19% regime, and 1% in the 22% regime. Since these losses are very low, no attempt was made to split up the height interval between thinnings, which is generally about 30 ft. The discrepancies involved may be considered negligible in this case.

Finally, in order to make predictions that refer to stand age rather than stand height, it is necessary to have reliable height-over-age curves for various sites throughout the country. Even curves for sites in the same forest may not be harmonious in trend. This means that for each forest sufficient height data have to be accumulated to enable representative curves to be derived for that forest. To explain the various steps in the prediction method developed here, it is assumed that the height-over-age curve shown in fig. 6 is representative of a given site in a given forest or region. Increment and yield under the various regimes can now be worked out by the following steps (see table 6):

1. From the percentage cut given in column 6 and from table 4, determine the percentage basal area cut in the first thinning (column 12).
2. Use the initial basal area given in column 7 to work out the basal area of the first thinning and of the residual stand (columns 10 and 9).
3. From the stems-per-acre figures in columns 3 and 5 and from the basal areas given in columns 7 and 10 respectively, work out the mean d.b.h. of the stand before first thinning and of the thinnings (columns 8 and 11).
4. Using fig. 2 or the formula  $I_b = I_h (B + 270)/(H + 50)$ , determine the gross basal area increment between the first and the second thinnings, and from this figure subtract the loss in basal area due to mortality read from fig. 4. Add this net increment to the basal area remaining after the first thinning in column 9, to find the basal area before the second thinning (column 7).
5. Repeat steps 1-4 for the second and later thinnings.

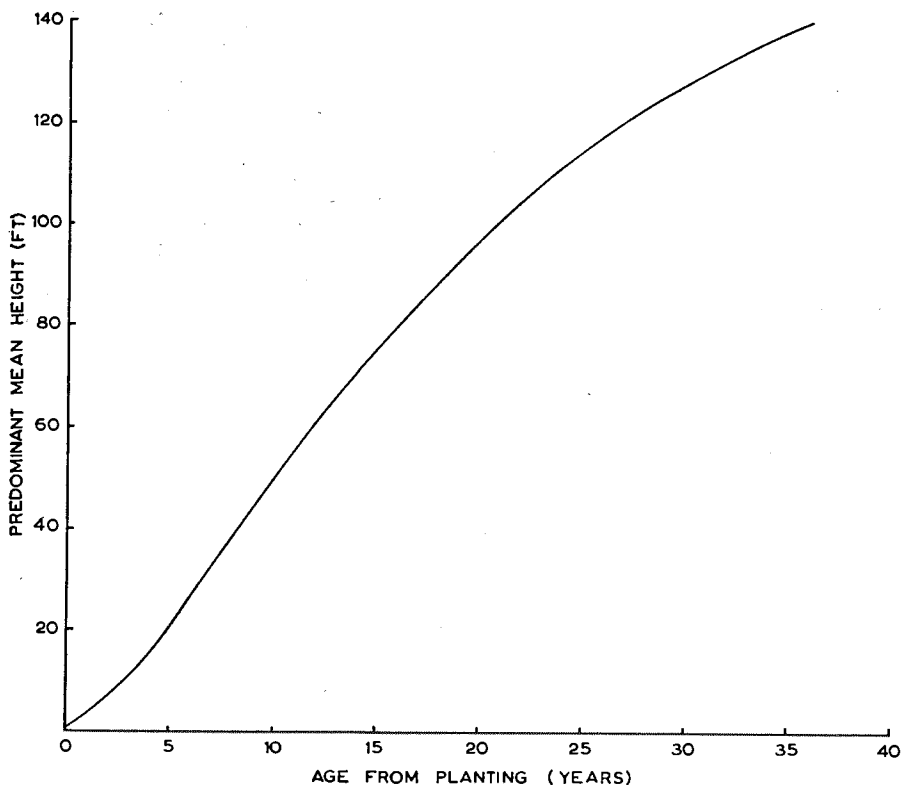


Fig. 6. The height-over-age curve used in the prediction table (table 6).

6. Enter the total volume per square foot of basal area at each thinning height from the formula  $V/B = 3 + 0.3H$  in column 13, and multiply by 0.975 to give the volume per square foot basal area for the thinnings (column 14).
7. Multiply the basal areas in columns 7 and 10 by the volumes per square foot of basal area in columns 13 and 14 respectively to give the total volume before thinning (column 15), and the total volume cut out (column 17). By subtraction find the total volume remaining (column 16).
8. Derive the between-thinning periodic increment in total volume from columns 15 and 16 (column 18). Note that this increment and the current annual increment derived from it (column 20) are entered against the height at the end of each growth period instead of the middle.
9. From fig. 6 read the age of the stand at each thinning height (column 2) and derive the mean annual increment (column 19) and the current annual increment, or more precisely the periodic mean annual increment (column 20), in the normal way.

10. From fig. 5 (or table 5) and the mean diameters given in column 11, determine the percentage reduction for 6 in. top volume and multiply by the total volume in column 17 to find the volumes cut out in terms of 6 in. volume (column 22). Derive the volumes to a 4 in. top diameter in the same way (column 24).

