PRUNING RADIATA PINE

IN NEW ZEALAND TO PRODUCE CLEARWOOD

by

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SUMMARY

The events leading to the decision to prune State-owned

forests of radiata pine on a wide scale in New Zealand are

reviewed. Future levels of clearwood demand and price were not

explicitly considered in the decision to prune.

A deductive analysis suggested that clearwood demand will be

highly price elastic. Producers should therefore examine how to

produce clearwood most efficiently.

A simulation model constructed to predict the yield of

clearwood from pruning showed that initial stocking, pruning and

thinning treatment, site index and rotation length affected

clearwood yield.

The probability distribution of clearwood yield for a

25 year rotation with heavy early thinning and severe pruning on a

site index of 29 m had a mode of 75 m^3/ha. The probability of

occurrence of the mode was only 0.209. Clearwood yields ranged

from 5 m^3/ha to 145 m^3/ha.

The modes for the probability distributions of the discounted

net worth of pruning were $ -5/ha on a site index of 24.4 m, and

$5/ha on site indices of 29 m and 33.5 m. The expected values of

the probability distributions were $2.4/ha, $7.05/ha and $13.44/ha

on site indices of 24.4 m, 29 m and 33.5 m respectively.

A deterministic analysis of the profitability of a sawlog

regime including pruning indicated an internal rate of return of

13 % for a 25 year rotation length on a site index of 29 m.

The costs of pruning are unlikely to be recouped by the value added to otherwise knotty lumber by pruning on site indices below 29 m. While the State is committed to supply increasing volumes of clearwood for the next 30 years, the clearwood production goals implicit in the New Zealand Forest Service pruning policy should be revised to ensure efficient allocation of scarce resources.

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CHAPTER ONE

INTRODUCTION

Pruning Policy

Early in the twentieth century it became apparent that the capacity of the indigenous forests to supply wood to the nation was rapidly approaching its limit in New Zealand. It was realised that an alternative source of wood of comparable quality would be required to supply the needs of future generations.

The State accordingly embarked upon an afforestation programme using exotic species, radiata pine (Pinus radiata D.Don) being the major component. The programme was given added impetus during the worldwide economic depression of the 1930's by the availability of otherwise unemployed labour. The planting rate decreased after the 1930's and the area planted during 1940-47 was negligible. However, an expanded afforestation programme is now National policy, and the current planting rate is about 29 140 ha per annum (New Zealand Forest Service, 1973).

The establishment of sawmills utilising plantation-grown logs of exotic species during the 1940's led to the development of visual grading rules, based mainly on relative knot-size and piece dimension, and on knot condition. Sawn timber in New Zealand is now sold by grade, the main categories in increasing order of quality being:

Box Grade

Merchantable Grade

Dressing Grade

Factory (clearcuttings) Grade

These grades apply to all timber sold as boards and to larger dimensions of timber used for structural purposes. In addition to these grades, common scantling is graded as No. 1 Framing, or as No. 2 Framing of lower quality. Table 1 shows the prices of a selection of grades and sizes of sawn timber taken from the current (May 1973) wholesale price list for Waipa State Sawmill.

TABLE 1. PRICES OF SELECTED GRADES AND WIDTHS OF SAWN TIMBER IN NEW ZEALAND.

Grade	Dimension	Price ($/m^3)
Box	15.24 cm wide	25.21
	22.86 to 30.48 cm wide	27.16
Dressing	10.16 x 2.54 cm	44.53
	22.86 to 27.94 cm wide	57.16
No.1 Framing	10.16 x 5.08 cm	44.53
	22.86 to 30.48 cm wide	59.79

The development of these grading rules reflected the detrimental influence of large knots in marketing radiata pine. Buyers were accustomed to high quality clear timbers available from the indigenous resource. However, clearwood from the long internodes of radiata pine found a ready market in industrial uses requiring only short lengths. This limited market suggested that long lengths of clear timber from radiata pine would find profitable markets (Hinds, 1962).

Pruning of large areas of plantations commenced during the post war years (Hinds, 1962). However the necessity for thinning to maintain stand health was not appreciated until the widespread occurrence of mortality associated with Sirex noctilio Fabricius during the late 1940's and early 1950's. The absence of markets for these thinnings of small dimension led in turn to the now widespread practice of thinning to waste in young stands. It was realised, however, that the yields of good quality timber from unpruned stands treated in this manner would be much less than those from the older stands which had been maintained for longer periods at much closer stockings.

Grade studies carried out in the 1960's elucidated the pattern of defect in radiata pine. Figure 1 (after Brown, 1965) shows the significance of defects induced by branches in determining grade yield. Encased knots, formed by the growth of the bole around retained dead branches, accounts for the major proportion of the defect in lower logs.

In the early 1960's Box grade accounted for 40% to 50% of the yield from exotic forests and it was difficult to sell. This situation still existed in 1970 (Cutler, 1970). Grainger (1960) concluded that by the year 2000 there would be an excess of 0.4 million cubic metres (169 million board feet (bd.ft.)) of Box grade and an almost equivalent deficiency of finishing grades. The policy of pruning final crop trees to about 6.1 m (20.0 ft.) was therefore adopted on a wide scale in State Forests, to reduce degrade and to maximise the production of clearwood and peeler grade logs (Sutton, 1972).
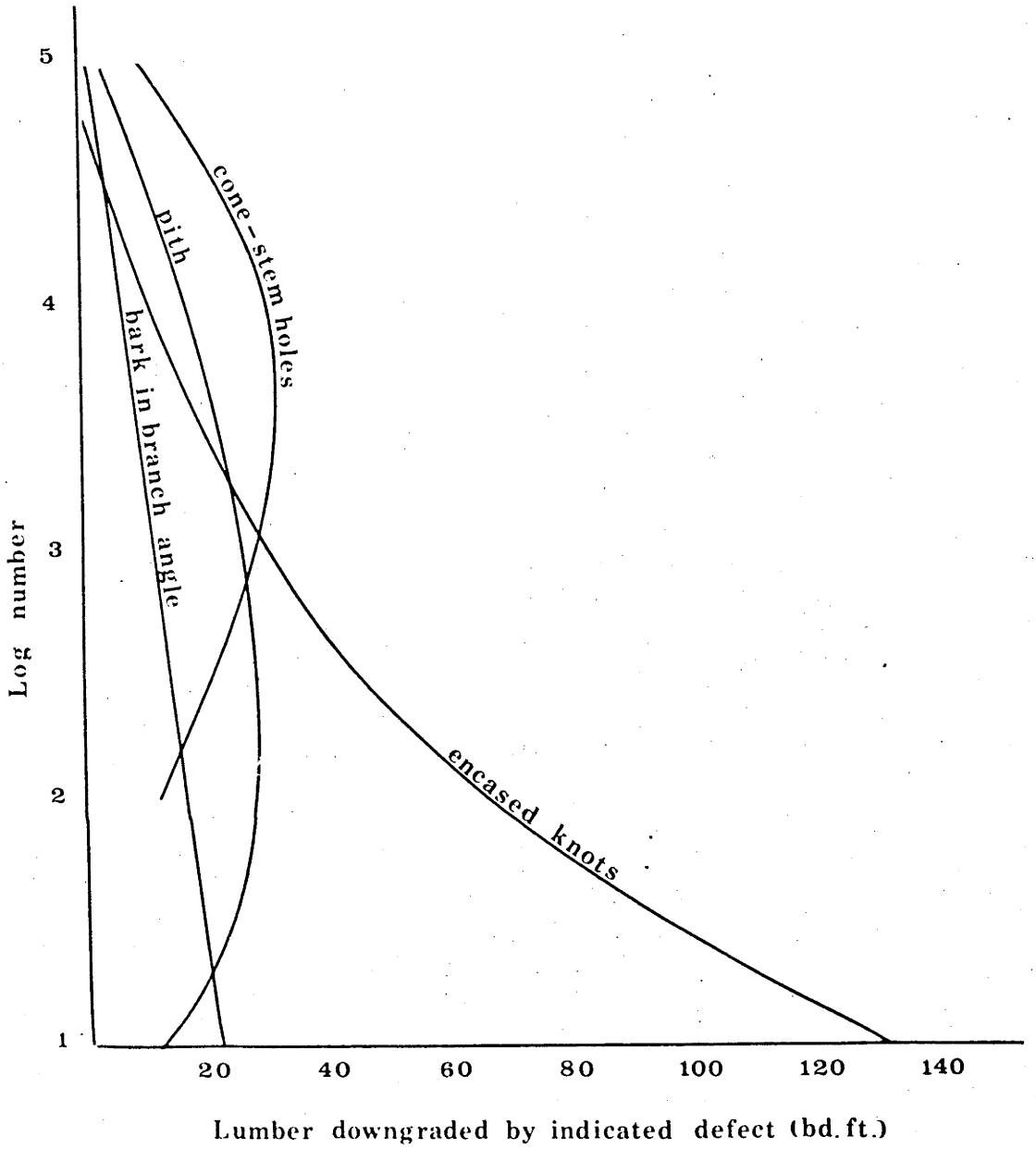
Figure 1   The sources of defect in radiata pine

The Aim and Structure of the Study

The New Zealand Forest Service pruning policy appears to be based upon the assumption that the allocation of resources to pruning is justified by the expected returns. The aim of this study is to critically examine the validity of this assumption.

The question of market opportunities is basic to the decision to prune and is examined in Chapter 2. In Chapter 3 factors affecting the yield of clearwood are reviewed and deficiencies in the knowledge of the determinants of clearwood yield identified. In Chapter 4 empirical analyses of the available data are described and the results are integrated with the results of other research to enable the yields of clearwood from stands to be predicted for a wide range of silvicultural treatments.

After verification of the prediction of the simulation model in Chapter 5, the yields of clearwood from a typical pruning regime and from other regimes are examined, in Chapter 6. In Chapter 7 the model is modified to enable a stochastic analysis of clearwood yield to be carried out. In Chapter 8 the profitability of a typical pruning regime is examined using the clearwood yields predicted by the simulation model.

CHAPTER TWO

THE MARKET FOR CLEARWOOD

Introduction

Investment in clearwood production by pruning is dependent
upon producers' expectations of future clearwood prices.   However,
price and quantity are interrelated through the interaction of
demand and supply and hence an analysis of pruning as an investment
must commence with a consideration of clearwood demand and supply.

The Demand for Sawn Timber in New Zealand

Recent estimates (Hosking, 1972) suggest that per capita
consumption of sawn timber in New Zealand will decrease from
0.571 m^3/cap./ann. in 1970 to 0.496 m^3/cap./ann. by the year 2000.
This is similar to trends forecast for other developed countries
(Gregory, 1970).   Increases in population, however, are expected to
raise New Zealand's total sawlog consumption from 3.81 million
m^3/ann. to 5.02 million m^3/ann. over the same period.   New
Zealand's forests are expected to be able to supply these quantities.

Such forecasts of consumption involve implicit assumptions
about both the demand for and supply of sawn timber which may affect
their reliability.   A demand schedule is a statement depicting how
the quantity of a commodity that purchasers are willing to purchase
in a given market in a given period of time, changes with price.
Similarly a supply schedule is a statement depicting how the quantity
of a commodity that producers are willing to sell, in a given market
in a given period time, changes with price (Saether, 1971).

A forecast of consumption thus involves forecasting the future positions of the demand and supply curves. The quantity of the commodity consumed, and the price of the commodity are defined by the intersection of supply and demand curves.

The New Zealand forecasts (Hosking, 1972) discussed above implicitly assume that the price of sawn timber will not change relative to the price of substitute materials. This assumption is valid only if the supply curve for sawn timber is perfectly elastic, or shifts in such a manner that price remains constant when demand changes. The former condition is clearly most unlikely because it ignores the responses of producers to changes in price. The latter condition is also unlikely because it implies producers can manipulate costs to coincide with the predetermined level of price (Gregory, 1955). These forecasts of sawn timber consumption in New Zealand should therefore be treated with caution.

The Demand for Radiata Pine Clearwood

Diverse opinions are held as to the likely future demand for clearwood from radiata pine. Brown (1972) stated that "anything knotty timber can do, clear timber can do better", and Cutler (1970) stated that "there will be markets for substantial quantities of clear timber .... of radiata pine ....". In contrast, statements by A non (1972) that " ...very high quality wood will be in demand for luxury purposes at luxury prices" and Kerr (1972) that "....there will not be a large continuing market for clearwood, .. apart from.... specialist producers there is no need at all for pruning Pinus radiata", express an almost directly opposite viewpoint.

Official forecasts (Grainger, 1960) of the desired proportions
by grades of sawn timber in the year 2000 are:

Finishing (Clears, Dressing and Factory grades)   30 %

Building (No. 1 and No. 2 Framing grades)   47 %

Rough (Box and Merchantable grades)   23 %

Thus, assuming that no clear grades are put to structural use,
the consumption of finishing and clear grades could reach about
1.5 million m^3/ann. by the year 2000 if the forecasts by Grainger (1960)
and Hosking (1972) are accepted.

As noted above, the forecasts upon which this estimate is
based should be treated with caution and an examination of the demand
for clearwood on a purely deductive basis may be more useful.

The demand for clearwood is obviously derived from the demand
for the commodities of which it is a component.   According to
classical economic theory (Marshall, 1947) the derived demand for a
product will be more inelastic:

(i)   the more essential the factor being examined,

(ii)   the more inelastic the demand for the final product,

(iii) the smaller the fraction of total cost that goes to the factor,

(iv)   the more inelastic the supply curves of other factors.

On the basis of current technology the major uses for radiata
pine clearwood could be for structural purposes, for joinery and
furniture manufacture, or for veneer manufacture.   Radiata pine
clearwood is not essential in any of these three uses.   This fact is
likely to be of overwhelming importance in determining its elasticity
of demand.   The demand for radiata pine clearwood is therefore likely
to be highly price elastic;   a small change in its price relative to

the price of substitutes could cause large changes in the quantity of clearwood demanded.

McConchie (1970 a) recognised potential substitution as an important consideration when examining proposals to produce clearwood by pruning. He suggested that substitutes in the form of reconstituted board products, and various forms of butt and edge jointed timber would be significant in determining the consumption of clearwood.

Fenton (1972 b) considered the risks of profitably marketing clearwood internationally to be low. Bunn (1970) and Sutton (1970 a) suggested that New Zealand has a comparative advantage in the production of radiata pine clearwood by virtue of exceptionally high growth rates. They considered that the North A merican market would provide a profitable outlet for all the clearwood that New Zealand is likely to produce. These opinions are not grounded on any rigorous economic analysis of international markets. The fact remains that the price of radiata pine clearwood relative to the price of substitutes will remain an important determinant of demand on both domestic and overseas markets.

The effects of other variables influencing the demand for clearwood in New Zealand are imperfectly understood. If clearwood is used for structural purposes the characteristics of demand are likely to be similar to those for sawn timber in general. Ferguson's (1973 a, b) work suggested that the income elasticity of demand for sawn timber in Australia was declining, but was approximately unity. The elasticity of demand with respect to the proportion of flats to dwellings, was less than unity. This fact was thought to be an important determinant of future levels of sawn

timber consumption in view of the shift from single to multifamily dwellings.

The demand for clearwood for joinery and furniture or veneers, however, may exhibit characteristics quite different from those expected of sawn timber. Aesthetic appeal is an important element in many of the final products and could result in an increasing income elasticity. Nevertheless, clearwood will still have to compete with new products in other commodity groups such as plastics, steel and glass and demand is therefore likely to be price elastic.

Clearly there is considerable scope for research into the factors affecting the demand for radiata pine clearwood in New Zealand. The evidence suggests that the total demand both in New Zealand and internationally will be highly price elastic. On the domestic market, the increases in demand associated with population may be offset by the decreases in per capita sawn timber consumption brought about by price substitution. Hence the net shift in the demand for clearwood may not be very large.

The Supply of Radiata Pine Clearwood

McConchie (1970 b) has estimated that if the area pruned in exotic State Forests is increased to 6 000 ha/ann. (15,000 acs./ann.) by 1975, 25 % (1.0 million m^3) of New Zealand's exotic sawlog requirement (sic) in 1990 could be supplied from pruned logs.

However, Fenton (1970) suggested that past pruning in State Forests had been so poorly executed that less than 8 093 ha (20,000 acs.) of the 40 064 ha (99,000 acs.) pruned before 1966

could be expected to yield substantial amounts of clearwood in the
next 30 years. Pruning carried out since 1966 was anticipated to
give better results, but little exotic clearwood was expected to be
available before the year 2000 unless pruned stems on high quality
sites were allowed to grow at a faster rate.

New Zealand Forest Products Ltd. has an estimated volume of
4.2 million m^3 of pruned logs available over the next 20 years
(Hyam, 1973), but the proportion of clearwood in this volume is not
known.

The estimates discussed above, and recent official estimates
(Hosking, 1972) of the supply of sawn timber are estimates of
availability rather than supply. They ignore the influence that
price will have upon the willingness of producers to supply
clearwood to the market. A s in the case of clearwood demand, a
deductive analysis of the supply of clearwood may be more useful.

The decision to invest in the production of clearwood by
pruning is dependent upon producers' expectations of profits. The
investment will be undertaken only if the profits are sufficiently
great. However, investment in clearwood production necessitates
investment in the production of other forms of wood. Once the
investment in pruning is made, it loses its identity and becomes
part of the larger investment in wood production.

In deciding to harvest a stand of pruned trees, producers
will consider the prices they expect to receive in relation to the
minimum acceptable price, or reservation price, which they have
established for the total investment in the stand. Since the
pruning investment has been made and is therefore a sunk cost, the
decision to cut is not likely to be affected appreciably by the

price of clearwood. The supply of clearwood is thus likely to be largely inelastic with respect to price.

Current management in New Zealand's exotic State Forests is dominated by the necessity to eke out wood supplies from the pre 1940 age classes to avoid an expected deficit in the 1986-1995 decade caused by the low planting rates of the 1930's. The supply of clearwood until the late 1980's will therefore be relatively static and small.

As pruned stands are utilised to supply the domestic and international demand for wood from 1990 onwards, the supply curve for clearwood will shift rapidly outwards. This movement will continue as the increasingly large acreages pruned since the 1940's are utilised.

However, subsequent shifts in the clearwood supply curve beyond the turn of the century will depend upon the expectations of profitability by today's potential clearwood producers. These profits will depend on the future prices. Hence the supply curve after the year 2000 may well be price elastic to some degree since we are no longer dealing with sunk costs.

The Price of Clearwood

Previous New Zealand studies of the profitability of afforestation have assumed that clearwood would currently command prices of approximately $55/m^3 to $68/m^3 (Fenton et al, 1963; Brown 1965, 1969; Fenton 1972).

With an elastic demand, which is not expected to increase substantially over the next 30 years, and an inelastic supply, the price of clearwood is not expected to change substantially

before the year 2000. Hence the above price range can be used as
an initial guide in an analysis of the pruning decision.

If pruning proves to be profitable at these prices, the
present policy will have been justified. Continuation of the
policy would ensure that future supply continues to shift outwards
roughly in balance with the expected aggregate demand. Future prices
beyond the turn of the century would therefore be unlikely to change
greatly from the present levels.

However, if pruning proves unprofitable, revision of the
pruning policy of the New Zealand Forest Service might result in a
static level of supply, or at least a lower rate of increase.
Increases in aggregate demand might then result in increases in the
price of clearwood relative to present levels which would in turn
improve profitability. This illustrates the interdependence of price
and quantity which must exist in a market where one seller is dominant.
In essence it means that a marginally unprofitable verdict based on
the existing forecasts of future price would necessitate a much closer
examination of the price-quantity relationship and re-examination of
the profitability of pruning in this light.

FACTORS AFFECTING THE YIELD OF CLEARWOOD FROM RADIATA PINE.

Introduction

Clearwood yield from a pruned log of a given length is determined by the interaction of sawing pattern and log characteristics. The most important log characteristics are log diameter, log shape, and the diameter of the knotty core, more accurately defined as the diameter over pruned stubs of the largest pruned whorl including an allowance for occlusion defect. Log characteristics are determined by the influences to which the pruned section of the tree was subjected during its life. Those influences include rotation length, thinning treatment, pruning treatment, site factors and genetic influences.

The Effect of Sawing Pattern

There have been a number of trials in which the yields of clearwood resulting from different sawing patterns have been examined. However, the effect of sawing pattern in these trials has been confounded by the different pruning and silvicultural histories of the stands yielding the pruned logs.

The logs sawn in the trial described by Brown (1965) had received intensive pruning to heights of 13.7 m to 15.2 m (45 ft to 50 ft) over a period of 20 years, with individual pruning lifts as little as 0.9 m (3 ft). The individual tree diameters at the top of each lift ranged from about 7.6 cm (3 inches) at the first pruning lift to about 17.8 cm to 20.3 cm (7 to 8 inches) at the last

pruning lift.

The logs sawn in a later trial reported by Brown (1969) were pruned to 4.9 m (16 ft) in three lifts occurring between stand heights of about 6.1 m (20 ft) and 12.2 m (40 ft) leaving a clear bole of 5.5 m to 6.1 m (18 ft to 20 ft) in length. Thinning of unknown intensity was carried out concurrently with pruning.

Fenton et al (1971) published the results of sawing butt logs of a stand which had been pruned to heights ranging from 6.1 m to 16.8 m (20 ft to 50 ft) by age 17 to 19 years. First pruning was to heights of 1.8 m to 2.4 m (6 ft to 8 ft) at age 6 years, and the second lift was 5.5 m (18 ft) at ages ranging from 8 to 10 years. First thinning was to 618 stems per hectare (s.p.h.) (250 stems per acre) at age 9 years and second thinning was to 198 stems per hectare (80 stems per acre) at ages 17 to 19 years.

Sawing patterns in all three trials produced mainly boards of 2.54 cm (1 inch) thickness. The trial reported by Fenton et al (1971) involved cutting one face until a defect appeared; the logs were then turned 180° and the process repeated. The remainder of the log was subsequently reduced to a cant of commercial width and conventional through and through sawing continued. This 'flat' sawing pattern was designed to yield the maximum volume of wide clear boards using a vertical band headrig fed by a Pacific log carriage.

Fenton (1967) showed that flat sawing of radiata pine logs gave higher conversions to sawn timber than logs that were either quarter or taper sawn. Clearwood yields were also correspondingly higher in logs that were flat sawn.

Clearwood yields obtained from experimental sawing trials are probably higher than those which would be obtained from normal commercial practice (Fenton, 1967). Calculations of the profitability of pruning based on the results of such sawing trials may therefore be biased. However, advances in the technology of sawing are likely to reduce the bias to negligible proportions over the long time horizon with which this study is concerned.

The Effect of Log Characteristics

Log diameter has been shown to be important in determining clearwood yields in both theoretical studies (Fenton et al, 1963; Sutton, 1970 b) and in sawing trials (Fenton et al, 1971; Brown, 1965, 1969).

In sawing trials the clearwood yields from pruned logs of varying diameter have been determined, and functions relating clearwood yield to log size, expressed as basal area, diameter breast height over bark (D.B.H.O.B.) or small end diameter inside bark (S.E.D.I.B.) have been established by regression analysis. Thus Brown (1969), using the data from two sawing trials (Brown 1965, 1969) suggested that the following equation should be used where pruning had produced a knotty core of less than 23 cm (9 inches) in diameter:

$$Y = -0.1652 + .000183\ X \qquad (1)$$

Where: Y = clearwood yield (m^3) from a 5.5 m (18 ft.) log,

X = small end diameter inside bark (cm).

The minimum length of clear board included in the data on which this equation was based was 1.5 m (5 ft).

Fenton et al (1971) presented the following equation to predict clearwood yield derived from data obtained by sawing 15 well-pruned dominant stems:

$$Y = -0.1185 + 1.3554 \, X \tag{2}$$

where Y = clearwood yield (m^3) from a 5.5 m log length,

X = tree basal area over bark (m^2).

The minimum length of clear board included in the data used to derive this regression was 1.8 m. The average knotty core diameter was 25.4 cm (10 inches).

The differences between equations (1) and (2) cannot be tested statistically because equation (1) was subjectively derived by Brown, and the independent variables differ. However, if due allowance is made for the difference between D.B.H.O.B. and S.E.D.I.B. the equations predict similar yields of clearwood from trees of equivalent D.B.H.O.B . Both equations indicate that clearwood yield increases in proportion to the square of the diameter of the pruned log.

Theoretical studies of expected clearwood yield have attempted to predict the volume of clearwood that could be sawn from a log by considering log size, log shape and specific cutting patterns. These studies have assumed that the logs were perfectly regular in shape, were symmetrical and had centrally placed defect cores (Brown 1965). The results of these studies indicated that clearwood yields were likely to range from 0 % of total sawn yield in small logs with large defect cores, to a maximum of about 95 % of

total sawn yield for a 66 cm (26 inch) D.B.H.O.B. log with a 10.2 cm (4 inch) core diameter.

These studies also indicated that an increase in D.B.H.O.B. of 6.4 cm (2.5 inches) was necessary to compensate for the clearwood lost by a 2.5 cm (1 inch) increase in knotty core diameter. This finding applied over a wide range of knotty core and butt log diameters (Sutton 1970 c).

Log shape also affects the efficiency of conversion to sawn timber. Lonn (1970) and MacDonald et al (1970) presented data indicating that the presence of sweep in a log will cause a large reduction in sawn yield. A 10 mm sweep, for example, in a 4.6 m log length will reduce timber yield by about 20 % compared with straight logs (Lonn, 1970). Theoretically, sweep becomes more important as log diameter decreases and as log length increases (MacDonald et al, 1970). Clearwood yields decrease as sweep increases.

The effect of taper on the efficiency of conversion does not appear to have been established quantitatively. With flat sawing, increased taper will reduce clearwood yields, but with taper sawing it may have little effect (K. Groves, pers. comm.).

Data from sawing trials described by Fenton et al (1971) were insufficient to establish empirically the influence of knotty core diameter in determining clearwood yield (Fenton et al, 1971). However, Brown (1969) used data from two sawing trials (Brown 1965, 1969) to establish a relationship between D.B.H.O.B. and knotty core diameter, excluding occlusion defect. The relationship was:

$$Y = -0.1010 + 0.000199 \times D^2 - 0.000094 \times K^2 \quad (3)$$

where:
Y = clearwood yield (m^3),

D = D.B.H.O.B (cm),

K = knotty core diameter (cm), excluding occlusion defect.

It is reported in Brown (1969) that "neither of the regressions on K nor K^2 can be regarded as significant. However the use of K (or K^2) in conjunction with D.B.H. (or D.B.H.^{2}) does result in a significant improvement in the regression." These statements are ambiguous because it is still not clear whether knotty core results in a significant improvement over and above that produced by D.B.H.O.B.

Knowles (1970) reported data on branch size and the radial growth required to occlude branch stubs. Sutton (1970 c) used this data together with equation (3) to calculate the increase in final log D.B.H.O.B. required to compensate for a 2.5 cm (1 inch) increase in knotty core diameter. In contrast to theoretical studies he found that an increase of only 1.0 cm to 1.3 cm (0.4 to 0.5 inches) in final log D.B.H.O.B. was necessary to compensate for a 2.5 cm increase in knotty core diameter. Sutton (1970 c) concluded that he had used equation (3) outside the range of the data used to derive it and that the equation had been based on data from a biased sample.

The results of Sutton's (1970 c) study however, together with
the negative coefficient for knotty core in equation (3), and the
results of the theoretical sawing studies, indicate that increases
in the knotty core diameter do reduce clearwood yield. However,
more research is required to establish precisely how clearwood yield is
related to knotty core diameter.

As expected the clearwood yields predicted from theoretical
considerations exceed those obtained in sawing trials. The
presence of unexpected and unpredictable defects, caused by for
example stem cone holes, and site induced defects such as resin
pockets, resin streaks, sweep and log eccentricity (Chandler, 1970)
would account for a substantial proportion of the discrepancies.

The Effect of Site and Rotation Length on Log Characteristics

Site Index is a measure of the productivity of a site. It is
normally expressed in New Zealand as the mean height on a stand
height-diameter curve corresponding to the 100 largest trees per acre
(Lewis, 1954). Basal area increment and volume increment over time
are generally well correlated with height increment over time. Thus
stands with high site indices produce larger trees in a given
rotation length: larger trees produce more clearwood.

Site also affects taper. Generally the better the growing
conditions, the greater the diameter increment on the lower bole.
Conversely, the less favourable the growing conditions, the less
increment is obtained. However, both trees and stands may react
differently to the same treatments depending upon the site (Whyte,1970).

Site affects knotty core diameter through its effect on stem diameter growth, tree shape, taper and branch growth.

An extensive pruning trial in New Zealand reported upon by Sutton et al (1968, 1970, 1972) provided some data concerning the relationship between D.B.H.O.B. and the diameter over stubs of the largest pruned whorl for various pruning lifts. In general, the diameter over stubs of the largest pruned whorl increased by 0.5 cm (0.2 inches) for every 0.31 m (1.0 ft) increase in stand mean height. The data from this trial indicated that diameters over stubs of the largest pruned whorl were equal to:

(i)   D.B.H. at time of pruning plus 4.1 cm in low pruning,

(ii)   D.B.H. at time of pruning plus 1.5 cm in a pruning lift with a base of 2.1 m,

(iii)   D.B.H. at time of pruning plus 0.8 cm in a pruning lift with a base of 3.1 m,

(iv)   D.B.H. at time of pruning minus 0.8 cm in a pruning lift with a base of 4.3 m.

No levels of reliability were given for these estimates, and the effect of stocking, if any, on these relationships was not considered.

This trial also provided an indication of how the diameter of the largest branch for the low pruning lift (0.00 m - 2.1 m) changed with an increase in stand height. The diameter of the largest branch in the lower 2.1 m of the stem increased by approximately 0.76 cm (0.3 in) with every 0.31m(1.0 ft.) increase in stand mean height. Again no estimate of the accuracy of the relationship was given, and the effect of stocking, if any, was not considered.

No estimates of relationships between stand height or D.B.H. and the largest branch diameter in other portions of the lower 6 m of a radiata pine stem appear to have been made.

Branch measurements from spacing trials in several localities clearly indicate that soil fertility has a marked influence on the initial stocking-branch size relationship (Bunn, 1970). Will (1970) has also shown that nutritional factors affect branch growth. Nitrogen and phosphorous deficiency reduced branch growth relative to stem growth in New Zealand. Cromer et al (1957) however, showed that initial stocking affected branch diameter only to the extent that stem D.B.H.O.B. was affected. Wright, J. (1970) stated that the effects of site index and silvicultural treatment on branch size are negligible over and above their effects on tree size.

Thus for a given site, branch size may be dependent upon stem diameter. However, site affects rates of diameter growth of branches over time because it determines the rate of stem diameter growth.

Studies in New Zealand (Knowles 1970) and in Australia (Brown et al, 1957) established that the amount of radial growth required to occlude a pruned branch stub was a function of the diameter of the branch at the time of pruning. A function relating the amount of radial growth required to occlude and branch diameter was established by Knowles (1970):

$$Y = 0.84 + 0.36 X \tag{4}$$

where: Y = radial growth (cm) required for occlusion,

X = branch diameter (cm) at the time of pruning.

Knowles (1970) stated that the regression was significant at the 99.9 % probability level. Equation (4) gives results similar to those given by an equation determined by Brown et al (1957) when shears were used as the pruning tool.

The effect of site on clearwood yield is thus twofold. On higher site indices, the rate of clearwood production is increased because the time required to reach a given final log diameter is decreased. However, stands on higher site indices must be pruned at an earlier age if the knotty core diameter is not to be increased and clearwood yield thereby reduced.

The Effect of Thinning on Log Characteristics

Clearwood yield would presumably be increased if increment could be concentrated as early as possible upon pruned stems. Thus if maximum clearwood yield is the objective, thinning to remove all but the final crop trees should be accomplished as soon as possible.

However, the effect of thinning on branch development in the lower 6 m of a radiata pine stem has not been established. If thinning prior to the completion of pruning increases knotty core diameter via an effect of branch diameters and the radial growth required for subsequent occlusion, clearwood yields may be reduced. For this reason Whiteside (1962) suggested that thinning should be delayed until pruning had been completed.

The timing of thinning treatment needs close attention in relation to pruning, both from the point of view of maximising clearwood yield and of minimising tending costs. The costs of non-commercial thinning to a nominated stocking increase as the stand ages, but the costs of pruning are decreased if carried out before

thinning (T. W. Johnson, pers. comm.). On the other hand, errors in tree selection can be rectified if pruning is carried out prior to thinning, and selection of trees to remain after a thinning is aided if selection for pruning has been carried out beforehand. Where pruning and thinning are scheduled at the same age the New Zealand Forest Service adopts the practice of completing the pruning operation before thinning.

No published research is available on the effect of thinning on taper of radiata pine stems. However, studies with other species (Whyte 1965) have established that thinning increases diameter growth at breast height to a greater extent than at points further up the stem. Taper therefore increases as the intensity of thinning increases.

Fenton et al (1971) reported that butt log volumes from trees with an average D.B.H.O.B. of 59.4 cm (23.4 in) taken from a radiata pine stand in New Zealand which had received moderate pruning and thinning treatment exceeded the average volume of butt logs of equivalent D.B.H. from unthinned stands by 10 to 12 %. This finding therefore conflicts with the evidence obtained from other species. Nevertheless, if the intensity of thinning is increased after pruning is completed the rate of clearwood production should increase ceteris paribus.

The Effect of Pruning on Log Characteristics

There is a lack of quantitative data describing the interaction of pruning treatment, stand density and taper in radiata pine stands in New Zealand.

Farrar (1961) concluded that the thickness of the annual rings
in a stem was greatest adjacent to the nodes whose branches carried
the greatest amount of foliage. A tree with green foliage extending
from the apex to the base produces an annual ring of approximately
uniform thickness, but which thickens slightly toward the base, and the
stem is therefore tapered. As a stand grows older, natural shading
causes the base of the green crown to rise and the thickness of the
annual ring near the base of the stem decreases. The region of
maximum annual ring thickness therefore moves up the stem and the
lower stem becomes more cylindrical. Green pruning accelerates the
rise in the base of the green crown, so that the point of maximum
annual ring thickness moves up the stem as the tree is pruned.

Heavy thinning stimulates diameter growth in the lower portion
of the bole. Green pruning stimulates diameter growth in the upper
portion of the bole. Combination of the two treatments causes the
stem to become more cylindrical, and as a result the volume of a
pruned log may exceed that found in unthinned and unpruned stands.
This probably explains the results found by Fenton et al (1971)
reported earlier.

The effect of pruning on branch development above the pruned
portion has been established by Jacobs (1938). Severe green pruning
of radiata pine in Australia increased the size and acuteness of
branches just above the pruned zone.

Pruning has been closely studied for its effect on basal area
increment, and hence for its effect on final log characteristics.
Brown (1962) summarised the effects of pruning on the growth of
conifers as follows:

(i)   Removal of 25 per cent of the green crown has little or
        no effect on either diameter or height increment.

(ii)   Removal of 75 per cent of the live crown causes a severe
        depressing effect on diameter increment, and there is
        likely to be permanent loss of total volume production.

(iii)   The effect of intermediate degrees of pruning is variable.
        Removal of 50 per cent of the crown may reduce increment
        for several years after pruning and there may be permanent
        loss of diameter growth, but there is little evidence if
        any that volume loss is economically important.

(iv)   The effect on height increment follows somewhat similar
        lines, but the relative magnitude of the effect is much
        less.

(v)   Where only a select proportion of the trees are pruned,
        unpruned neighbours may suppress pruned stems.

        In contrast to much of the earlier work on which the above
conclusions are based, pruning may have quite severe depressing
effects on height increment in the case of radiata pine in New
Zealand (Sutton et al, 1970, 1972).

        The severity of a pruning treatment should be expressed as the
proportion of green crown removed (Brown, 1962). Removing the
shade crown (Beekhuis, 1965) may not depress increment because
moribund branches have been shown to be parasitic on the green
crown in some species (Smith, 1962). In the past, pruning severity
has often been expressed as the height to which pruning was
carried out. Alternatively, the height of pruning as a proportion
of tree height has been used to express pruning severity. For
this reason, most of the results of the effect of pruning severity
on diameter increment

reviewed by Mar; Moller (1960) are open to criticism.

Brown (1962) in discussing the severity of pruning treatments, defined 'potential green crown depth' as the length of the crown from the crown tip to the crown base (a point midway between the lowest green branch and the lowest green whorl) which would exist in an unpruned radiata pine stand at a given stand density. A number of workers (Whiteside, 1962; Brown, 1962; Beekhuis, 1965) have investigated the rise in the base of the green crown as a stand ages. The trend for the base of the green crown to rise once a critical stand height has been reached is well established. This critical height is dependent upon stocking, with wider spacings maintaining deeper green crowns at a given stand height. Site may also influence the relationship between green crown depth and stocking, and the rate at which the base of the green crown rises may be influenced by age independently of stocking. In younger stands, the base of the green crown rises at a more rapid rate over time than it does in older stands (Beekhuis, 1965).

Brown (1962) developed the data in Table 2 from data presented by Mar:Moller (1960). These data relate the proportion of potential green crown removed by pruning to the proportion of annual basal area increment lost. Brown suggested that the data would be applicable to radiata pine in New Zealand.