### COMPARISON OF THINNINGS GRADES

An examination of the data presented in these tables shows very little difference in total yield under the various regimes. In terms of 6 in. volume, a low initial stocking (560 s.p.a.) or heavy cutting (two thinnings instead of three) will reduce the total yield by about 400–500 cu. ft. Final-crop diameters in stands of low initial stocking are no higher than in stands of higher initial stocking receiving the same grade of thinning. This no doubt results from the fact that thinning is designed to free the stand at the moment mortality begins, or at least very shortly afterwards. Thus the stand of high initial stocking has just reached crown closure when it is reduced to a stocking lower than that in the stand of low initial stocking. Where all thinnings can be utilised, it does not pay to give the stand of low initial stocking an early thinning, because this would keep basal area at a low level and cause increments to be low.

The 22% grade shows a decided advantage as far as final diameter is concerned, but at the same time the volume removed in the final felling is lower and probably of poorer quality (larger branches, more taper) than in the lighter grades. However, in areas of high mortality this may be a safer regime.

The difference in yield between the two-thinning and the four-thinning regime shows the advantage of the more intensive treatment as far as volume yield is concerned, and also no doubt as far as tree selection is concerned. To judge solely by the mean annual increments, the selection of 130 ft as the final height for clear felling would appear to be correct for the regimes discussed here, provided of course that one is dealing with sites that can be represented by the height-age curve in fig. 6.

The finding that the type of treatment has little effect on total yield is confirmed by graphs prepared for total, 6 in., and 4 in. volume of thinned stands against controls, grouping thinnings into light, medium, and heavy grades as before. On the whole, these graphs showed no conclusive trends, though this may be because the material included in each group was too variable.

### DERIVATION OF A COMBINED STAND TABLE FOR THINNINGS AND FOR THE STAND JUST BEFORE THINNING

It is important to be able not only to predict volume and yield for the entire stand, but also to split this yield up into size assortments, especially when estimating financial returns. The basic requirement for such calculations is a stand table showing the distribution of diameter classes at successive stages of stand development.

For this purpose a separate study was made of the diameter distribution in stands immediately before thinning and of the diameter distribution of the thinnings themselves. The procedure was to group the data into 1 in. diameter classes on the basis of the mean d.b.h. of the stand before thinning and of the

mean d.b.h. of the thinnings, and to draw up cumulative-frequency distributions for each mean d.b.h. class. These showed the number of stems of any given size and over – again using 1 in. classes – as a percentage of total stocking. In addition, the cumulative distributions for thinnings were divided into three groups – those from thinnings that removed less than 30% of the number of stems, those that removed between 30% and 50%, and those that removed more than 50%. A separate curve was drawn to represent the cumulative distribution for each of these intensities. Apart from minor variations, no clear difference could be detected between the curves for the same mean diameter in each of the three groups. Moreover, when the data for the three groups were pooled and the cumulative-distribution curves for thinnings of given mean diameter were compared with those for stands of the same mean diameter immediately before thinning, no marked differences could be detected. Although it is possible that more data would bring out such differences, it seems unlikely that these would be of any great importance for prediction purposes. But it has to be admitted that the range of the present data does not allow reliable predictions for mean diameters greater than about 18 in., because there are virtually no older stands that have received adequate thinning treatment by present standards.

Since there was no detectable difference between the distribution curves for thinnings and those for the stand immediately before each thinning, all data were combined to produce a single set of cumulative-frequency curves, i.e., one curve to represent each mean d.b.h. class. These curves show a steady increase in the dispersion of diameters about the mean d.b.h. as the latter increases. For instance, in a stand of 12 in. mean d.b.h., the largest 20% of the stems will have a diameter of 13.60 in. and over, i.e., a deviation of 1.60 in. or more from the mean. In a stand of 16 in. mean d.b.h., the 20% limit lies at 17.78 in., or 1.78 in. from the mean, and in a stand of 20 in. mean d.b.h. it lies at 21.97 in., or 1.97 in. from the mean. These are the exact limits and therefore cannot be directly compared with the figures given in the stand table to be presented later in this paper, which refer to 1 in. diameter classes.

It will be noticed that the deviation from the mean in the above example is not directly proportional to the increase in the mean d.b.h. itself, nor to its square. However, if the deviations for any given percentage of stems are plotted over the corresponding mean d.b.h. on double logarithmic paper, an almost perfect linear trend is obtained for all data relating to stands with a mean d.b.h. of about 6 in. or more. Moreover, it was found that the same gradient, 0.475, could be used for the various percentages, so that the relationship could be written as:

$$L - D = aD^{0.475}$$

where  $L$  is the limiting diameter for any fixed percentage of total stocking in stands of varying mean diameter  $D$ , and " $a$ " is a constant for any fixed percentage. The values for " $a$ " read from the graph were:

$$F(d) \approx \varphi \left( \frac{d-b}{0.475} \right)$$

TABLE 8: VALUES OF  $a$  IN THE FORMULA  $L - D = aD^{0.475}$

Percentage of Total Stocking	Value of $a$	Percentage of Total Stocking	Value of $a$
$100(1-F(a))$			
0	+ 2.18	60	- 0.27
2	+ 1.42	70	- 0.45
5	+ 1.12	80	- 0.67
10	+ 0.84	90	- 0.97
20	+ 0.48	95	- 1.22
30	+ 0.28	98	- 1.54
40	+ 0.09	100	- 2.12
50	- 0.09		