TABLE 2:   THE RELATIONSHIP BETWEEN THE PROPORTION OF ANNUAL
BASAL AREA INCREMENT LOST AND THE PROPORTION OF POTENTIAL
GREEN CROWN REMOVED BY PRUNING

Proportion of Potential green crown removed	Proportion of annual basal area increment lost
0.20	0.01
0.30	0.08
0.40	0.20
0.50	0.37
0.60	0.57
0.70	0.76

Expressing pruning severity as the proportion of potential
green crown removed implies that the severity of pruning depends
upon age and stocking, and that the effect of pruning on basal area
increment will be temporary.   The data in Table 2 appear to
confirm this.   Pruning will have less effect on increment if
stands are closely spaced, and the effect will be reduced as the
stand ages and the base of the green crown rises, reducing the
proportion of green crown removed by pruning to a given height.

The Effect of Initial Stocking on Log Characteristics

Initial stocking will influence the characteristics of the log and the yield of clearwood primarily through its effect on the diameter of the stem at the time of pruning. Wide initial spacing would increase stem diameter but increase taper at a given age, and _ceteris paribus_, may increase the diameter of the defect core.

Larger branches at the time of pruning associated with wider spacings will increase the radial growth required to occlude cut stubs. However, branch development is no greater between than along rows (Sutton, 1968) and the advantages conferred by wide initial spacings in respect of establishment and thinning costs will be realised by using rectangular spacing. Rectangular spacings have been recommended for most of the recently published sawlog regimes involving pruning (e.g. Fenton, 1972 a).

The Effect of Genetic Influences on Log Characteristics

Shelbourne (1970) provided a comprehensive review of progress with breeding radiata pine in New Zealand.

The rate of growth determines the rotation length required to produce a tree of a given size. Growth rate is genetically controlled and moderately heritable. Improvements of growth rates of the order of 16 % are possible if the most vigorous clones are selected.

Bole straightness is of particular importance to the yield of clearwood. Sinuousity in the knotty core increases its effective diameter and reduces the proportion of defect free boards produced. The heritability of bole straightness is high,

but fertile sites generally produce more bole sinuousity than infertile sites.

There is a wide range in the number of whorls produced each year in radiata pine, and uninodal and multinodal extremes are distinguishable. This characteristic is highly heritable, but the characteristics of branches within each tree type are only moderately heritable.

Branch size is correlated with nodality, uninodal trees having fewer larger branches than multinodal trees. Branch angle and the incidence of stem cone holes is important for board production. Steeply angled branches tend to be of larger diameter, and clusters of steeply angled branches form weak points in the stem that are liable to wind breakage. This characteristic is not highly heritable. The occurrence of stem cones is also not highly heritable but uninodal trees are much less likely to produce stem cones in the second and higher logs.

The desirability of uninodal or multinodal branching habit in trees where butt logs will be pruned rests largely on the characteristics of the logs above the butt, apart from the effect of branching habit on pruning costs and the radial growth required for occlusion. Where production of boards is the objective, uninodal trees are desirable because boards with a large proportion of short clears (factory grade) can be produced from between the nodes. Multinodal trees grown at spacings required to maximise increment on pruned butts will result in large proportions of the lower timber grades being produced from the second log (5.5 - 11.0 m). Unfortunately, truly uninodal trees are not common, and this has led

to the proposal by Fenton (1972 a) to prune the second log, in order
to maintain grade yields.

Shelbourne (1970) ranked genetically controlled characteristics,
in order of decreasing importance for the production of boards,
short clear grades, and clear veneers as follows:

(i)   straightness, fast growth, and freedom from malformation

(ii)   uninodality

(iii)   long lived branches

(iv)   small branch diameter

(v)   flat branch angle

(vi)   freedom from stem cones in the second and higher logs.

He concluded, however, that further progress in tree
improvement in New Zealand is limited more by the lack of
quantitative knowledge concerning the economic significance of
tree characteristics in the production of particular end products,
than by any other factor.

Conclusions

Sawing pattern influences the yield of clearwood from a
pruned log, but the volume of clearwood in the log and the physical
characteristics of the log are more important than the sawing
pattern.

Research has shown that the diameter of the knotty core, and
the diameter of the log at rotation age are important characteristics
amenable to manipulation by appropriate silvicultural practices.

Site is also an important determinant in clearwood
production through its influence on growth.

Thus pruning treatment, thinning treatment, site index, initial stocking and rotation length interact to determine the clearwood yield. No attempt has yet been made to integrate these factors to enable the effects of different management strategies on clearwood yield to be tested prior to practical implementation.

Although there are many deficiencies in the present knowledge of factors affecting clearwood yields, the results of the research described above suggested that the construction of a model to predict clearwood yields for various alternative management strategies would be extremely useful.

CHAPTER FOUR

A SIMULATION MODEL TO PREDICT THE YIELD OF

CLEARWOOD FROM RADIATA PINE

Introduction

Clearwood production in radiata pine depends mainly upon
the diameter of the pruned log, and the diameter of its knotty core.
The first step in predicting clearwood yields is thus prediction of
these characteristics of pruned logs.

The Prediction of Increment and Yield

A growth model to predict the yield and increment of radiata
pine in New Zealand has been constructed by Beekhuis (1966). The
predominant mean height of the stand is used as an independent
variable, instead of age, from which to predict basal area and
volume increment. Predominant mean height is defined as the mean
height of the 40 tallest trees per acre selected one in each 1/40 th
of an acre.

In the model, gross basal area increment is given by the
equation:

$$I_G = I_h \times ((B + 62.0) / (H + 15.2)) \qquad (5)$$

where: I_G = gross basal area increment (m^2/ha) during the growth
period,

I_h = increment in predominant mean height (m) during the
growth period,

B = stand basal area (m^2/ha) at the commencement of the
growth period

H $=$ predominant mean height (m) at the commencement of the growth period.

In the Beekhuis yield model, mortality in terms of stocking is determined from relative spacing. Relative spacing refers to the average distance between trees expressed as a percentage of the predominant mean height of the stand. Mortality first occurs at a relative spacing of 30 %. As predominant mean height increases over time, mortality gradually reduces relative spacing until a minimum value of relative spacing is reached. Thereafter relative spacing tends to remain constant, with further increases in predominant mean height offset by reductions in stocking. Mortality trends in terms of the number of stems which die, are presented graphically in Beekhuis (1966), but Grant (1970) provided a method of calculating mortality algebraically using stocking and height as independent variables. Grant's method was used throughout this study. The mortality trends were derived in the absence of abnormal drought or insect or fungal attack.

Mortality in terms of loss of basal area increment over the growth period is given by the following equation (Beekhuis, 1966) :

$$M = 0.000268 \times D.B.H.^2 \times N \tag{6}$$

where: M $=$ basal area loss (m^2/ha) due to mortality,

D.B.H. $=$ diameter breast height over bark (cm) of the tree of mean basal area at the commencement of the growth period,

N $=$ losses in stems per hectare during the growth period.

Henceforth stand mean diameter refers to the diameter breast height over bark of the tree of mean basal area.

Net basal area increment during the growth period is given by the following equation (Beekhuis, 1966) :

$$I_N \quad = I_G \quad - \quad M \qquad\qquad (7)$$

where I_N equals net basal area increment (m^2/ha) and I_G and M are as defined above.

Total stand volume per unit of basal area is given by the following equation (Beekhuis, 1966) :

$$V/B \quad = \quad 0.914 \quad + \quad 0.3 \quad x \quad H \qquad\qquad (8)$$

where: V = total stand volume (m^3/ha),

B = stand basal area (m^2/ha),

H = predominant mean height (m).

Equations 5, 6, 7 & 8 have been widely used to predict the growth and yield of radiata pine in New Zealand (e.g. Fenton and Sutton, 1968; Fenton and Tustin, 1972; Fenton, 1972 a), but the model has some limitations for predicting clearwood yields on various sites, as follows:

(i) the model is a product of averaged trends, and may be biased if used to predict growth on specific sites (Whyte, 1970),

(ii) the effect of pruning on basal area increment is not specifically incorporated in the model. The bulk of the data on which the model was based was taken from stands aged 11 years or more (Beekhuis, 1966) and it is unlikely that these stands would have received much pruning,

(iii) height-age curves for site indices other than 29 m were not given in the original publication,

(iv)   the model may be unreliable if used to predict growth

in stands where stand basal area (in $ft.^2/ac.$) is less

than predominant mean height (in ft.) (Beekhuis, 1966),

(v)   in the model, thinning is restricted to occur at a

predominant mean height greater than 7.9 m (26.0 ft),

(vi)   the effect of initial stocking on basal area increment

is not incorporated in the model.

In this study the model was used to examine broad growth
trends so the fact that the model is the product of averaged trends
was considered to be of no significance.   However, the effects of
initial stocking and pruning on basal area increment are important
in this study, because basal area increment affects the diameter of
the knotty core and the log size at rotation age, which are
important determinants of clearwood yield.   Furthermore, it
appeared that the thinnings which would yield most clearwood would
occur before predominant mean height reached 7.9 m, and the
resultant basal areas (in $ft.^2/ac.$) would therefore probably be
less than predominant mean height (in ft.) for a portion of the
life of the stands.   It was also considered desirable that the
effect of site index on clearwood yield be incorporated in the model.

Further research and development was therefore undertaken to
enable the Beekhuis model to be used to predict clearwood yields in
stands which covered a range of initial stocking, pruning and
thinning treatment and site index.

Height-Age Curves for Other Site Indices

Site index is expressed as mean top height at age 20 years. Beekhuis (1966) considered mean top height to be synonymous with predominant mean height for all practical purposes and this assumption was adopted for this study.

A set of anamorphic height-age curves (Carron, 1968) was constructed for site indices ranging from 24.38 m (80.0 ft.) to 33.53 m (110.0 ft.) using the height-age curve for a site index of 29 m published by Beekhuis (1966) as the guiding curve. This allowed the effect of site index on growth to be incorporated in the model.

The Effect of Initial Stocking on Basal Area Increment

Both stand height and stocking appear likely to affect early basal area growth. Data from Beekhuis (1966), Wright, G. (1970), Fenton and Tustin (1972), Fenton (1972 a) and from temporary plots established at Kaingaroa Forest were used to establish a relationship between stand basal area, stand predominant mean height and stand stocking. The definitions of stand height differed among the various sets of data and this necessitated the adjustment of stand height to predominant mean height, on the basis of the writer's experience. Predominant mean height is hereafter referred to as stand height.

A number of regressions involving stand height and stocking were tested and the following regression proved most satisfactory:

$$\ln BA \quad = \quad -4.87 \quad + \quad 1.85 \quad \ln H \quad + \quad 0.48 \ln S \qquad (9)$$

where: BA $=$ stand basal area (m^2/ha),

H $=$ stand height (m),

S $=$ stand stocking (stems per hectare),

ln $=$ logarithm to the base e.

Figure 2 illustrates this regression and the range of the data. The analysis of variance is given in Table 1 Appendix A. Both independent variables are significant at the 95 % probability level.

Prediction of Basal Area Remaining After Thinning

Data from Kaingaroa Forest were used to estimate a relationship between the proportion of total stocking remaining after a thinning and the proportion of total basal area remaining after the thinning. The data illustrated in Figure 3 were obtained from stands established at initial stockings ranging from 1 500 to 5 000 stems per hectare on site indices ranging from 24 m to 36 m. First and second thinnings from below had been carried out at stand heights ranging from 5.5 m to 13 m. The estimated relationship was :

$$\ln Y \quad = \quad 0.179 \quad + \quad 0.818 \ln X \qquad (10)$$

where: Y $=$ the proportion of the original basal area

remaining after thinning,

X $=$ the proportion of the original stocking remaining

after thinning.

The regression satisfies the necessary condition of passing through the origin but does not pass through the point (1.0, 1.0). Thus if a thinning removed less than about 20 % of the original stocking, the resulting basal area would be slightly biased. This bias however
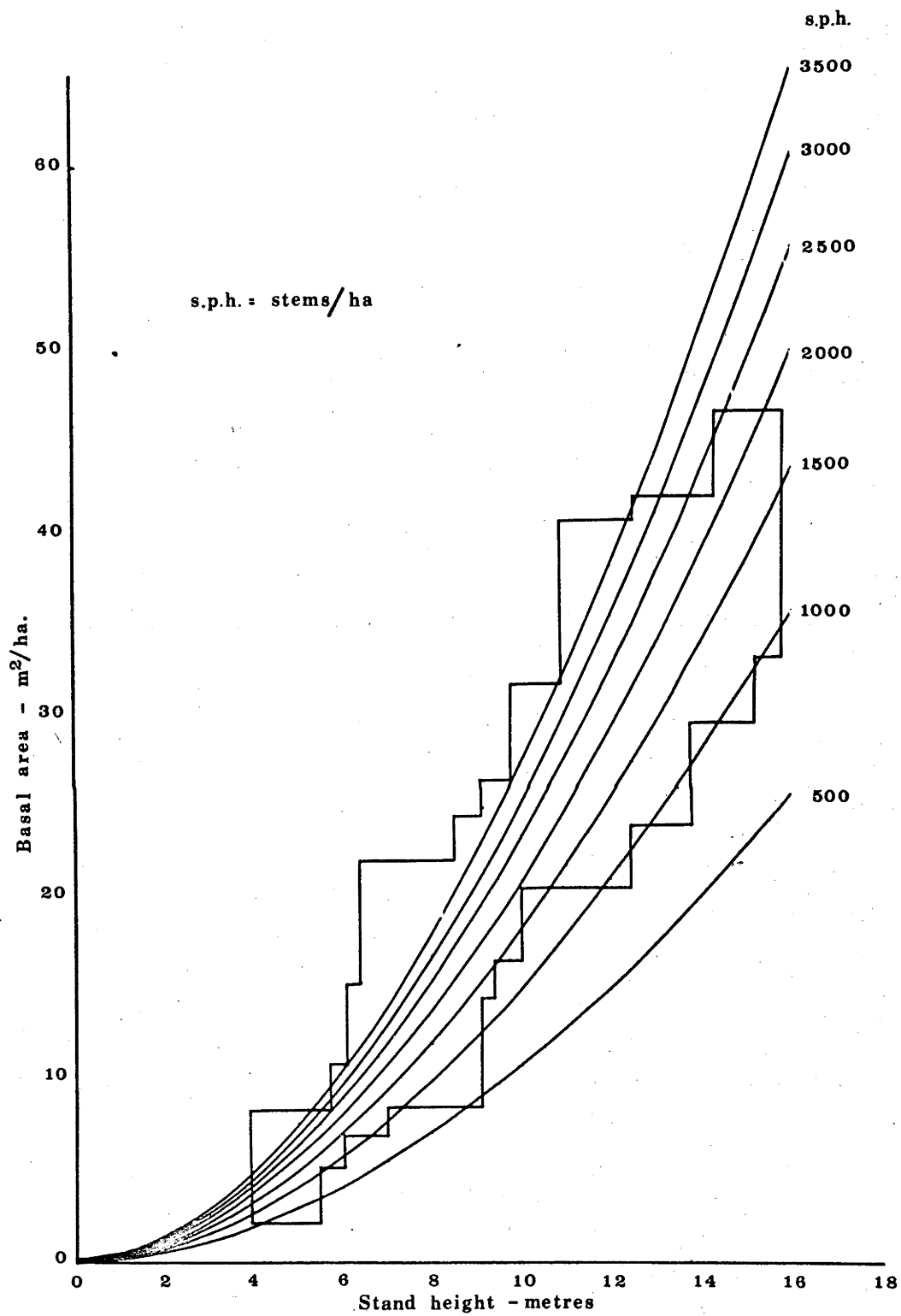
Figure 2   The relationship between stand basal area, stand height and stand stocking
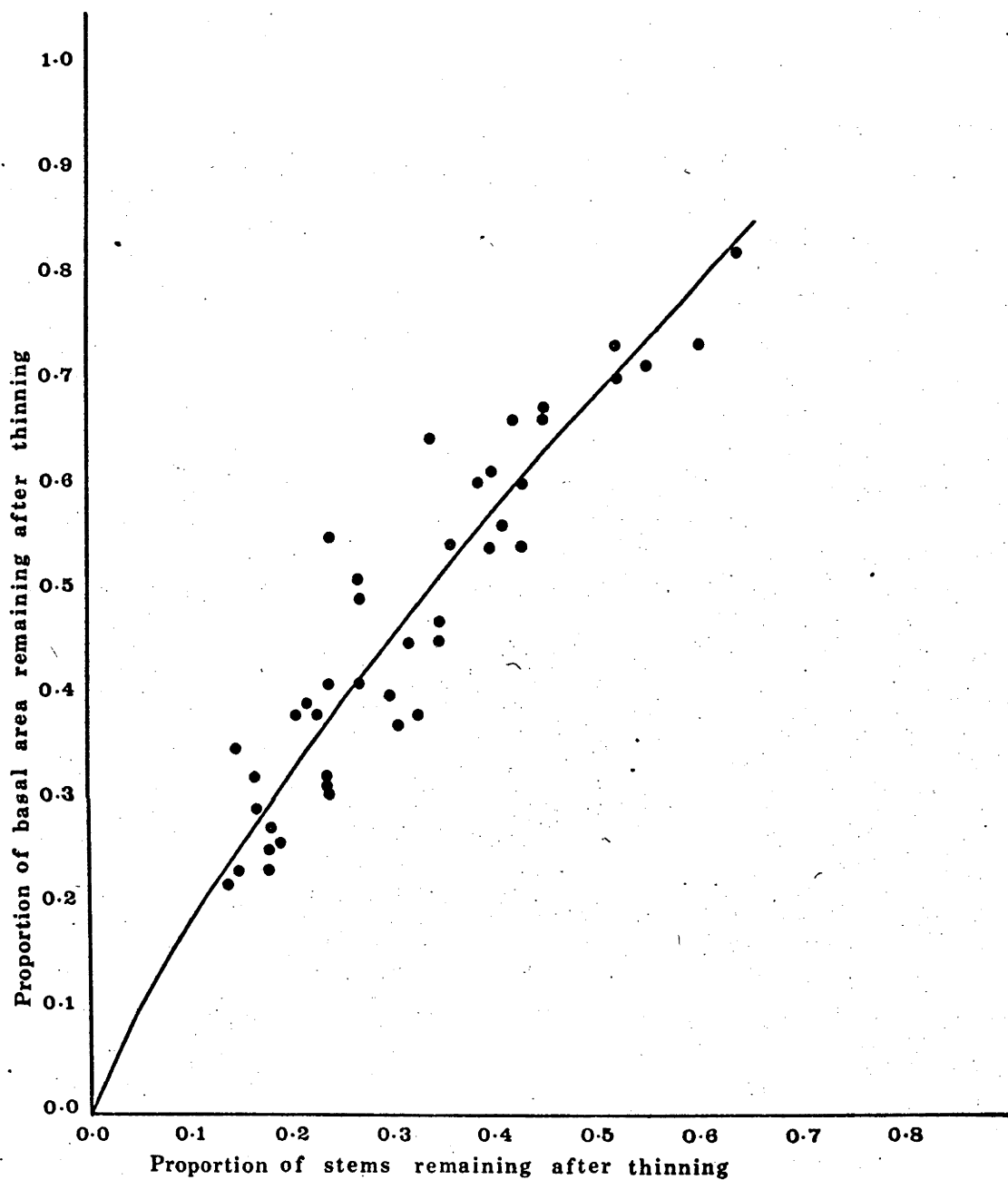
Figure 3   The relationship between the proportion of basal
            area remaining after thinning and the proportion
            of stems removed in thinning

was of no practical significance as all the thinnings examined in subsequent research removed more than 20 % of the original stocking. The analysis of variance for equation 10 is given in Table 2 Appendix A. The regression is significant at the 95 % probability level.

Prediction of Basal Area Increment when Stand Height exceeded Stand Basal Area

A prerequisite for the use of the Beekhuis yield model in the past was an estimate of stand basal area and height taken from a stand in which basal area (in ft.^{2}/ac.) exceeded stand height (in ft.) These data were required to predict basal area increment from the commencement of the first growth period.

In this study, equation 9 was used to calculate the basal area increment before first thinning. Basal area increment in a thinned stand was assumed to be equivalent to that obtained in an unthinned stand of equivalent height and stocking derived from equation 9, until stand height (in ft.) reached the numerical value of stand basal area (in ft.^{2}/ac.). From this point onwards, the basal area increment predicted by the Beekhuis model was used.

An exception to this procedure occurred where basal area (in ft.^{2}/ac.) reached the numerical value of stand height (in ft.) before pruning had been completed. In this case equation 9 was used to calculate increment until pruning was completed. Following pruning the Beekhuis model was used.

In calculating basal area increment it was assumed that mortality in stocking, and hence basal area increment loss associated with mortality, would not occur until pruning was completed and stand height (in ft.) reached the numerical value of basal area (in ft.^{2}/ac.). In most cases, all pruning operations and thinning to about 250 stems per hectare had occurred by the time stand height reached 12 m, and this assumption was probably valid.

Ure et al (1964) showed that the periodic annual basal area increment for the 6 to 7 years following thinning in radiata pine stands between stand heights of 7.3 m to 12.8 m was a function of the stand height at thinning, residual stocking and residual basal area. The use of equation 9 to calculate basal area increment also implies that increment is dependent upon these three variables. Thus, although the method used in this study to calculate basal area increment is somewhat unorthodox, it does not appear to be unreasonable.

The Effect of Pruning on Basal Area Increment

(i)   the severity of pruning

Data on green crown depths at various stockings were collected from stands in Kaingaroa Forest by Brown (1962). Details of the ages and histories of these stands are unknown, but the data would be predominantly from stands occupying a site index of 29 m. A number of regressions relating green crown depth to stocking were fitted to the data but the following relationship proved most satisfactory :

$$D = 1.13 + 367.6 \; x\sqrt{\frac{1}{S}} \tag{11}$$

where: D   = potential green crown depth (m),

        S   = stocking in stems per hectare,

The data are illustrated in Figure 4. Each point is the mean of several observations made by Brown (1962). The regression is significant at the 95 % probability level. The analysis of variance is given in Table 3 Appendix A. Equation 11 gives results similar to those given by an equation derived theoretically by Brown (1962) by considering the amount of growing space available to an individual tree in a stand at various levels of stocking.

By knowing the potential green crown depth existing at a given stand density, the stand height and the height of pruning, the proportion of green crown removed by pruning to a particular height can be determined. The proportion of green crown removed was used as an index of the severity of pruning.

(ii)   the relationship between the severity of pruning and increment loss

An equation relating the proportion of annual basal area increment lost through pruning to the proportion of the green crown removed in pruning to a specific height was estimated from the data provided by Brown (1962). (See Table 2 in the previous chapter). This equation was :

$$\ln Y = 1.23 + 3.4 \ln X \tag{12}$$

where: Y   = proportion of annual basal area increment lost,

        X   = proportion of green crown removed,

       ln   = logarithm to the base e.

The equation is illustrated in Figure 5.
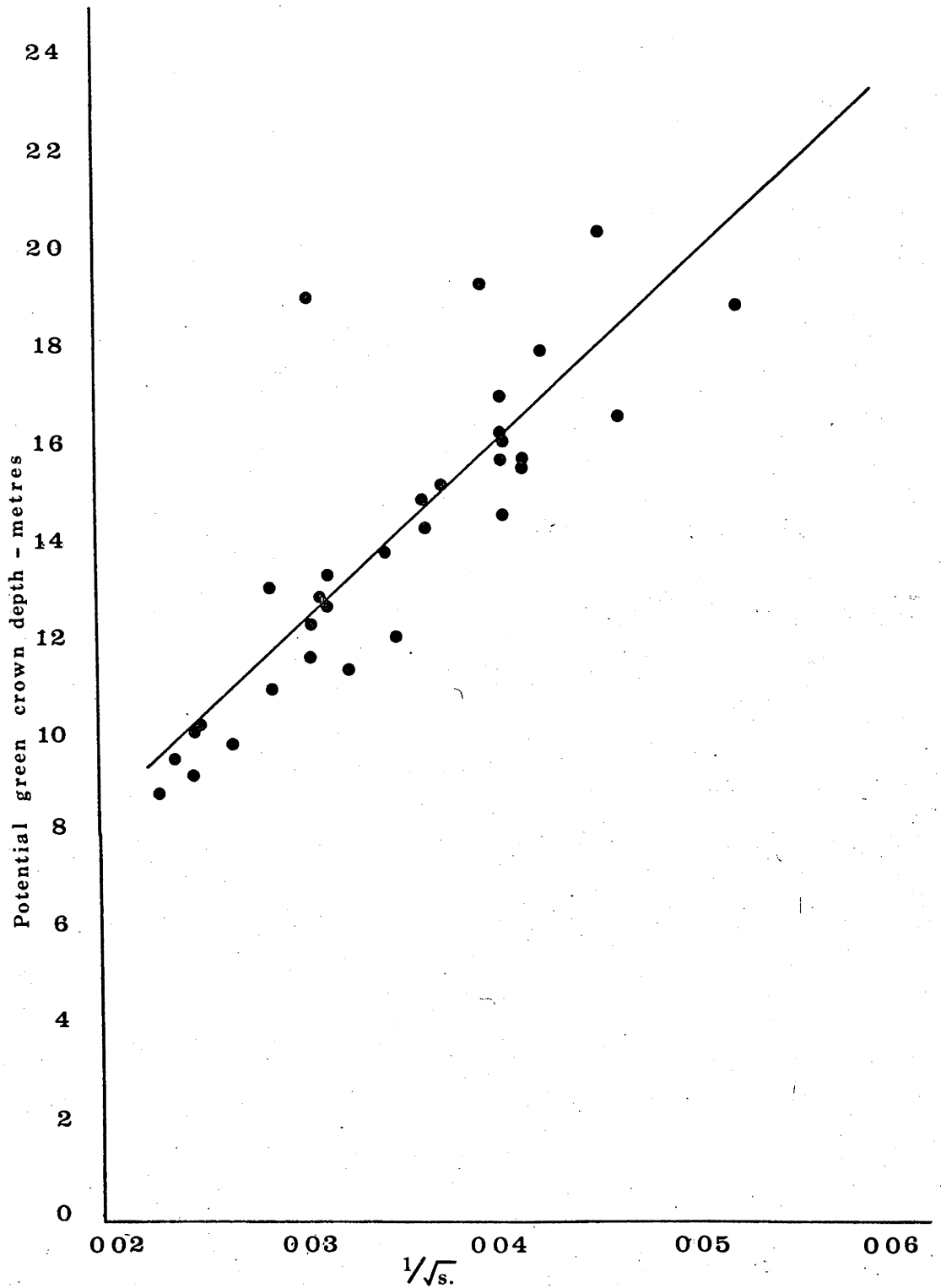
Figure 4   The relationship between stocking and
potential green crown depth
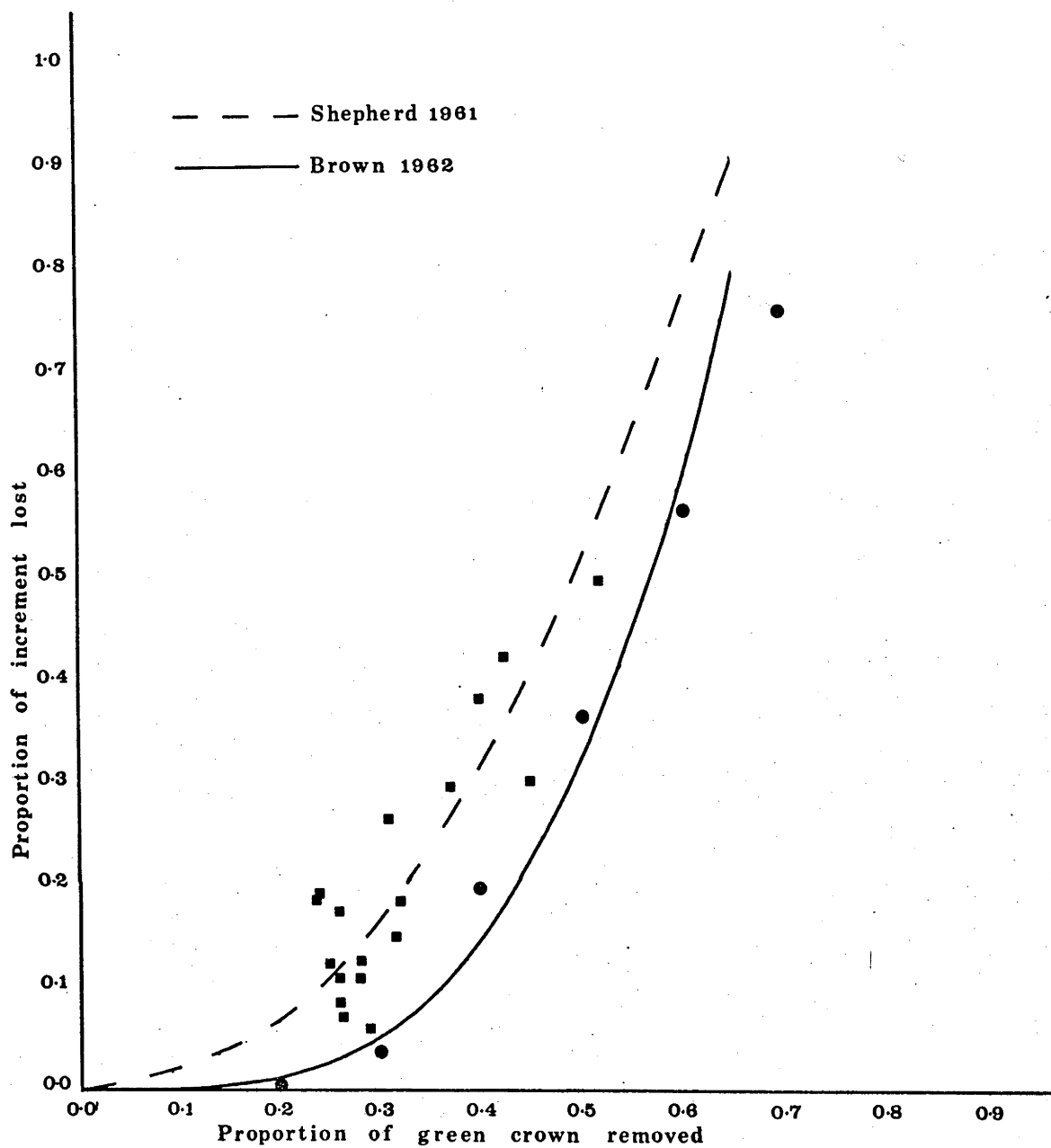
Figure 5   The relationship between the proportion of green
             crown removed and the percentage of annual basal
             area increment lost

Equation 12 implies that no increment in basal area will occur in the growth period following pruning if more than 70 % of the green crown is removed. There appears to be general support in the literature reviewed by Brown (1962) for this result, although the equation may overstate the increment loss under a severe pruning treatment. Nevertheless, commercial pruning is not likely to attain such levels of severity and the estimated function appears quite sensible for use in this study.

Shepherd (1961) provided data from an Australian pruning trial which enabled an equation analagous to equation 12 to be derived. This equation was :

$$\ln Y = 0.83 + 2.147 \ln X \tag{13}$$

where X and Y are as defined in equation 12. The analysis of variance is given in Table 4 Appendix A. The regression is significant at the 95 % probability level, and is illustrated in Figure 5.

The data on which equation 13 is based were taken from stands pruned to a height of about 3.4 m at stand heights ranging from 6 m to 13 m between ages of 6 to 9 years. Initial stocking in the 25 plots was about 1600 stems per hectare. In deriving equation 13 the assumption was made that the green crown extended to ground level, and thus the increment loss predicted by the equation may be conservative. However equation 13 implies that pruning has a more severe effect on increment than does equation 12.

Evidence from radiata pine in New Zealand (Sutton et al, 1972) suggested that pruning to 6.1 m by a stand height of about 11 m would cause a 38 % to 57 % reduction in stand basal area by age

7 to 10 years. This assumes that pruning takes place in three approximately equal evenly spaced lifts commencing when stand height is about 5 m. Such a pruning treatment would involve a maximum green crown removal of about 55 % corresponding to a maximum annual increment loss of about 45 % and 65 % predicted by equations 12 and 13 respectively. Thus the evidence, slight as it is, suggests that equation 12 may be more appropriate under New Zealand conditions.

Prediction of the Knotty Core Diameter

Knotty core diameter was defined as the maximum diameter over the pruned stubs of the largest whorl plus the growth in stem diameter required for the bole to occlude around the branch stubs.

Following conventional New Zealand Forest Service practice, pruning was assumed to occur in three lifts as follows:

    (i)   low pruning   -   0.0 m - 2.4 m

    (ii)   medium pruning   -   2.4 m - 4.3 m

    (iii) high pruning   -   4.3 m - 6.1 m

Pruning to produce clearwood in the 2nd log (6.1 m to 12.2 m) was not considered. Stems pruned were also assumed to be perfectly straight and deviations from stem straightness were not considered in calculating knotty core diameter.

These assumptions were made because data were not available to enable knotty cores to be calculated for pruning other than to 6.1 m, nor for pruning the lower 6.1 m in other than the three lifts. Furthermore, no data were available to enable the effects of deviations from stem straightness of knotty core diameter to be

incorporated.

None of the assumptions is likely to be critical. Pruning reasonably straight stems to 6.1 m has been normal New Zealand Forest Service practice (New Zealand Forest Service, 1972), and pruning the second log is more appropriately examined as a separate and subsequent issue.

Calculation of knotty core diameter proceeded in five separate steps. Firstly the diameter of the pruned stem of mean basal area at the time of pruning was calculated for use as an independent variable from which to predict the diameter of the largest pruned whorl in each lift. The diameter breast height was also used as an independent variable to predict the diameter of the largest branch in each lift. The diameter of the largest branch was subsequently used as an independent variable from which to predict the growth in the diameter of the bole required to occlude over the branch stubs. The diameter of the knotty core was then formed by the addition of the diameter of the largest whorl, and the diameter growth required for occlusion. A t the completion of the three pruning lifts, the largest knotty core diameter was selected as an independent variable to predict clearwood yield in a subsequent calculation.

Calculation of the Mean Diameter of Pruned Stems

When the pruned stocking differed from total stand stocking, it was assumed that the basal area of the pruned stems would equal the residual stand basal area resulting if the stand was simultaneously thinned to the pruned stocking.

With the basal area and stocking of pruned stems known, the diameter of the tree of average pruned basal area was given by the equation:

$$\text{D.B.H.} = \sqrt{\text{B.A.}/\text{S} \times 1.0 \,/\, 0.0000785} \qquad (14)$$

where: D.B.H. = diameter breast height over bark (cm) of the tree of mean pruned basal area,

B.A. = basal area (m^2/ha) of the pruned stems,

S = pruned stocking (stems per hectare).

Prediction of the Diameter of the Largest Pruned Whorl in each Pruning Lift

Data for radiata pine in New Zealand were available from Sutton et al (1968, 1970) consisting of a range of stand mean diameters and the corresponding stand mean diameters of the largest pruned whorl in each of three sections of the bole (i.e. 0.0m - 2.13 m, 2.13 m - 4.3 m, 4.3 m - 6.1 m).

Three regressions, one for each pruning lift, relating stand mean diameter to the diameter over stubs of the largest pruned whorl were estimated from the data. The equations for the 0.0 m - 2.13 m and 2.13 m - 4.3 m lifts were adjusted slightly to correspond to lifts of 0.0 m - 2.4 m and 2.4 m - 4.3 m respectively. The resulting set of equations was:

(i) low pruning (0.0 m - 2.4 m) :

$$\text{DOS}(1) = 3.45 + 1.09 \times \text{D.B.H.} \qquad 15\,(a)$$

(ii) medium pruning (2.4 m - 4.3 m) :

$$\text{DOS}(2) = -0.25 + 1.1 \times \text{D.B.H.} \qquad 15\,(b)$$

(iii)   high pruning (4.3 m - 6.1 m):

$$DOS(3) = -0.08 + 0.95 \times D.B.H. \qquad 15 \ (c)$$

where: $DOS(I)$ = diameter over pruned stubs of the largest whorl,

I = 1,2,3,

$D.B.H.$ = mean diameter of the pruned stems.

The equations, showing the approximate range of the data, are illustrated in Figure 6.

Prediction of the Diameter of the Largest Branch in Each Pruning Lift

Data relating the mean diameter of pruned stems to the diameter of the largest branch in each pruning lift came from the following sources:

(i)   low pruning (0.0 m - 2.4 m) :

Sutton et al (1970) provided data enabling the following relationship to be established:

$$DLB(1) = 1.88 + 0.14 \times D.B.H. \qquad 16 \ (a)$$

where: $DLB(1)$ = the diameter of the largest branch,

$D.B.H.$ = mean diameter of the pruned stems.

The regression is illustrated in Figure 7.