Plotted on linear probability paper, these values very nearly define a straight line. Between 20% and 80% of total stocking, the line is virtually straight, but for percentages outside these limits there are slight deviations. For instance:

for 2% one reads $a = 1.34$	for 90% one reads $a = 0.98$
for 5% one reads $a = 1.05$	for 95% one reads $a = 1.24$
for 10% one reads $a = 0.80$	for 98% one reads $a = 1.52$

These deviations may well be due to the low frequencies encountered at the ends of such distributions. When more data have been collected, it will be possible to check this point in more detail. In the present study it was decided to fit an S-shaped curve to the data and read the " $a$ " value for each percentage. Next, the above process, i.e., finding the limiting diameter for a given percentage of largest stems in a stand of given mean diameter, was changed to one where for a stand (or thinnings) of given mean diameter one has to find the cumulative percentage of largest stems down to a fixed diameter-class limit. This was derived from  $a = (L - D)/D^{0.475}$ , using the computed value of " $a$ " to find the corresponding percentage of total stocking. After slight adjustments to the extremities of the distributions to correct for inconsistencies, the stand table (table 9) was derived.

This table shows the diameter classes used in the distribution as plus or minus deviations from the mean d.b.h. of the stand given in the first column. For each mean d.b.h. class, both cumulative and individual class frequencies are shown as percentages of total stocking. For instance, with a mean d.b.h. of 9 in. one may expect 19% of the total number of stems (thinnings or stems before thinning) to fall within the 11 in. diameter class and over, 55% in the 9 in. class and over, and 88% in the 7 in. class and over. The percentage of stems in each class is given immediately below the previous figure: 9% in the 11 in. class, 20% in the 9 in. class, and 14% in the 7 in. class.

#### DIAMETER INCREMENT OF LARGEST 100 STEMS PER ACRE IN THINNED AND IN UNTHINNED STANDS

The diameter measure most generally used in yield predictions is the mean diameter of the stand, or more correctly the diameter of the tree of average