(ii)   medium pruning (2.4 m - 4.3 m) and high

        pruning (4.3 m - 6.1 m) :

Data from Sutton (1970 b), Valentine (1970), Purnell (1970) and Whiteside (1962) were used to establish relationships between the diameter of pruned stems and the diameter of the largest branch in the 2.4 m - 4.3 m and 4.3 m - 6.1 m sections. In both cases the regression was significant at the 95 % probability level. The
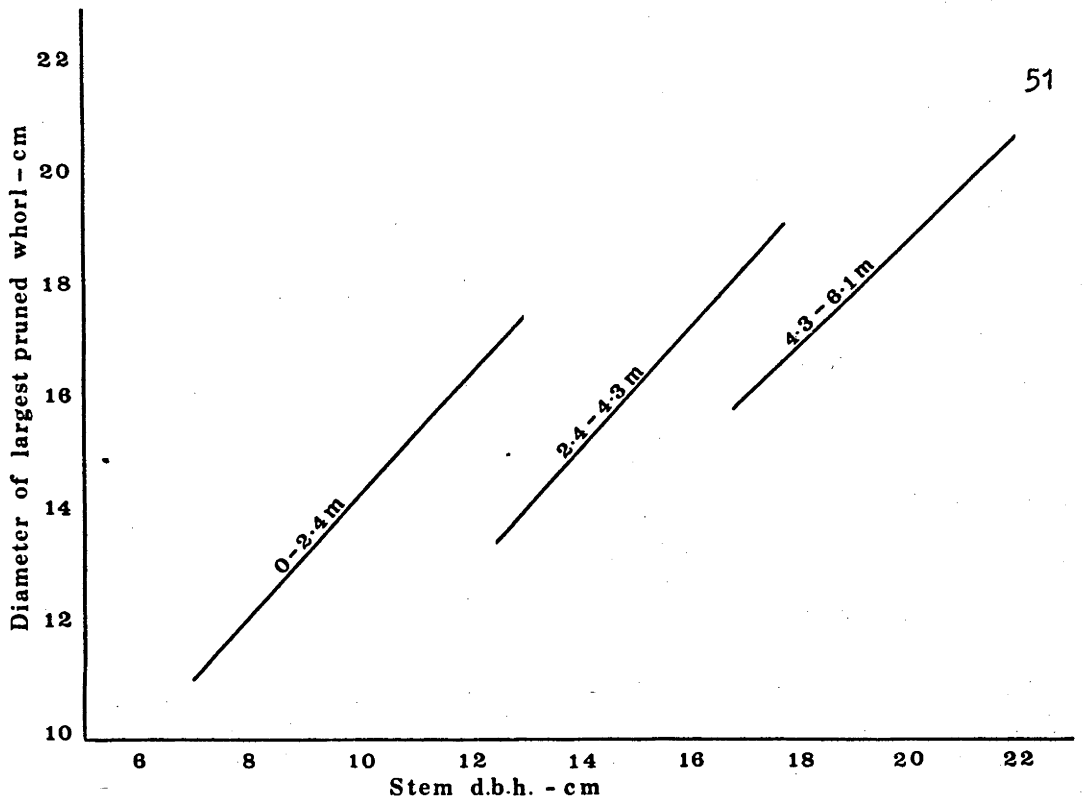
Figure 6   The relationship between stand mean diameter
and the diameter of the largest pruned whorl
in each pruning lift
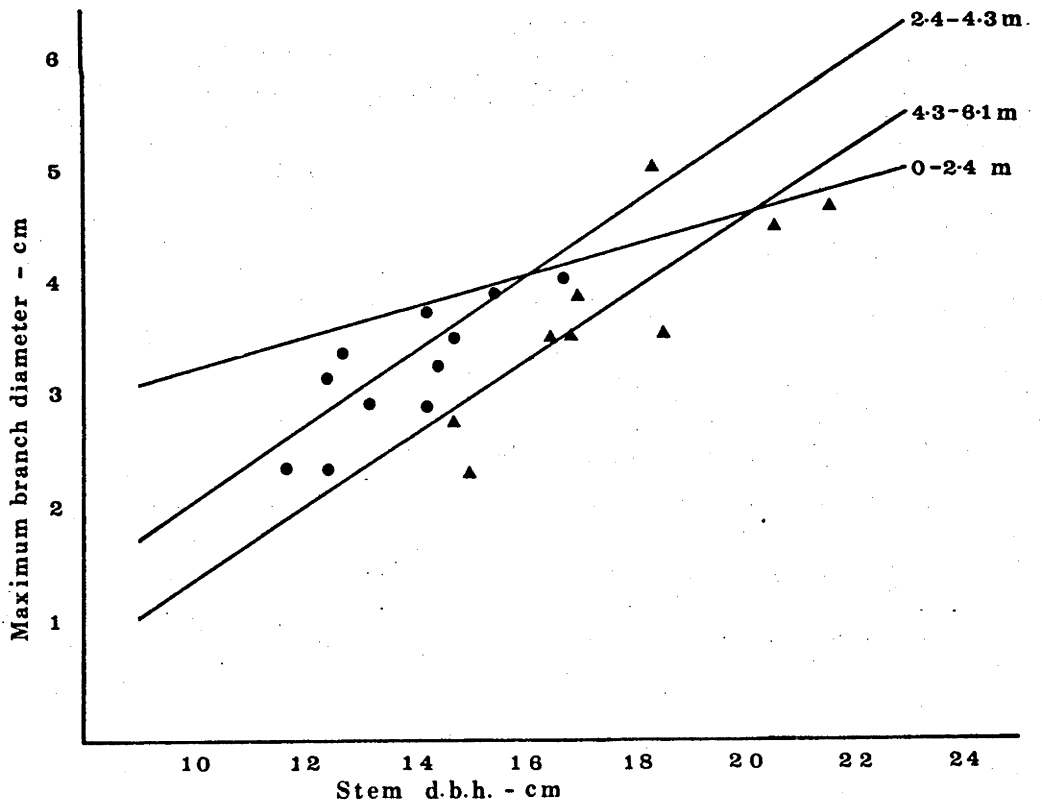
Figure 7   The relationship between stand mean diameter
and the diameter of the largest branch in
each pruning lift.

analyses of variance are given in Tables 5 and 6 Appendix A. The data are illustrated in Figure 7. The regressions were :

ii (a)   medium pruning (2.4 m - 4.3 m) :

$$DIB \ (2) \ = \ -1.22 \ + \ 0.33 \ x \ D.B.H. \qquad\qquad 16 \ (b)$$

ii (b)   high pruning (4.3 m - 6.1 m) :

$$DIB \ (3) \ = \ -1.80 \ + \ 0.32 \ x \ D.B.H. \qquad\qquad 16 \ (c)$$

where DIB (2) and DIB (3) are the diameters of the largest branches in the medium and high pruned sections respectively.

Prediction of Clearwood Yield from Diameter Breast Height and Knotty Core Diameter

The sawing trials reported by Brown (1965, 1969) and Fenton et al (1971) are of particular relevance in predicting the yield of clearwood which would be expected from a pruning designed to achieve a knotty core diameter of 25 cm or less. Clearwood yields from these trials were graphed against tree basal area in Figure 8. The sawing patterns and silvicultural treatments differed among these trials. An analysis of covariance (Table 7, Appendix A) showed that there were significant differences in clearwood yields among the three trials at the 95 % probability level. Inspection of the data in Figure 8 suggested this was probably due to the data from Brown (1965) which was perhaps less representative of the conditions examined in this study. Therefore the data from Fenton et al (1971) and Brown (1965) were pooled and a single relationship between clearwood yield and basal area was determined.
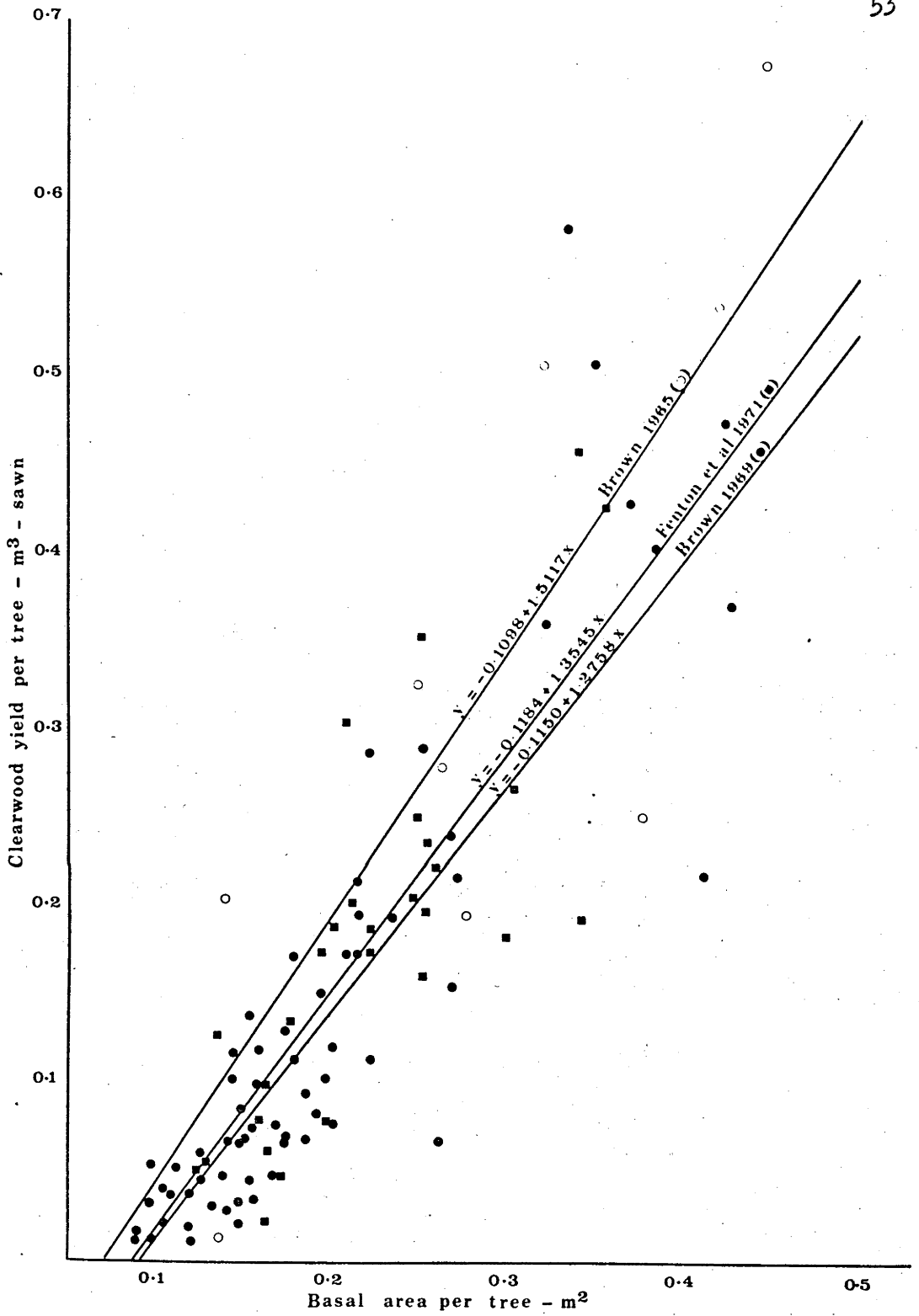
Figure 8   The relationship between tree size and the
sawn yield of clearwood

This regression was :

$$Y = -0.1157 + 1.989 X \qquad (17)$$

where: Y = clearwood yield per tree (m^3),

X = basal area per tree (m^2).

The analysis of variance is given in Table 8, Appendix A. The regression was significant at the 95 % probability level. The weighted average knotty core diameter of the logs providing the data for equation 17 was 24 cm.

The proportion of clearwood volume which could be sawn from butt logs with a knotty core of 24 cm in diameter was determined as follows :

(i)   the volume of butt logs 5.5 m in length in trees ranging from 30 cm to 76 cm in D.B.H. and 35 m in height were extracted from taper tables for unthinned radiata pine stands (Duff 1954). These volumes were increased by 10 % since butt log volumes from pruned and thinned stands exceed the volumes of butt logs of equivalent D.B.H. in the taper tables by 10 % to 12 % (Fenton et al 1971)

(ii)   the volumes determined above were converted to sawn volumes using a relationship between S.E.D. and conversion factor derived from data presented by Fenton et al (1971)

(iii)   sawn clearwood yields from trees ranging from 30 cm to 76 cm in D.B.H. were calculated from equation 17 relating clearwood yield to tree basal area, and expressed as a proportion of the total sawn volume of trees of equivalent D.B.H. determined in step (ii) above.

The proportions determined in step (iii) above were then graphed against D.B.H. in Figure 9 (lower dotted line).

The effect of knotty core diameter on clearwood yield was incorporated in the model as follows:

(i) the most optimistic clearwood yields predicted by Sutton (1970 c) from the theoretical studies discussed in the previous chapter were added to Figure 9 (upper dotted line),

(ii) the proportion of clearwood sawn from logs of varying D.B.H. and knotty core diameter were then interpolated between the upper and lower dotted lines roughly following the guidelines established by Sutton (1970 c), (i.e. a 2.5 cm increase in knotty core diameter required a 6.4 cm increase in D.B.H. if clearwood yield was not to be reduced),

(iii) the curves obtained in step (ii) above were then smoothed to obtain the curves illustrated in Figure 9.

When expressed in absolute terms, the data of Figure 9 yielded the following equation, relating clearwood yield to knotty core diameter and D.B.H. :

$$Y = -0.0447 - 0.0045 \times K + 2.3882 \times B.A. + 0.032 \times K \times B.A. - 0.0028 \times B.A. \times K^2 \tag{18}$$

where: Y = clearwood yield per tree (m^3),

K = knotty core diameter (cm),

$B.A.$ = tree basal area (m^2).

Thus by predicting the tree D.B.H. at rotation age and the knotty core diameter, the yield of clearwood could be determined.
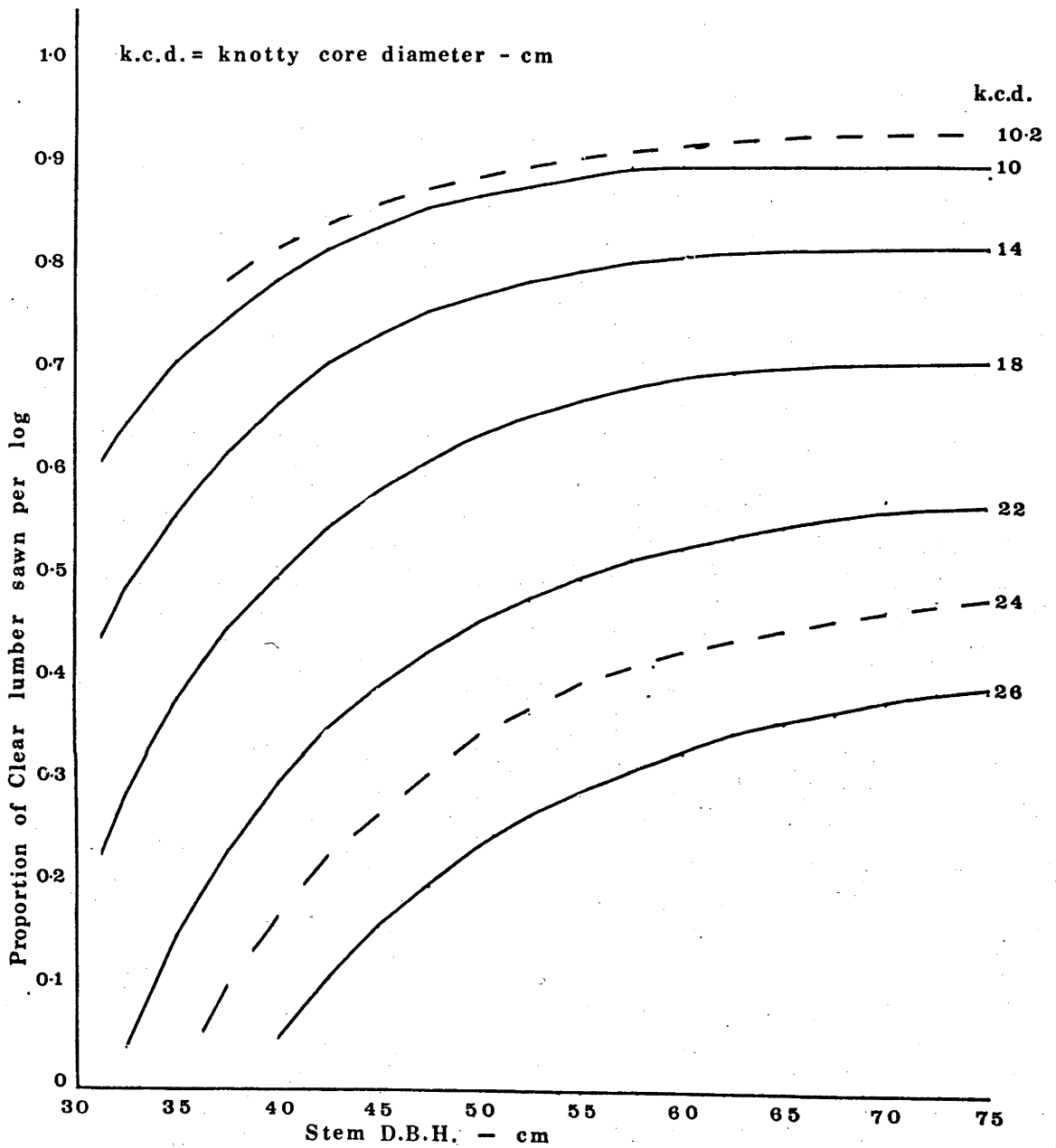
Figure 9   The effect of log size and knotty core diameter on clearwood yield

Summary of the Model

A flow chart describing the structure of the model is illustrated in Figures 10 a to j. It is assumed that:

(i)   no more than three pruning treatments and two thinning treatments will be imposed upon the stand,

(ii) first thinning and low pruning if prescribed will occur simultaneously,

(iii) second thinning and high pruning if prescribed will occur simultaneously.

However, any or all of the pruning and/or thinning treatments may be omitted independently by setting the input variables for the operation equal to zero.

The variables required as input to the model are :

		Symbol
1.	initial stocking in stems per hectare	SO
2.	stems per hectare remaining after first thinning	S1
3.	stems per hectare pruned at low pruning	S2
4.	stems per hectare pruned at medium pruning	S3
5.	stems per hectare pruned at high pruning	S4
6.	stems per hectare remaining after second thinning	S5
7.	height (m) of low pruning	P1
8.	height (m) of medium pruning	P2
9.	height (m) of high pruning	P3
10.	stand height (m) at first thinning and/or pruning	H1
11.	stand height (m) at medium pruning	H2
12.	stand height (m) at high pruning and/or second thinning	H3
13.	stand height (m) at rotation age	HF

The output from the model consists of :

		Symbol
1.	clearwood yield at rotation age (m^3/ha)	CWYID
2.	stand mean diameter (cm) at rotation age	DBH
3.	knotty core diameter (cm)	AK
4.	stems per hectare at rotation age	S
5.	total stand volume (m^3/ha) at rotation age	VOL

Other variables used in the model are defined in Appendix B.