$$d \sim N(d, \frac{D}{3})$$

TABLE 9: COMBINED STAND TABLE FOR THINNINGS AND FOR STANDS JUST BEFORE THINNING

Mean d.b.h. (in.)	Diameter Class (Expressed as deviation from mean d.b.h. in inches)																
	-7	-6	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5	+6	+7	+8	+9 +10
Percentage of Total Number of Stems*																	
5	..	..	..	100	99	95	81	58	32	13	4	1	..	..	..	..	..
	..	..	..	1	4	14	23	26	19	9	3	1	..	..	..	..	..
6	..	..	..	100	98	92	79	57	33	15	6	2	..	..	..	..	..
	..	..	..	2	5	14	22	24	18	9	4	2	..	..	..	..	..
7	..	..	..	100	97	91	77	56	34	16	7	2	..	..	..	..	..
	..	..	..	3	6	14	21	22	18	9	5	2	..	..	..	..	..
8	..	..	100	99	96	89	75	56	34	18	9	4	1	..	..	..	..
	..	..	1	3	7	14	19	22	16	9	5	3	1	..	..	..	..
9	..	..	100	99	95	88	74	55	35	19	10	4	1	..	..	..	..
	..	..	1	4	7	14	19	20	16	9	6	3	1	..	..	..	..
10	..	..	100	98	94	86	72	54	35	19	10	4	1	..	..	..	..
	..	..	2	4	8	14	18	19	16	9	6	3	1	..	..	..	..
11	..	..	100	98	93	85	71	54	36	20	11	5	2	1	..	..	..
	..	..	2	5	8	14	17	18	16	9	6	3	1	1	..	..	..
12	..	..	100	98	93	84	71	54	36	21	12	6	3	1	..	..	..
	..	..	2	5	9	13	17	18	15	9	6	3	2	1	..	..	..
13	..	100	99	97	92	83	70	53	37	22	13	7	4	2	1	..	..
	..	1	2	5	9	13	17	16	15	9	6	3	2	1	1	..	..
14	..	100	99	96	91	82	69	53	37	23	14	8	4	2	1	..	..
	..	1	3	5	9	13	16	16	14	9	6	4	2	1	1	..	..
15	..	100	99	95	90	81	68	53	37	23	14	8	4	2	1	..	..
	..	1	4	5	9	13	15	16	14	9	6	4	2	1	1	..	..
16	..	100	99	95	89	80	68	53	37	23	14	8	4	2	1	..	..
	..	1	4	6	9	12	15	16	14	9	6	4	2	1	1	..	..
17	..	100	98	94	88	79	67	52	38	24	15	9	5	2	1	..	..
	..	2	4	6	9	12	15	14	14	9	6	4	3	1	1	..	..
18	..	100	98	93	87	78	66	52	38	25	16	10	6	3	2	1	..
	..	2	5	6	9	12	14	14	13	9	6	4	3	1	1	1	..
19	..	100	98	93	87	78	66	52	38	25	16	10	6	3	2	1	..
	..	2	5	6	9	12	14	14	13	9	6	4	3	1	1	1	..
20	..	100	97	92	86	77	65	52	38	25	16	10	6	3	2	1	..
	..	3	5	6	9	12	13	14	13	9	6	4	3	1	1	1	..
21	..	100	97	92	86	77	65	52	38	26	17	11	7	4	2	1	..
	..	3	5	6	9	12	13	14	12	9	6	4	3	2	1	1	..
22	..	100	97	92	85	76	65	52	38	26	17	11	7	4	2	1	..
	..	3	5	7	9	11	13	14	12	9	6	4	3	2	1	1	..
23	100	99	96	91	84	75	64	51	39	27	18	12	7	4	2	1	..
	1	3	5	7	9	11	13	12	12	9	6	5	3	2	1	1	..
24	100	99	96	91	84	75	64	51	39	27	18	12	7	4	2	1	..
	1	3	5	7	9	11	13	12	12	9	6	5	3	2	1	1	..
25	100	99	96	91	83	74	63	51	39	27	18	12	7	4	2	1	..
	1	3	5	8	9	11	12	12	12	9	6	5	3	2	1	1	..
26	100	99	96	91	83	74	63	51	39	28	19	13	8	5	3	2	1
	1	3	5	8	9	11	12	12	11	9	6	5	3	2	1	1	..
27	100	99	96	91	83	74	63	51	39	28	19	13	8	5	3	2	1
	1	3	5	8	9	11	12	12	11	9	6	5	3	2	1	1	..
28	100	99	96	90	82	73	62	51	39	28	20	14	9	6	4	3	2
	1	3	6	8	9	11	11	12	11	8	6	5	3	2	1	1	1
29	100	99	96	90	82	73	62	51	39	28	20	14	9	6	4	3	2
	1	3	6	8	9	11	11	12	11	8	6	5	3	2	1	1	1
30	100	99	96	90	82	73	62	51	39	29	20	14	9	6	4	3	2
	1	3	6	8	9	11	11	12	10	9	6	5	3	2	1	1	1

\*For each mean d.b.h. class, the top line shows the cumulative percentage of stems, the bottom line the percentage by individual classes.

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$$\text{Burr dist. } F(x) \approx 1 - \left[ 1 + \left( a \frac{x-b}{D^{0.475} + b} \right)^c \right]^{-1}$$