The programme consists of a main programme and subroutines INCRT, PRUNE, MORTAL, KCD, MAXAK and THIN. The main programme controls the input and output, orders the sequence of silvicultural operations and calculates clearwood yield, stand stocking, total volume and stand mean diameter at rotation age. The functions of the subroutines are as follows:

1. Subroutine INCRT

This calculates the basal area increment (INC) associated with each unit increase in stand height (H). Equation 9 is used to calculate increment until high pruning (if prescribed) has been completed and/or stand basal area (in ft.^{2}/ac.) exceeds the numerical value at stand height (in ft.). (The metric equivalent of the latter condition is that stand basal area (m^2/ha) multiplied by 1.33 must exceed the numerical value of stand height (m)). After these conditions have been met the Beekhuis yield table is used to calculate basal area increment until rotation age is reached and the loss of basal area (M) due to mortality in stocking (N) is taken into consideration.

2.   Subroutine MORTAL

      this subroutine is called from subroutine INCRT.   It
calculates mortality in stocking (N) associated with a unit
increase in stand height.

3.   Subroutine PRUNE

      This subroutine is called from subroutine INCRT.   It
calculates the potential green crown depth (D) for a given stand
stocking (S) and then calculates the proportion of green crown
removed (PCR) by pruning to a given height (P).   The proportion
of green crown removed is then used to calculate the factor (LOSS)
by which the basal area increment must be multiplied on return to
subroutine INCRT to allow for the effect of pruning on increment.

4.   Subroutine KCD

      This calculates the mean diameter of the pruned stems,
subsequently used to calculate the diameter of the largest pruned
whorl (DOS(I), I = 1, 2, 3), and the diameter of the largest
branch (DLB(I), I = 1, 2, 3) in each pruning lift.   The diameter of
the largest branch in each lift is used to calculate the radial
growth of the bole required for occlusion (OD(I), I = 1, 2, 3) in
each lift.   The knotty core diameter in each lift
($\hat{A}$ KCD(I), I = 1, 2, 3) is formed by the addition of the diameter
of the largest pruned whorl and the diameter growth required to
occlude.   On return to the main programme, the appropriate value
of the knotty core (K(I), I = 1, 2, 3) is selected.

5. Subroutine MAXAK

This calculates the diameter of the largest knotty core (AK) to use in calculating the clearwood yield.

6. Subroutine THIN

This calculates the basal area (B1) of a nominated stocking (S⁺) and returns the value of B1.
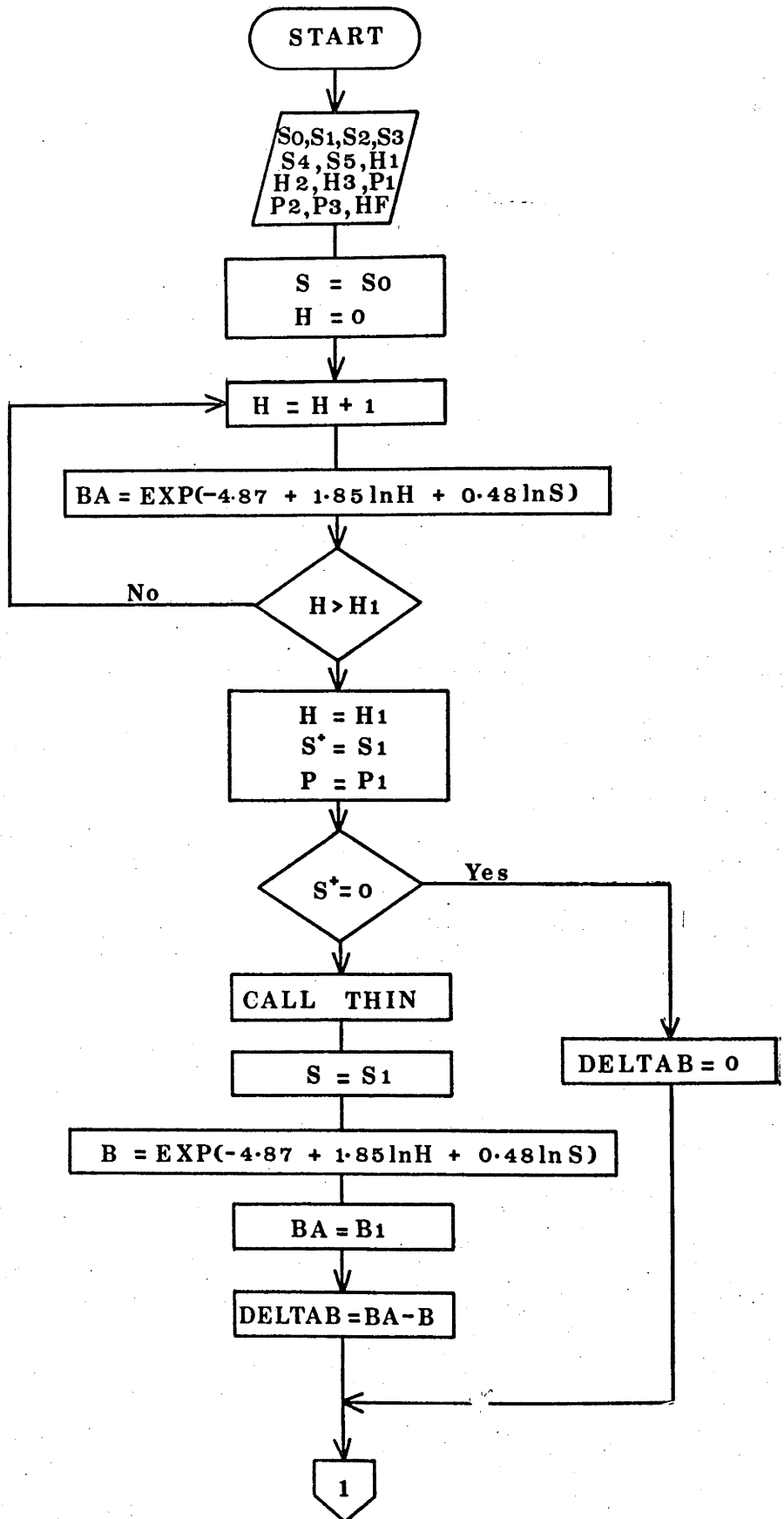
Figure 1C a   Simulation model flow chart
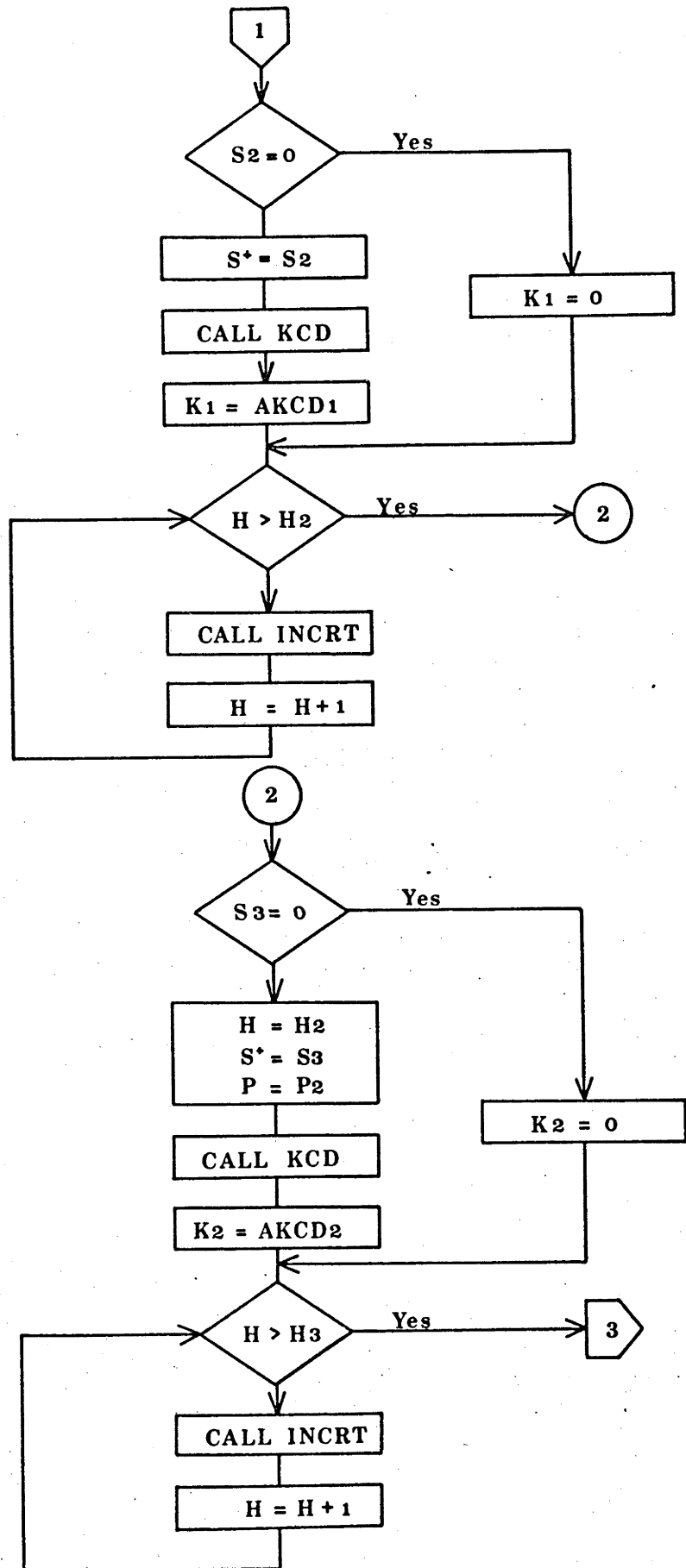
Figure 10 b
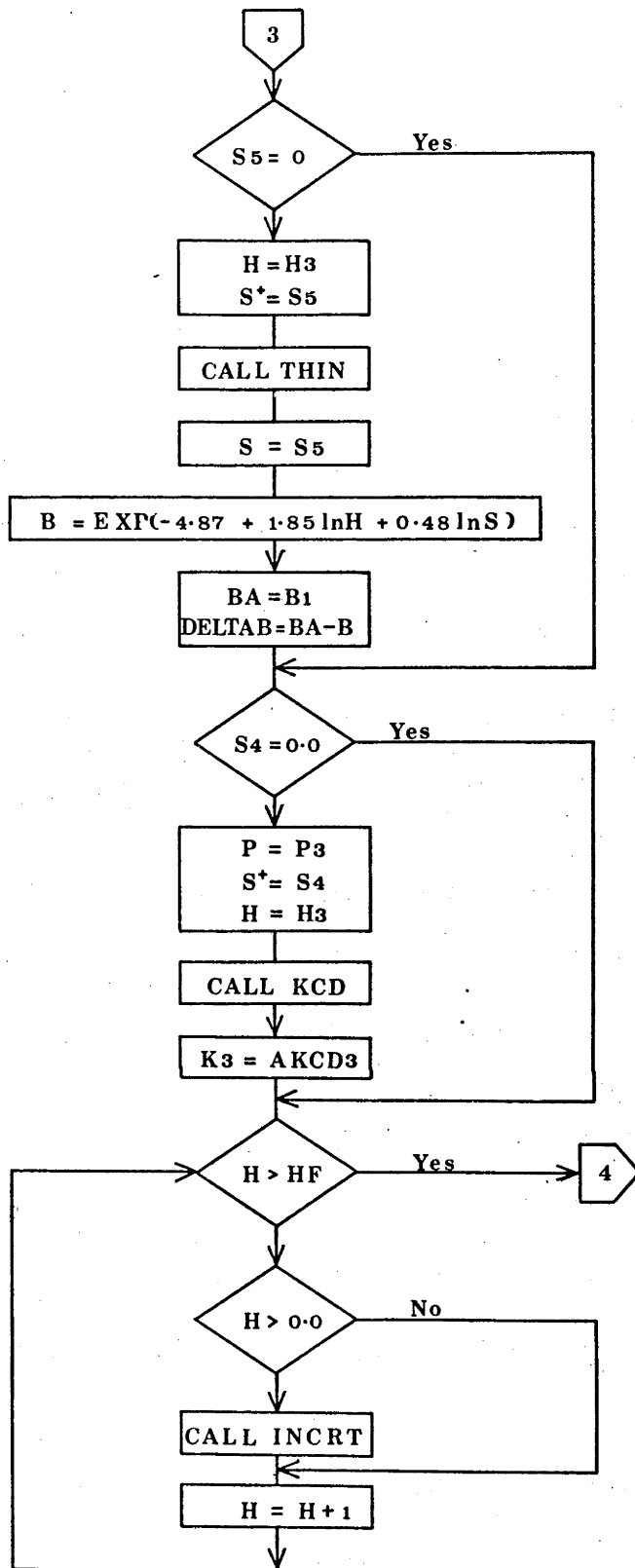
Figure 10 c
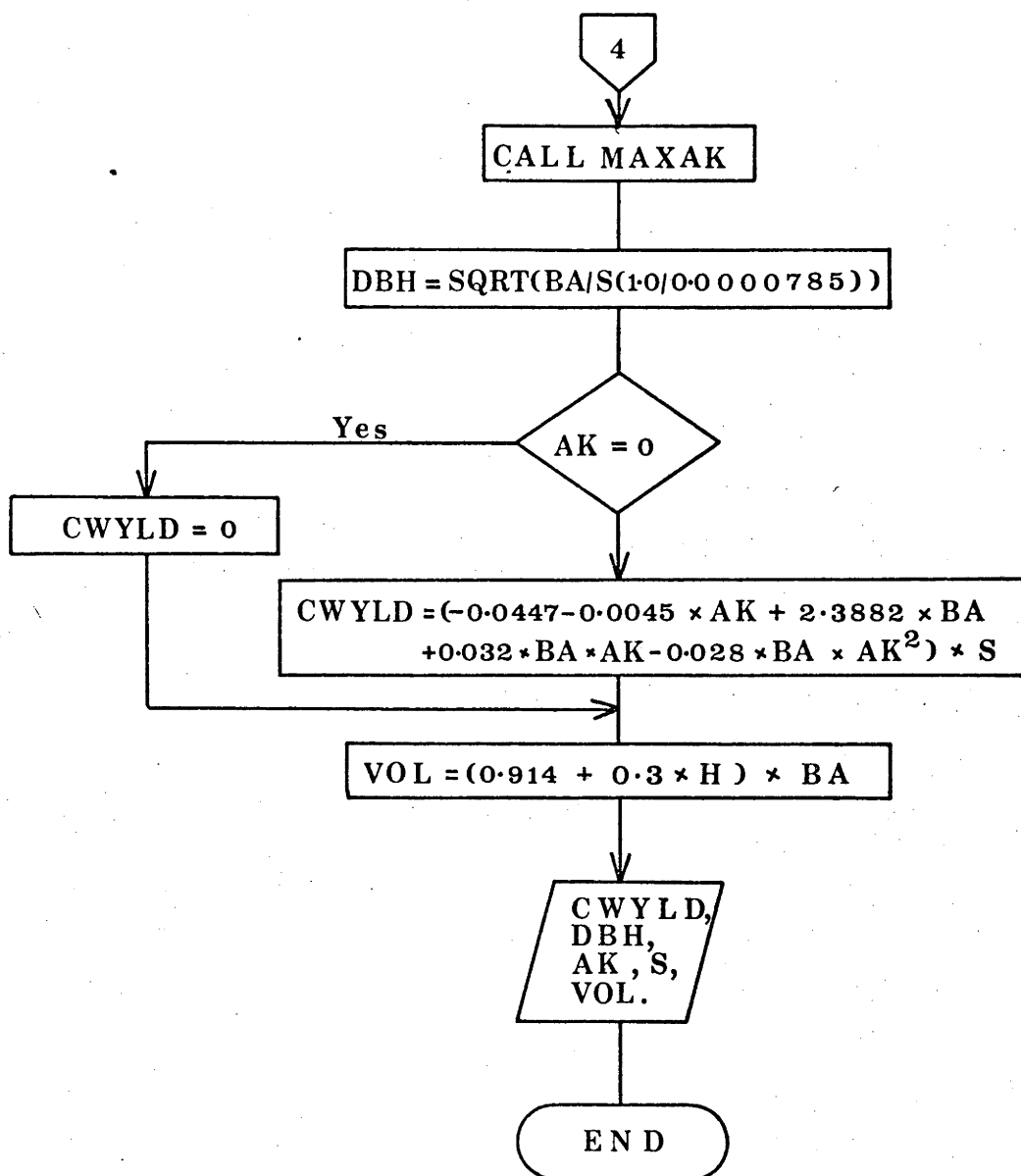
Figure 10 d
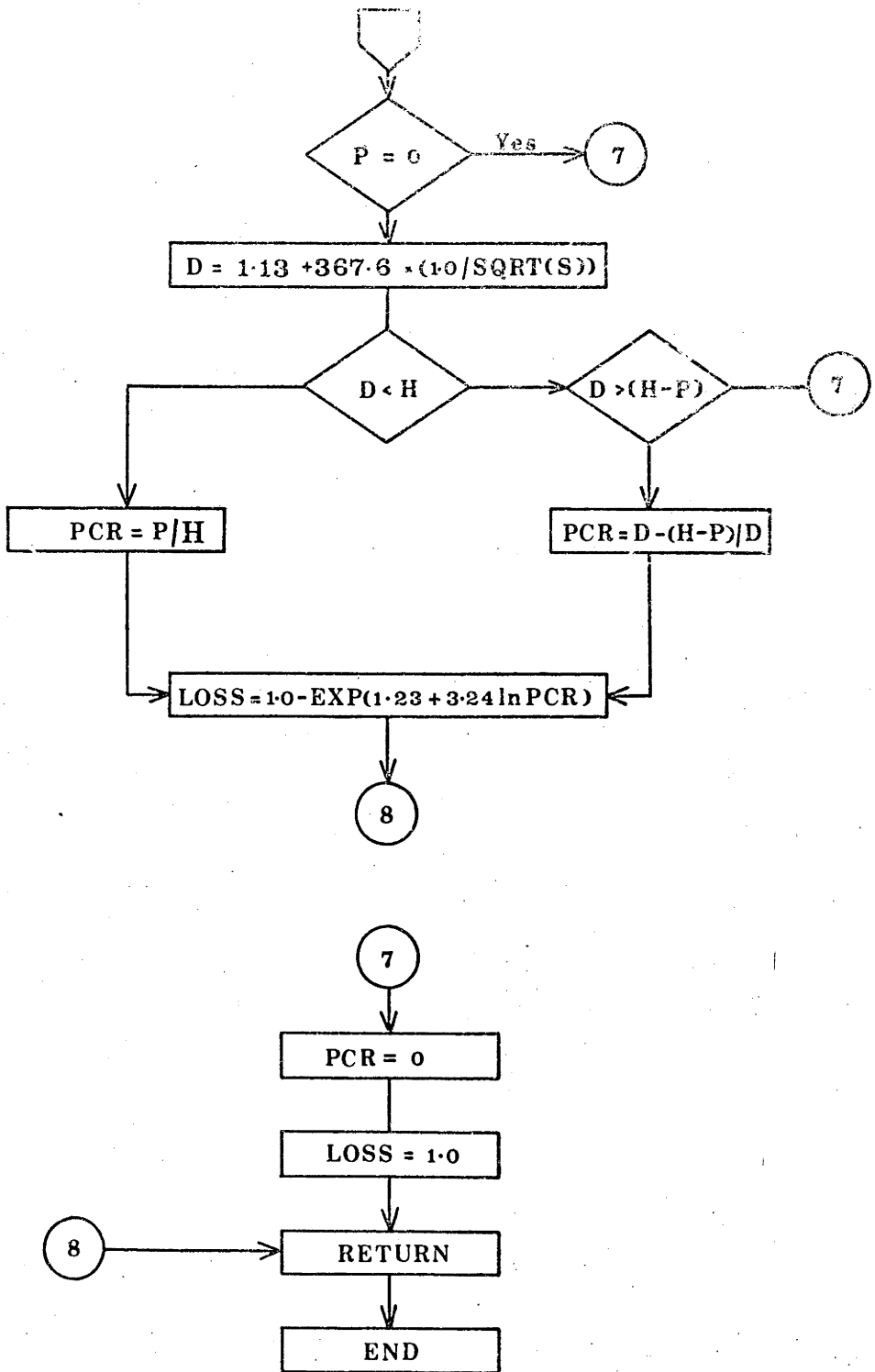
Figure 10 e

Subroutine INCRT

$$BA^+ = BA \times 1\cdot 33$$

$$BA^+ > H \quad \text{Yes} \quad H > H3 \quad \text{Yes} \quad 5$$

$$B = EXP(-4\cdot 87 + 1\cdot 85 \ln H + 0\cdot 48 \ln S)$$
$$BTEMP = B + DELTAB$$
$$INC = (BTEMP - BA) \times LOSS$$
$$BA = BA + INC$$
$$DELTAB = BA - B$$

6

5

$$BA = BA + ((BA + 62\cdot 0)/(H + 15\cdot 2))$$

CALL MORTAL

$$M = 0\cdot 000268 \times DBH^2 \times N$$

$$BA = BA - M$$

6 → RETURN

END
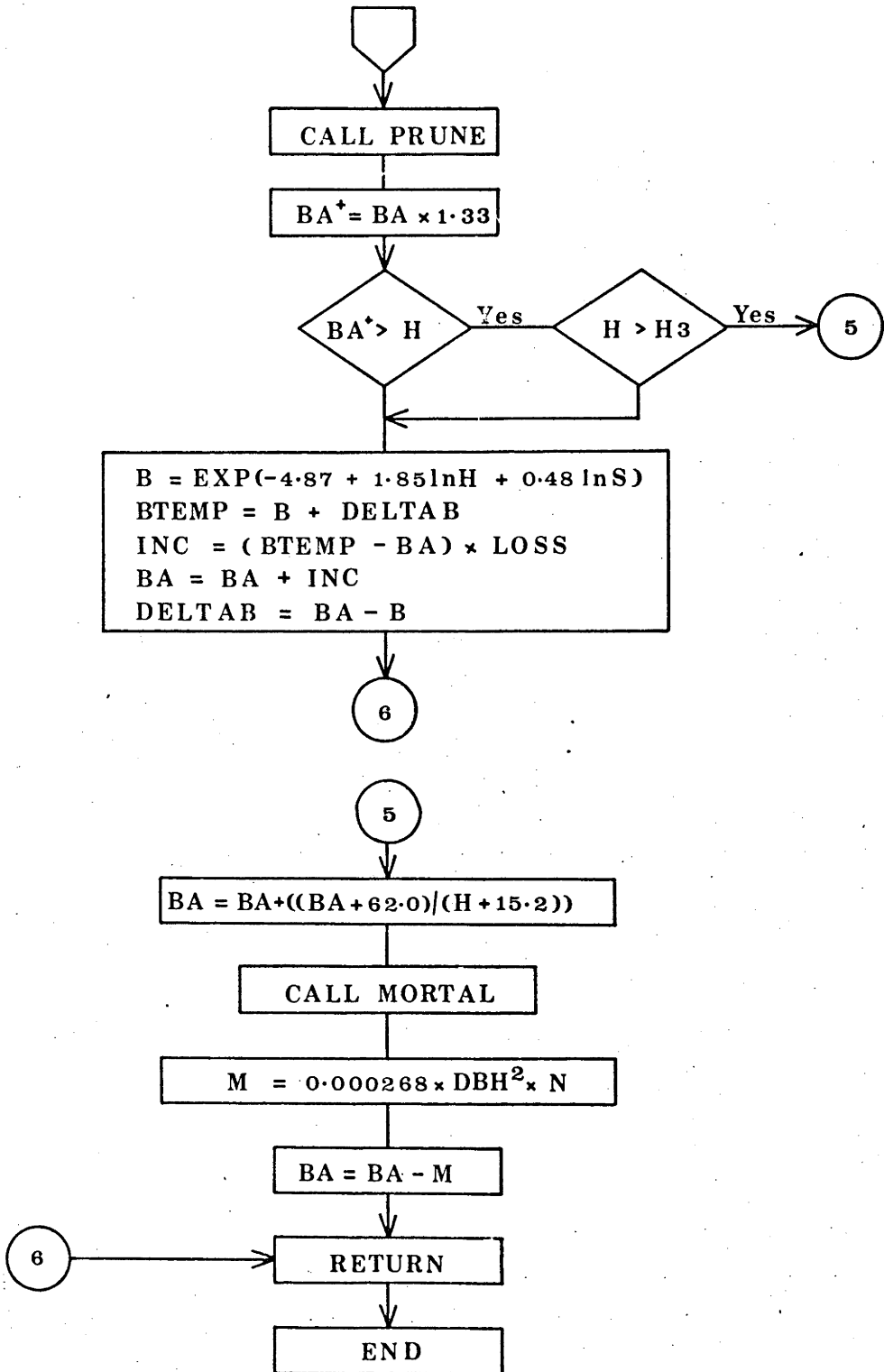
Figure 10 f

Subroutine MORTAL

A1 = 0·897463
A2 = 0·619661
A3 = 1·112247
A4 = 26·11846
A5 = 0·114741
A6 = 12·96
A7 = 2·301529
A8 = 1·582864
A9 = 0·666667
A10 = 4156779·5

$S = S / 2·471$
$H = H \times 3·28$
$RS = (224·27/SQRT(S)) \times 100/H$

$11·0 < RS$ Yes → $30·0 > RS$ Yes → 9

10 → $S^+ = A10/(H+1)^2$

$S^+ = S$

$DBH = SQRT(BA/S \times 1·0/0·0000785))$

11 → $N = (S - S^+) \times 2·471$
$S = S^+ \times 2·471$
$H = H / 3·28$

RETURN

END

Figure 10 g

$$Z1 = (A2 + A1/RS + SQRT(A5 + A3/RS - A4/RS^2))$$
$$*(224.27/SQRT(S))$$
$$Z2 = (H+1)/A6$$

9

$Z1 > Z2$ — Yes → **10**

$$Z3 = Z2 \times A7$$
$$Z4 = A8 \times Z1^2$$
$$Z5 = (H+1/10.0)\times(A9 \times Z1) - (H+1)^2/100$$
$$S^+ = (224.27/(Z3 - SQRT(Z5 + Z4)))^2$$

11

Figure 10 h

Subroutine KCD

$$S^+ < S$$

No

$$B_1 = BA$$

CALL THIN

$$DBH = SQRT(B_1 /S \times 1.0/0.0000785))$$

$$DOS_1 = 3.45 + 1.09 \times DBH$$
$$DOS_2 = -0.25 + 1.10 \times DBH$$
$$DOS_3 = -0.08 + 0.95 \times DBH$$

$$DLB_1 = 1.88 + 0.14 \times DBH$$
$$DLB_2 = -1.22 + 0.33 \times DBH$$
$$DLB_3 = -1.80 + 0.32 \times DBH$$

$$OD_1 = 0.84 + 0.36 \times DLB_1$$
$$OD_2 = 0.84 + 0.36 \times DLB_2$$
$$OD_3 = 0.84 + 0.36 \times DLB_3$$

$$AKCD_1 = DOS_1 + OD_1 \times 2$$
$$AKCD_2 = DOS_2 + OD_2 \times 2$$
$$AKCD_3 = DOS_3 + OD_3 \times 2$$

RETURN

END

Figure 10 i

Subroutine AK

Subroutiné THIN ·

$$B1 = BA \times EXP(0.818 \ln(S^+/S) + 0.179)$$

Figure 10 j

CHAPTER FIVE

VERIFICATION OF THE MODEL

Purnell's Plots at Kaingaroa Forest

In order to test the model and the effects of equation 12
compared with equation 13, three silvicultural regimes described
by Bunn (1970) were simulated. The data from Bunn were derived
from Purnell's (1970) work and consisted of the basal area at a
stand height of 12.2 m of selected portions of three radiata pine
stands at Kaingaroa Forest which had undergone different thinning
treatments. The initial stocking in each stand was 4 324 stems
per hectare, and the pruning treatments common to all three stands
were as follows (Purnell 1970) :

   (i)   low pruning: 741 stems per hectare pruned to 2.4 m
                                     at stand height 7.6 m,

   (ii)   medium pruning: 371 stems per hectare pruned to 4.3 m
                                       at stand height 10.4 m,

   (iii) high pruning: 371 stems per hectare pruned to 6.1 m
                                       at stand height 12.2 m

The comparisons of basal area growth summarised in Table 3 were
made in two simulations, one using equation 12 to calculate the
increment loss from pruning, and the other using equation 13. The
original data from Bunn (1970) were expressed in imperial units.
They have been converted to metric units to facilitate the comparison,
using standard conversion factors.

Table 3 shows that equation 12 results in a higher predicted basal area than does equation 13 .

TABLE 3:   COMPARISON OF ESTIMATED AND ACTUAL BASAL AREAS (m^2/ha) AT STAND HEIGHT 12.2 m.

Treatment		Equation 12	Equation 13	Bunn (1970)
(i)	thinned to 741 s.p.h. at stand height 7.6 m			
	(a) best 198 s.p.h.	6.2	5.6	5.3
	(b) best 371 s.p.h.	10.4	9.43	9.8
	(c) best 741 s.p.h.	15.3	13.9	16.9
(ii)	thinned to 1 482 s.p.h. at stand height 7.6 m			
	(a) best 198 s.p.h.	5.4	5.0	4.4
	(b) best 371 s.p.h.	9.1	8.4	7.6
	(c) best 741 s.p.h.	16.0	14.8	13.8
(iii)	unthinned (4 324 s.p.h.)			
	(a) best 198 s.p.h.	4.2	4.2	4.2
	(b) best 371 s.p.h.	7.1	7.1	7.8
	(c) best 741 s.p.h.	12.5	12.5	13.5
$\dfrac{\Sigma (O - E)^2}{N}$		1.47	1.41	

O = observed basal area,   E = estimated basal area,   N = 9

The mean squared deviation of observed basal area from predicted basal area is slightly less when equation 13 is used. Equation 13 therefore appears to be superior to equation 12 in predicting the

effect of pruning on basal area increment, but the difference

may not be significant.

The mean diameters over stubs of the largest pruned whorl

in each of the three pruning lifts are compared in Table 4 with

the relevant data obtained from the sample plots established

by Purnell (1970) :

TABLE 4: COMPARISON OF THE DIAMETERS OF THE LARGEST PRUNED
WHORLS PREDICTED BY THE MODEL WITH DATA PUBLISHED BY PURNELL (1970)

Treatment	Equation 12	Equation 13	Purnell (1970)
(i) thinned to 741 s.p.h. at stand height 7.6 m			
(a) low pruning (0.0 m – 2.4 m)	13.77	13.77	13.72
(b) medium pruning (2.4 m – 4.3 m)	17.41	16.91	17.78
(c) high pruning (4.3 m – 6.1 m)	17.88	17.03	17.78
(ii) thinned to 1 482 s.p.h. at stand height 7.6 m			
(a) low pruning (0.0 m – 2.4 m)	13.77	13.77	13.72
(b) medium pruning (2.4 m – 4.3 m)	16.40	16.00	15.24
(c) high pruning (4.3 m – 6.1 m)	16.69	16.07	14.48
(iii) unthinned (4 324 s.p.h.)			
(a) low pruning (0.0 m – 2.4 m)	13.77	13.77	13.72
(b) medium pruning (2.4 m – 4.3 m)	14.50	14.50	16.00
(c) high pruning (4.3 m – 6.1 m)	14.74	14.74	15.24

$$\frac{\Sigma (O - E)^2}{N}$$ 0.99 0.77

O = observed diameter, E = estimated diameter, N = 9

Equation 13 appears to give a slightly better fit to the published data than that using Equation 12 but the differences in the predicted values are probably not significantly different.

As Table 4 shows, the model predicts that the largest diameter over stubs will occur in the high pruning lift, irrespective of the thinning treatment, whereas the sample plot data indicates that the largest diameter will occur in the medium pruning lift. More information is needed to clarify this aspect of knotty core formation.

Table 4 also shows, as expected, that the diameter of the largest pruned whorl in the medium and high pruned sections increases as the thinning becomes more severe.

The diameter of the largest branch in each pruning lift cannot be compared with the relevant data published by Purnell (1970), because the data were used in construction of the model. However, the values of the diameter of the largest branch predicted by the model are summarised in Table 5 for illustrative purposes:

TABLE 5:   ESTIMATES OF THE DIAMETER (cm) OF THE LARGEST

BRANCH IN EACH PRUNING LIFT

Treatment	Equation 12	Equation 13
(i) thinned to 741 s.p.h. at stand height 7.6 m		
(a) low pruning (0.0 m - 2.4 m)	3.20	3.20
(b) medium pruning (2.4 m ⊕ 4.3 m)	4.08	3.94
(c) high pruning (4.3 m - 6.1 m)	4.24	3.96
(ii) thinned to 1 482 s.p.h. at stand height 7.6 m		
(a) low pruning (0.0 m - 2.4 m)	3.20	3.20
(b) medium pruning (2.4 m - 4.3 m)	3.78	3.66
(c) high pruning (4.3 m - 6.1 m)	3.84	3.63
(iii) unthinned (4 324 s.p.h.)		
(a) low pruning (0.0 m - 2.4 m)	3.20	3.20
(b) medium pruning (2.4 m - 4.3 m)	3.20	3.20
(c) high pruning (4.3 m - 6.1 m)	3.18	3.18

Table 5 shows that equation 12 predicts larger branches in
the medium and high pruned lifts, in the thinned stands, but the
diameters are little different in the unthinned stands.   As
expected, heavier thinning increases the branch diameters in the
medium and high pruning lifts.

The clearwood yields, stand basal areas, knotty core diameters
and stand mean diameters given in Table 6 were calculated assuming

that a thinning to 247 stems per hectare would occur at a stand

height of 23 m.   Rotation age was assumed to be 30 years.

TABLE 6:   ESTIMATES OF CLEARWOOD YIELD, STAND MEAN DIAMETER,
KNOTTY CORE DIAMETER AND STAND BASAL AREA AT AGE 30 YEARS ON
A SITE INDEX OF 29 m.

Treatment		Equation 12	Equation 13
(i)	thinned to 741 s.p.h. at stand height 7.6 m		
	(a) D.B.H. (cm)	54.0	63.3
	(b) knotty core diameter (cm)	22.6	21.5
	(c) basal area (m^2/ha)	54.5	63.2
	(d) clearwood yield (m^3/ha)	57.6	61.6
(ii)	thinned to 1 482 s.p.h. at stand height 7.6 m		
	(a) D.B.H. (cm)	53.7	52.6
	(b) knotty core diameter (cm)	21.1	20.3
	(c) basal area (m^2/ha)	53.2	51.8
	(d) clearwood yield (m^3/ha)	65.1	65.8
(iii)	unthinned (432 s.p.h.)		
	(a) D.B.H. (cm)	51.7	50.8
	(b) knotty core diameter (cm)	18.7	18.7
	(c) basal area (m^2/ha)	49.9	48.2
	(d) clearwood yield (m^3/ha)	70.2	66.6

Table 6 shows that clearwood yield decreases as the thinning
is made more severe, because even although the stand mean diameter
at rotation age is increased by heavier thinning, the knotty core
diameter is also increased, and the latter effect outweighs the
former, thus reducing clearwood yield.

In the unthinned stand, equation 13 results in a stand mean diameter at rotation age of about 1 cm less than that using equation 12 and the clearwood yield is reduced by about 4 m^3/ha. However, as thinning increases in severity, equation 13 predicts increasingly larger clearwood yields compared with equation 12. This is because the reduction in knotty core diameter predicted using equation 13 more than compensates the reduction in stand mean diameter at rotation age.

The results presented in Tables 3, 4, 5 and 6 indicate that the model produces reasonable and logical results. They suggest that the clearwood yields predicted by equation 12 may be slightly conservative.

Fenton's (1972) Short Rotation Sawlog Regime

In an attempt to provide more evidence on which to choose between equation 12 or 13, a silvicultural regime proposed by Fenton (1972 a) was simulated and the resulting yields examined. The simulation was made in three runs, once with no pruning, once using equation 12 and once using equation 13. The silvicultural regime was:

(i)   establish 1 532 stems per hectare,

(ii)   prune 741 stems per hectare to 2.1 m at stand height 4.9 m,

(iii)   thin to 741 stems per hectare at stand height 4.9 m,

(iv)   prune 371 stems per hectare to 4.3 m at stand height 7.9 m,

(v)   prune 198 stems per hectare to 6.1 m at stand height 10.7 m

(vi)   thin to 198 stems per hectare at stand height 10.7 m,

(vii)   clearfall at age 26 years at stand height 35.1 m on a site

index of 29 m.

Fenton (1972 a) used the Beekhuis yield model (Beekhuis 1966) to calculate the yields. As a starting point he accepted a basal area of 4.67 m^2/ha on 198 stems per hectare at stand height 10.7 m. Basal area increment for the next 3.1 m increase in stand height was assumed to be 3.9 m^2/ha, as this was the increment found in practice (Fenton 1972 a), and thereafter the full basal area increment predicted by the Beekhuis model was used to rotation age.