$\hat{a}$   $\hat{b}$   $\hat{c}$   $\hat{D}$   $\text{max}|a|$   $-\ln L$

M.L. 0.2388 0.5987 4.142 7.049 1.121 251.3

Minimax 0.2538 0.6487 4.301 5.588 0.648

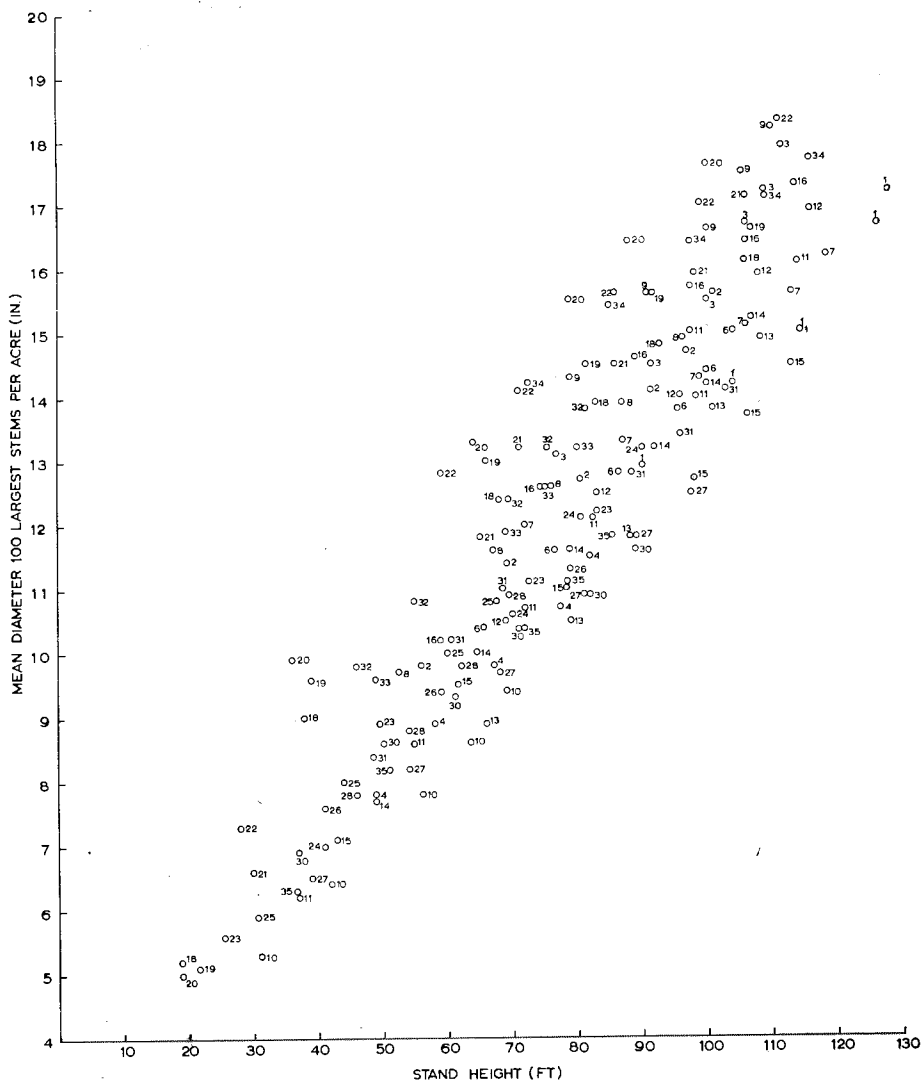


Fig. 7. Progress of diameter of 100 largest stems per acre with increasing stand height in unthinned stands. Corresponding numbers refer to successive measurements in the same plot.

basal area. However, in comparisons between thinned and unthinned stands, or between lightly thinned and more heavily thinned stands, this measure has its limitations. The mean diameter of a stand, like the mean height, is a computed value, the increase of which does not necessarily correspond to the

actual growth in diameter of a given number of stems per acre. Removal of trees in thinning or the death of trees over the years will cause a sudden or gradual rise in mean diameter, irrespective of whether any diameter growth has taken place in the stand or not. Moreover, in studying the effect of thinning on diameter increment, one is less interested in the average size of the entire crop than in the diameter of the trees that will form the final crop or some part of it. A more suitable measure for this purpose, therefore, is the diameter of the 100 largest stems per acre, briefly referred to here as  $D_{100}$ .

When  $D_{100}$  values for the various plots included in this study were plotted over stand height, some interesting results were obtained, and though it is not possible at this stage to say what values of  $D_{100}$  can be considered typical of stands derived from normal  $6 \times 6$  ft,  $8 \times 6$  ft, and  $8 \times 8$  ft plantings in different regions, the major trends derived so far in this study are worth considering here.

As a first step, diameter development in unthinned stands was studied. Fig. 7 shows the progress of  $D_{100}$  with increasing stand height in unthinned control plots. The normal inaccuracies of height measurement have caused the values plotted for any one plot at successive measurements to fluctuate considerably, but the overall trend for most plots appears to be linear from about 40 ft to 110 ft stand height. Further, the gradients for the different plots vary but little – from about 0.11 to 0.12. The steeper angles are generally associated with plots that have suffered greater mortality, and in extreme cases such plots cannot be looked upon as truly representative of unthinned stands. If these exceptional cases are discarded, the regression coefficient works out at  $0.1147 \pm 0.0065$  (5% probability level) as an average for all localities, i.e., an increase of 1.15 in. in  $D_{100}$  for every 10 ft increase in stand height.

In stands derived from normal planting espacements from  $6 \times 6$  ft to  $8 \times 8$  ft, this typical growth rate, which may be said to represent restricted growth after competition has become fully effective, applies only when a stand height of 40 ft or more has been reached. At lesser heights, the trends become steeper and curvilinear. Unfortunately, there are no data for stands at heights below 30 ft to extend these curves towards the origin. Theoretically they should all branch off from a common curve representing the increase in diameter under conditions of free growth, i.e., before the effects of mutual shelter and competition are felt. From a careful stem analysis of a solitary 23-year-old self-sown *Pinus radiata* felled at Waiotapu Forest, it is estimated that  $D_{100}$  under such conditions could reach a value of 1.5 in. at 10 ft, 4 in. at 20 ft, 7.5 in. at 30 ft, and 11.5 in. at 40 ft, after which diameter increases steadily at the rate of about 4.5 in. for every 10 ft increase in height. This clearly shows the marked difference between the two extremes, free growth and restricted growth in unthinned stands.

A further comparison of data from unthinned plots in spacing trials at Kaingaroa (fig. 8), Rotoehu, and Golden Downs confirms the findings from control plots (fig. 7), and shows how the trends for the various spacings array themselves in parallel order one above the other after growth becomes restricted,

first in the closer spacings and later in the wider spacings. Since the stems-per-acre figures in later years are not always in agreement with the original spacing differences, some trends tend to overlap, e.g., for the  $3 \times 3$  ft and  $4 \times 4$  ft spacing in fig. 8, but on the whole the trends derived from these three trials show very much the same pattern. These results seem to confirm earlier conclusions reached by Ferguson (1950), who studied the development of mean diameter in *Pinus merkusii* stands of different initial espacement.

In the second part of this study, the increase of  $D_{100}$  in thinned stands was compared with the increase in unthinned stands. For this purpose treatments were grouped as before in three classes, viz, light thinning (18% relative

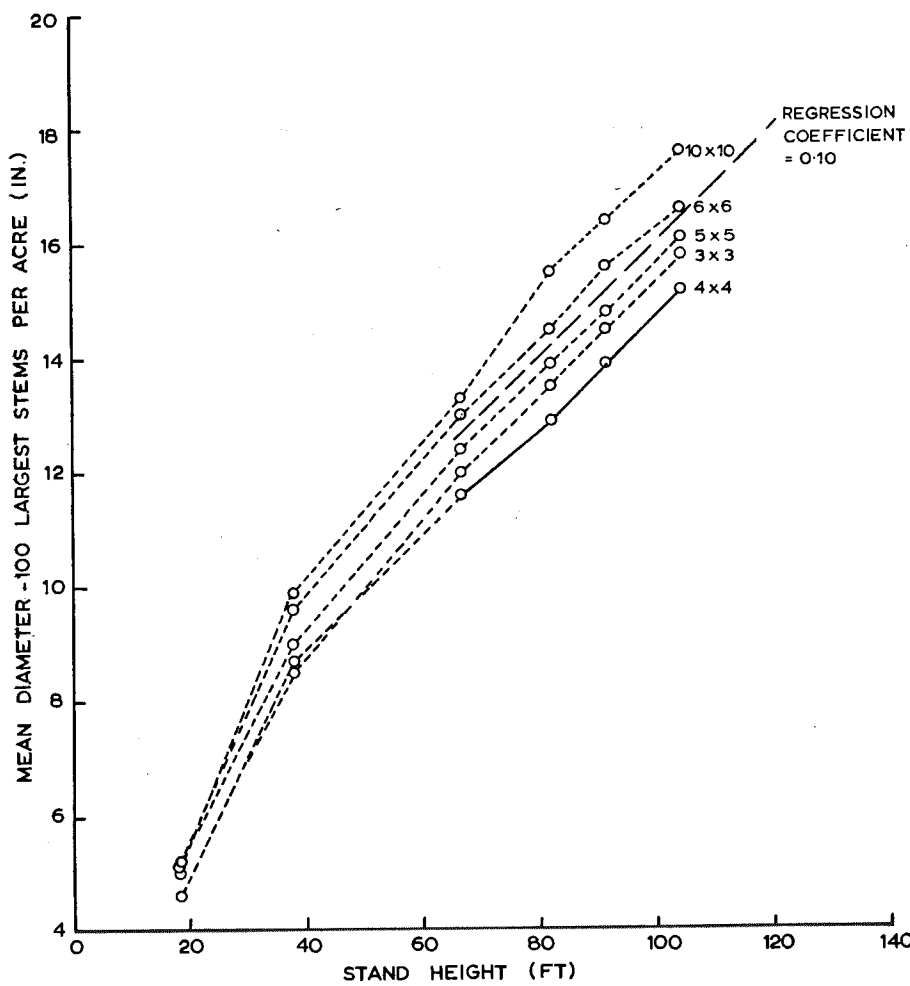


Fig. 8. Progress of diameter of 100 largest stems per acre with increasing stand height in unthinned controls, Kaingaroa spacing trial.

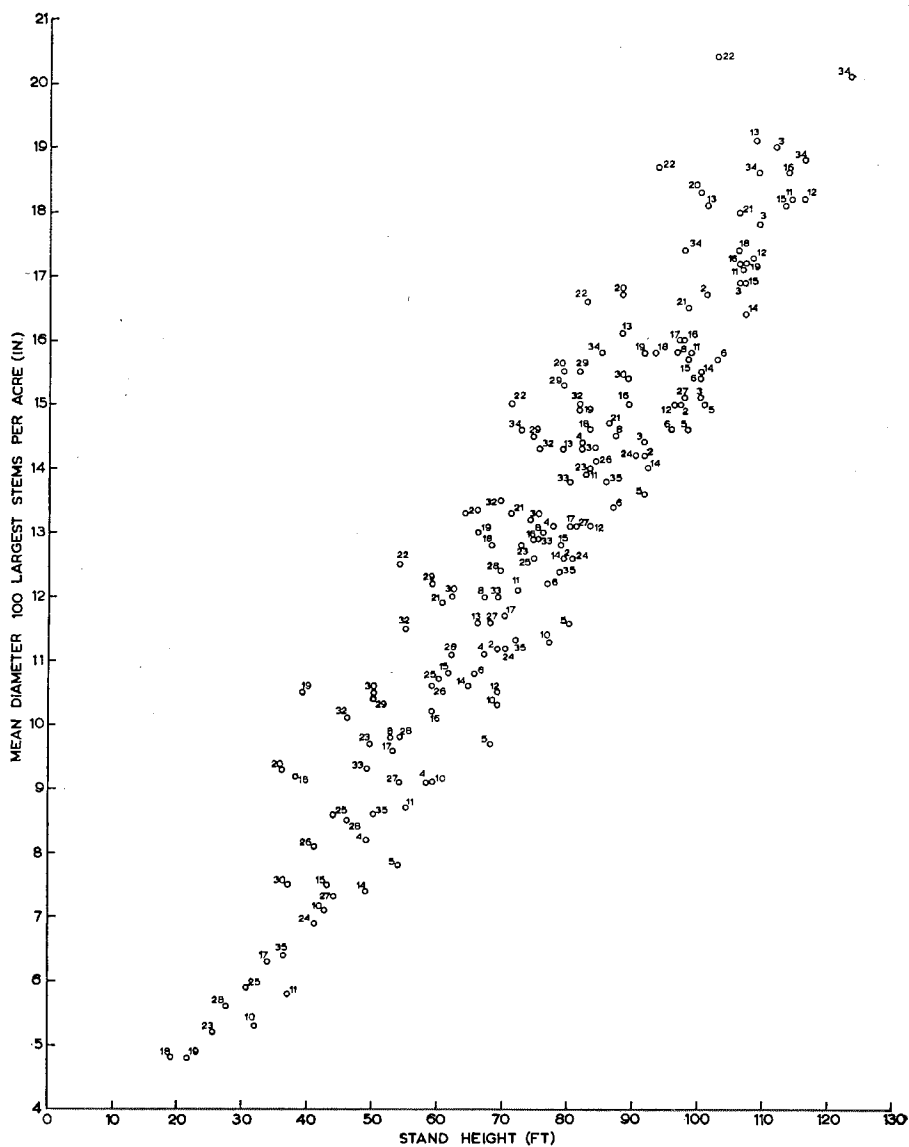


Fig. 9. Progress of diameter of 100 largest stems per acre with increasing stand height in thinned stands. Corresponding numbers refer to successive measurements in the same plot.

spacing or less), medium thinning (19% to 22%), and heavy thinning (23% or more). Trends of  $D_{100}$  over stand height were drawn for individual plots within each group. These proved to vary a great deal. This no doubt results from the fact that thinning treatments included in each group are still far from uniform, despite the mean relative spacing assigned to them in this analysis. The only group worthy of close examination is that of the medium thinning grades (fig. 9), which contains the bulk of the data. The average mean relative spacing percentage for plots included in this group was 21.06%, and the regression coefficient was  $0.1506 \pm 0.0104$  (5% probability level). The difference between this coefficient and the value 0.1147 for unthinned stands proved highly significant.

### PREDICTION OF DIAMETER OF THE 100 LARGEST STEMS FROM THE STAND TABLE

An alternative method of deriving  $D_{100}$  values in thinned stands uses the stand table presented in the previous section. The following example will illustrate the procedure for computing  $D_{100}$ , or the diameter or basal area of any other portion of the crop, from this table.

Suppose we wish to trace the development of the 100 largest stems per acre in the 1,000/3/130/16% regime presented in table 6. Just before the first thinning, which is scheduled at a stand height of 44 ft, there are 930 stems per acre with a mean d.b.h. of 5.6 in. The 100 largest stems per acre therefore represent 10.75% of the total stocking. Table 9 shows that in a stand of 5 in. mean d.b.h. trees of 8 in. diameter and over may be expected to comprise 4% of the stocking, while those of 7 in. and over comprise 13%. This means that the 100 largest would include 6.75% in the 7 in., 3% in the 8 in., and 1% in the 9 in. class. Their basal area would therefore be:

$$0.005454 \times 9.30 (6.75 \times 49 + 3 \times 64 + 1 \times 81) = 30.6 \text{ sq. ft.}$$

Similarly the basal area of the 100 largest stems in a stand of 6 in. mean d.b.h. would be:

$$0.005454 \times 9.30 (4.75 \times 64 + 4 \times 81 + 2 \times 100) = 42.0 \text{ sq. ft.}$$

In these computations the percentages in each class are multiplied by the squares of the class diameters. These products, added together, are multiplied by the ratio 930/100 to correct for stocking and by 0.005454 to convert the squared diameters in inches to basal area in square feet.

However, since we are not concerned here with the basal area in the 5 in. or 6 in. class, but have to interpolate for a mean d.b.h. of 5.6 in., the entire calculation can be abbreviated to:

$$100(D_{100})^2 = 9.30 [0.6 (4.75 \times 64 + 4 \times 81 + 2 \times 100) + 0.4 (6.75 \times 49 + 3 \times 64 + 1 \times 81)]$$

$$\text{or } 100(D_{100})^2 = 6,866 \text{ (i.e., b.a. of 100 largest stems} = 6,866 \times 0.005454 = 37.4 \text{ sq. ft.)},$$

so that  $D_{100} = \sqrt{68.66} = 8.3 \text{ in.}$

As a matter of interest,  $D_{100}$  values, computed for the remaining thinnings in the 16% regime as well as for the 19% and 22% regimes of the same series in table 6, gave the following results:

TABLE 10: MEAN DIAMETER OF 100 LARGEST STEMS IN THINNED STANDS

16% Regime		19% Regime		22% Regime	
Stand Height (ft)	D <sub>100</sub> (in.)	Stand Height (ft)	D <sub>100</sub> (in.)	Stand Height (ft)	D <sub>100</sub> (in.)
44	8.3	37	7.7	32	6.9
73	12.2	68	12.4	65	13.0
101	16.1	99	17.0	97	18.0
130	19.7	130	21.9*	130	25.0†

\*Final crop 80 s.p.a.

†Final crop 60 s.p.a.

The diameters 21.9 in. and 25.0 in. at 130 ft height in the 19% and 22% regimes refer to final crops of 80 and 60 stems per acre respectively, so that they overestimate  $D_{100}$  accordingly. When the values of  $D_{100}$  shown in table 7 are plotted over the corresponding stand heights, a perfect linear trend is obtained in the 16% and in the 19% regime, while that in the 22% regime is very nearly linear. The gradients are 0.132, 0.150, and 0.175 for the 16%, 19%, and 22% regimes respectively, representing increases of 15%, 30%, and 52% respectively – from the time the first thinning takes effect – over the growth rate of the 100 largest stems in unthinned stands.

Finally, the above gradients for the 16%, 19%, and 22% regimes were plotted in a graph over the relative spacing percentage of each regime. A smooth curve was fitted to the data, starting from a minimum value of 0.115 for unthinned stands. The following values were read from this curve:

Treatment (relative spacing before thinning)	Gradient $D_{100}$ over $H_{40}$	Treatment (relative spacing before thinning)	Gradient $D_{100}$ over $H_{40}$
Unthinned	0.115	17% grade	0.138
12% grade	0.118	18% grade	0.144
13% grade	0.121	19% grade	0.150
14% grade	0.124	20% grade	0.158
15% grade	0.128	21% grade	0.167
16% grade	0.132	22% grade	0.175

These figures refer to regimes with fixed relative spacing immediately before thinning, while the gradient of 0.1506 computed earlier for medium-grade plots refers to regimes that fluctuate about a fixed mean relative spacing of 21.06%, so that their relative spacing before thinning is less than 21.06%. The results obtained by the two methods are therefore in close agreement. Unfortunately, the estimated diameter increase of 0.45 in. per foot height growth of free-grown trees cannot be incorporated as a maximum value in the above list because 100 trees per acre would not remain free growing for very long. For the same reason there is no point in reading extrapolated values for regimes that maintain a relative spacing of more than 22%.

Of course there is no reason why the diameter increase of the 100 largest stems cannot be replaced by that of a smaller number, e.g., the 40 largest. This would eliminate the difficulty encountered where the number of final-crop trees in thinned stands drops below 100. Within normal rotations it would certainly not drop to less than 40 stems per acre. The diameter development of the 40 largest stems per acre may be determined directly from the stand table by the same procedure as before. However, the comparison with the growth rate of free-grown trees would still not be valid, because conditions of free growth do not relate to a fixed number of stems per acre but to a variable number depending on their size.



### Appendix

#### THE DETERMINATION OF PREDOMINANT MEAN HEIGHT AS A BASIS FOR PREPARATION OF HEIGHT-OVER-AGE CURVES

In order to derive local yield tables by the prediction methods presented in this paper, it is essential to accumulate height data from a large number of stands in the area concerned, and to compare trends to decide the magnitude of the differences involved and allocate stands to various site classes on this basis. To eliminate individual variation, it is important to base each trend on data from a number of stands rather than from a single stand.

These height measurements should be distributed evenly throughout the forest to provide a set of curves for future use. At the same time some idea of height growth in earlier years may be gained from a stem analysis of predominants of average size on typical sites. To eliminate individual variation and obtain an average trend, it is again necessary to fell several predominants in the same area. Results from stem analysis will have to be checked against normal height measurements in later years.

Provided that the stand concerned is reasonably uniform, the height measurement of 10 or 12 predominants will provide a reliable estimate of its predominant mean height. As a check, one may compute the probable limits of error. If the error is too great, more trees can be measured to reduce it to whatever standard is desired.

The normal method of selecting a sample of predominants for height measurement is to locate centres every so many chains or paces apart, depending on what area of the stand one wishes to sample. The tallest tree within a radius of 18.6 ft from each centre (i.e., within an area of  $\frac{1}{40}$  acre) is selected and its height and diameter are measured (the predominant mean d.b.h. provides another useful stand measure). The stocking surrounding each centre should not differ much from the average for the stand; this point may be checked by the angle-count method if necessary.

In all cases the tallest tree should be selected, irrespective of form, and height measured to the topmost living part, whether it be the main terminal or a competing lateral. Sometimes it is difficult to establish which tree is the tallest, especially when one is working in young stands or on steep slopes. In *Pinus radiata* stands it has been found that the tallest tree is generally the one of largest diameter, provided that the tree so selected is of good form and normal taper. Therefore no serious error should result from adopting this procedure in a few special cases, although it should be noted that any errors caused by selecting the wrong tree lead to an underestimate of predominant mean height.

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