The basal area growth predicted by the model between establishment and stand height 20 m under conditions of no pruning, and of using equations 12 and 13 to calculate the increment loss due to pruning, is compared with the data published by Fenton (1972 a) in Figure 11.

Equation 13 predicts a basal area increment loss of about 27% by stand height 10.7 m compared with the unpruned stand. Equation 12 predicts a basal area loss of about 15 % by stand height 10.7 m.

After thinning at stand height 10.7 m, the residual basal area estimated by equation 12 is closer to that estimated by Fenton (1972 a) from plot measurements than is that estimated with equation 13. Between stand heights 10.7 m and 13.7 m the basal area increment predicted with equation 12 is closer to that assumed by Fenton (1972 a) on the basis of plot measurements than is that predicted with equation 13.

Table 7 summarises predictions and the original data for stand mean diameter, basal area and total stand volume at age 26 years. The increment loss from pruning predicted by equation 13 has a much greater effect on total volume production than does that predicted
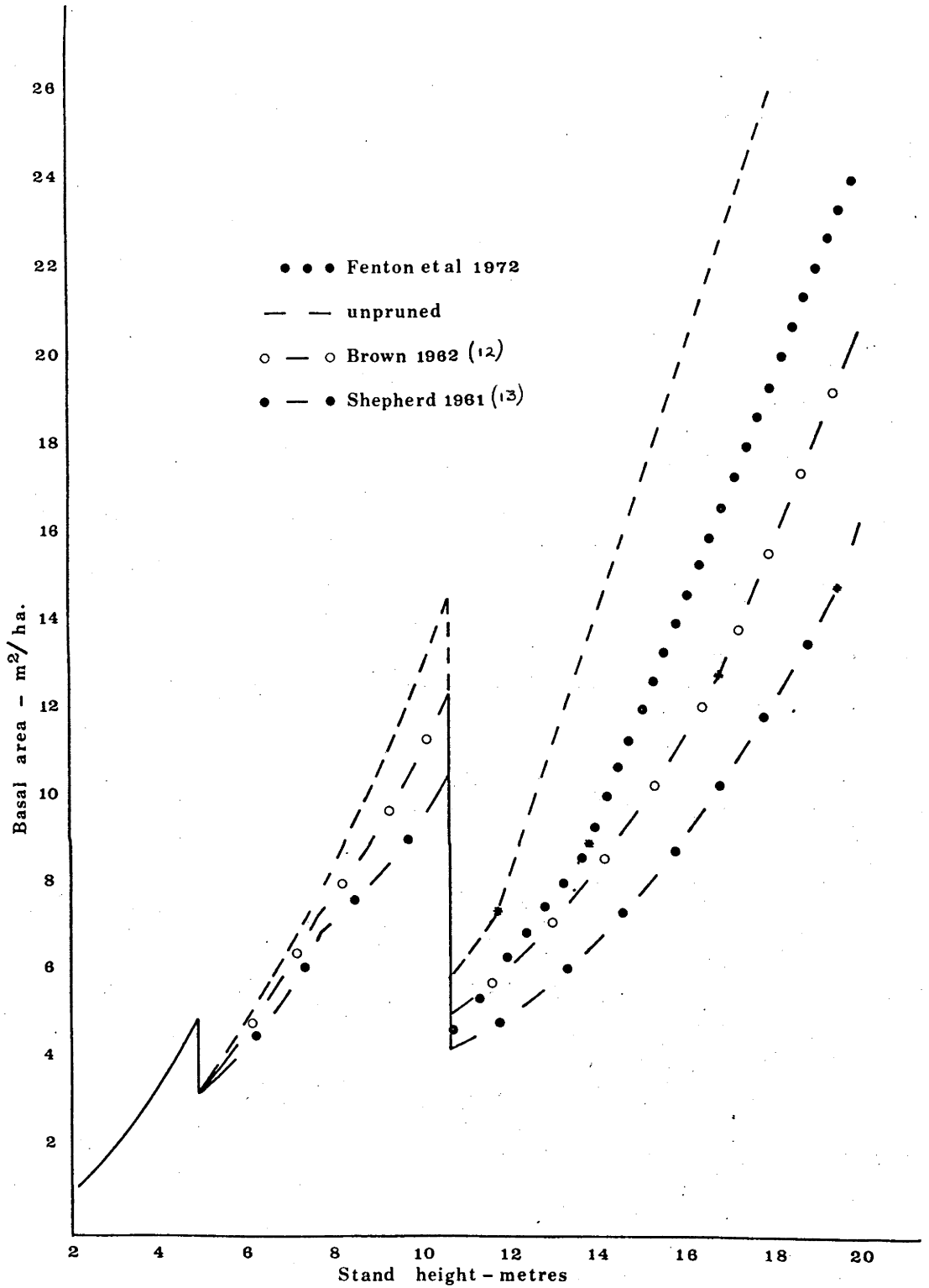
Figure 11   Comparison of basal area growth predicted by the model with that published by Fenton (1972 a)

with equation 12, but both equations predict a smaller total stand volume at age 26 years than that published by Fenton (1972 a).

TABLE 7:   COMPARISON OF THE STAND MEAN DIAMETER, TOTAL STAND VOLUME, AND STAND BASAL AREA PREDICTED BY THE MODEL WITH DATA PUBLISHED BY FENTON (1972 a)

		Simulation Model		
	Fenton 1972 a	Equation 12	Equation 13	No pruning
D.B.H. (cm)	61.7	59.5	56.0	64.1
Basal area (m^2/ha)	59.1	56.0	49.5	65.0
Total stand volume (m^3/ha)	676.0	639.0	656.3	742.9

The evidence summarised in Tables 3, 4, 6 and 7 together with the evidence from the pruning trial described by Sutton et al (1972), discussed in Chapter 4 suggested that the use of equation 12 to calculate the increment loss due to pruning would be marginally more appropriate than the use of equation 13.   Except where stated therefore equation 12 was used in this study.

It has been clearly shown that the effect of pruning on basal area increment is critical to both clearwood and total volume yields.   Although the effect of pruning on growth has been widely studied, its effects are still not accurately known. Research of a more discriminating nature is required to define precisely the consequences of pruning for yield production.

Deficiencies of the Model

The model is necessarily rather unsophisticated because it is based on the available data which come from a wide variety of sources and which has been collected for a variety of purposes. The experiments with the model described in this chapter highlighted a number of deficiencies in the model:

(i)   Most of the published data dealing with the growth and yield of radiata pine in New Zealand relate to stand aggregates rather than to individual stems. Clearwood production is essentially a characteristic of each individual log in a stand, and thus a model based on the growth of individual trees, rather than a stand model as has been constructed would be preferable. However, the complete lack of suitable data obviated any attempt to construct a tree based simulation model.

(ii)   A stand model ignores the effects of selective pruning on the growth of individual stems. Where a pruning is imposed the model assumes that all stems in the stand receive the same treatment and that the basal area growth of pruned stems is no different from the average.

(iii)   The effects of pruning and thinning on tree form are not included in the model.

(iv)   Equation 18 is quadratic in knotty core diameter. However, in the model it is used to predict the clearwood yield for the stand as a whole. This will cause a bias in the yields of clearwood predicted, the extent depending upon the distribution of diameters about the mean and the

association of knotty core sizes with particular final
tree diameters.

(v)   The model is deterministic.   It assumes that the probability
of occurrence of the estimated outcome is unity.   This is
obviously a gross over simplification since any one regime
of treatment on a given site index will produce a variety
of outcomes in practice.

(vi)   The model assumes that height growth is unaffected by
pruning: an assumption supported by research with species
other than radiata pine.   However there are indications
that the assumption may be less valid for radiata pine in
New Zealand, but there was no alternative other than to
accept the assumption in the absence of conclusive
quantitative data.   If height growth is appreciably
affected by pruning, the yields predicted by the model
will be biased upwards, and the extent of the bias will
increase as pruning becomes more severe.

However, in spite of these deficiencies, the tests
described in this chapter indicated that the model could be used
for predictive purposes with some degree of confidence.
Certainly the model makes best use of the data available, and it
was therefore used to predict clearwood yields and total volume
yields throughout the remainder of the study.

A DETERMINISTIC ANALYSIS OF CLEARWOOD YIELDS FROM RADIATA PINE

Introduction

Once a particular silvicultural strategy has been selected, a knowledge of the sensitivity of clearwood yield to the variables under the control of management is important to ensure that management objectives are met most efficiently. If clearwood yield is especially sensitive to a particular variable, then management must ensure that silvicultural operations involving the variable are controlled most closely. Conversely, if clearwood yield is insensitive to a particular variable, the control function can be transferred to more critical operations.

A silvicultural strategy similar to one considered recently for use at Kaingaroa Forest (K. Chandler pers.comm.) was selected, and the clearwood yields resulting from this regime and variants of it were examined. The regime was:

(i)   establish 1 482 stems per hectare,

(ii)   prune 194 stems per hectare to 2.4 m at stand height 6.1 m,

(iii)   thin to 494 stems per hectare at stand height 6.1 m,

(iv)   prune 370 stems per hectare to 4.3 m at stand height 12.2 m,

(v)   prune 247 stems per hectare to 6.1 m at stand height 12.2 m,

(vi)   thin to 247 stems per hectare at stand height 12.2 m .

The Effect of Thinning on Clearwood Yield

(a)   thinning at 12.2 m

Most forestry organisations in New Zealand in which pruning is

a standard silvicultural operation prescribe completion of pruning and thinning by stand height 9.0 m to 15.0 m. Prescribed residual stockings range from 240 to 750 stems per hectare (Bunn 1970).

Thinnings to stockings ranging from 247 to 998 stems per hectare were simulated at a stand height of 12.2 m in a stand established at 1 482 stems per hectare and pruned by the schedule described above. Clearwood yields were calculated at rotation ages ranging from 20 to 30 years on a site of index 29 m.

Figure 12 shows that clearwood yield increased as the thinning was made more severe because stand mean diameter at rotation age increased. The effect of rotation length on clearwood yield became more marked as the thinning became more severe.

Delaying the thinning to 247 stems per hectare until stand height reached 13.7 m, or advancing the timing of the thinning progressively to stand height 6.1 m decreased clearwood yield. The yields are illustrated in Figure 13 and the effect of the timing of the thinning on basal area growth in Figure 14. Advancing the timing of the thinning did not cause a loss of total basal area production, but increment was concentrated earlier on pruned stems, and stand mean diameter at rotation age increased.

Increasing the intensity of thinning after pruning had been completed increased clearwood yields because final log size was increased. However, advancing the timing of the thinning increased final log size but decreased clearwood yield because of the increase in knotty core diameter.

These results indicate that with the given pruning treatment, thinning at a stand height other than 12.2 m to a stocking exceeding 247 stems per hectare will reduce clearwood yield.

(b)   thinning at 6.1 m
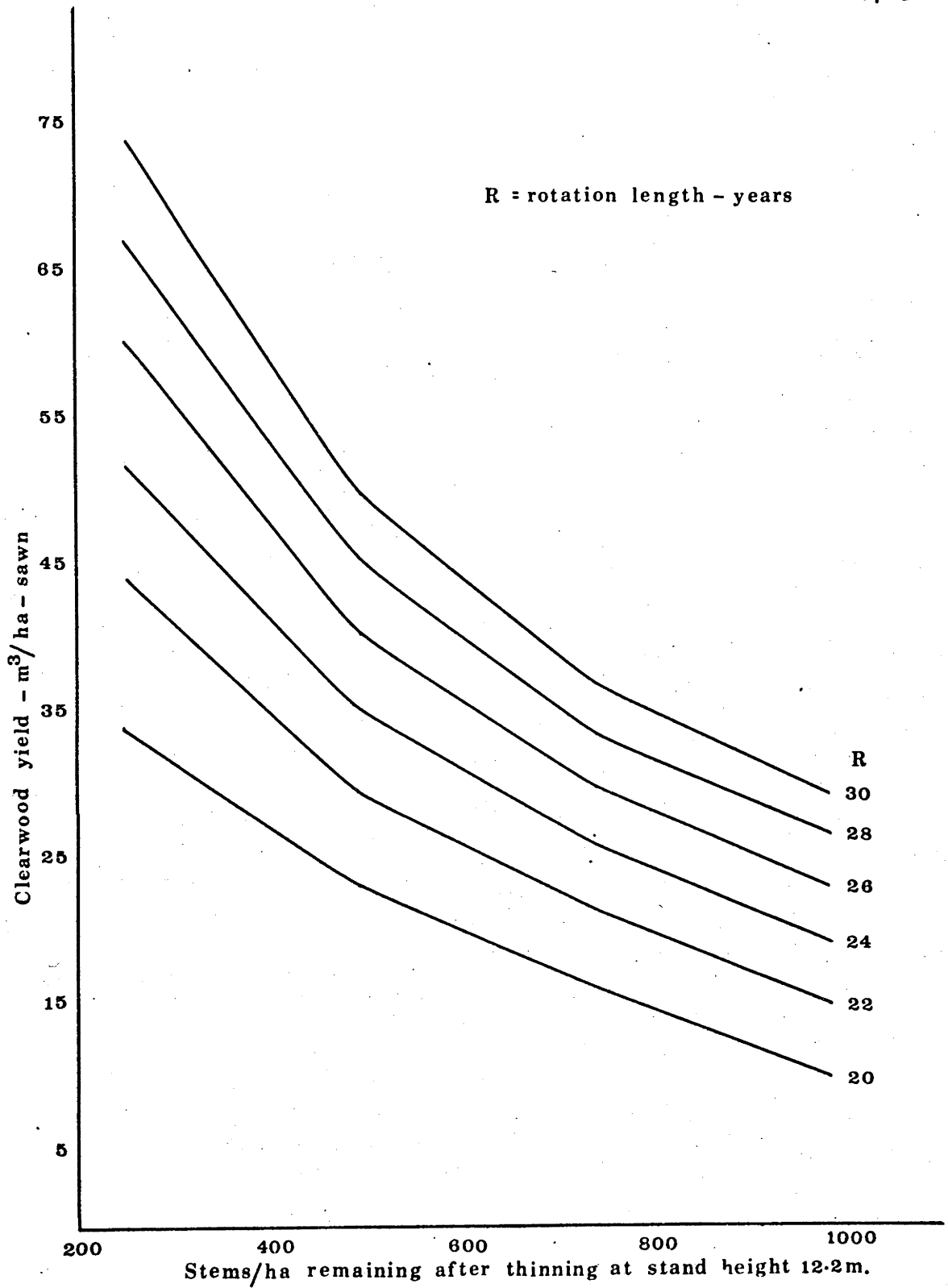
Figure 12   The effect of stems remaining after thinning
at stand height 12.2 m on clearwood yield
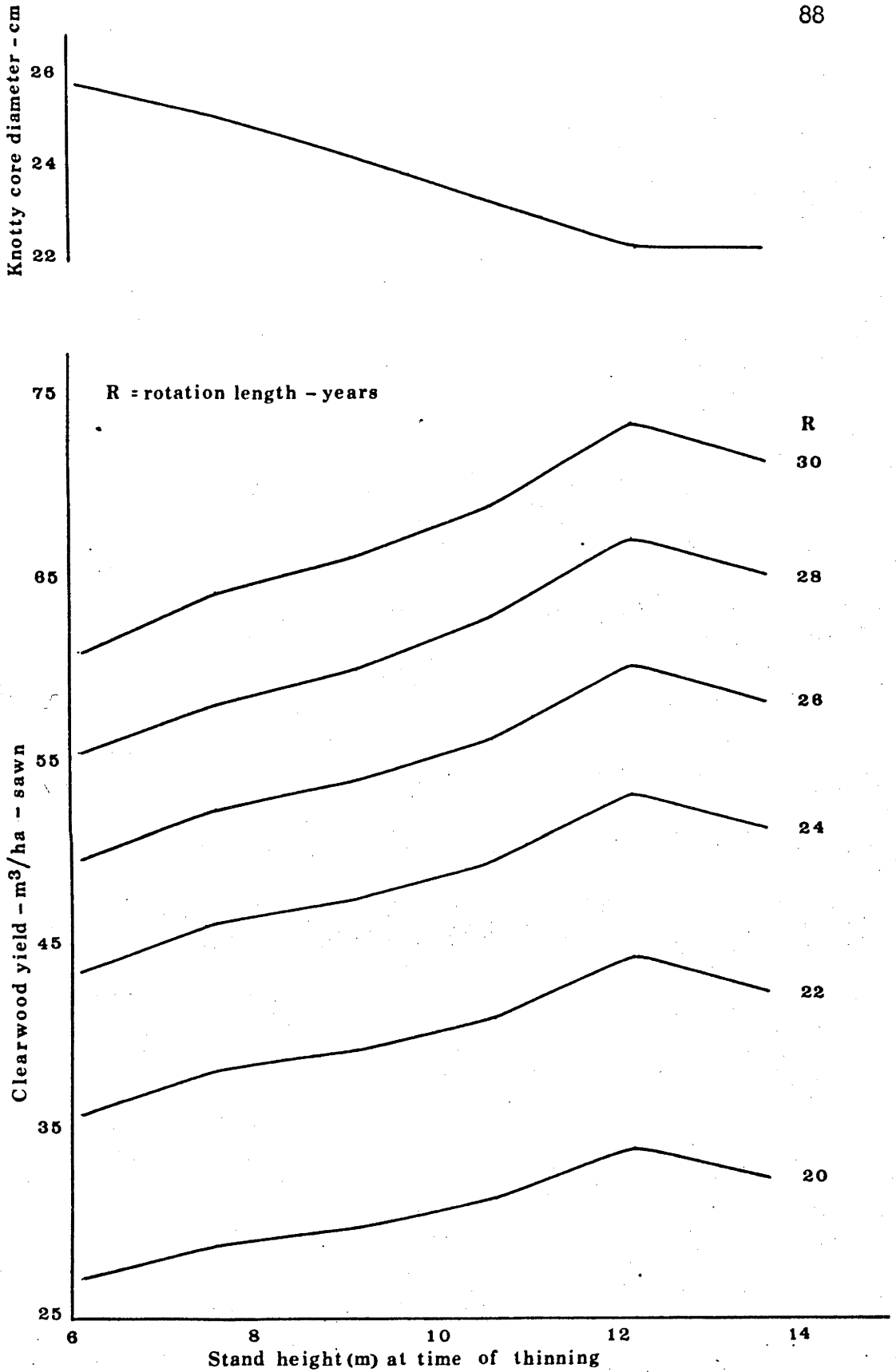
Figure 13   The effect of the timing of thinning to 247 stems
              per hectare on clearwood yield and knotty core
              diameter
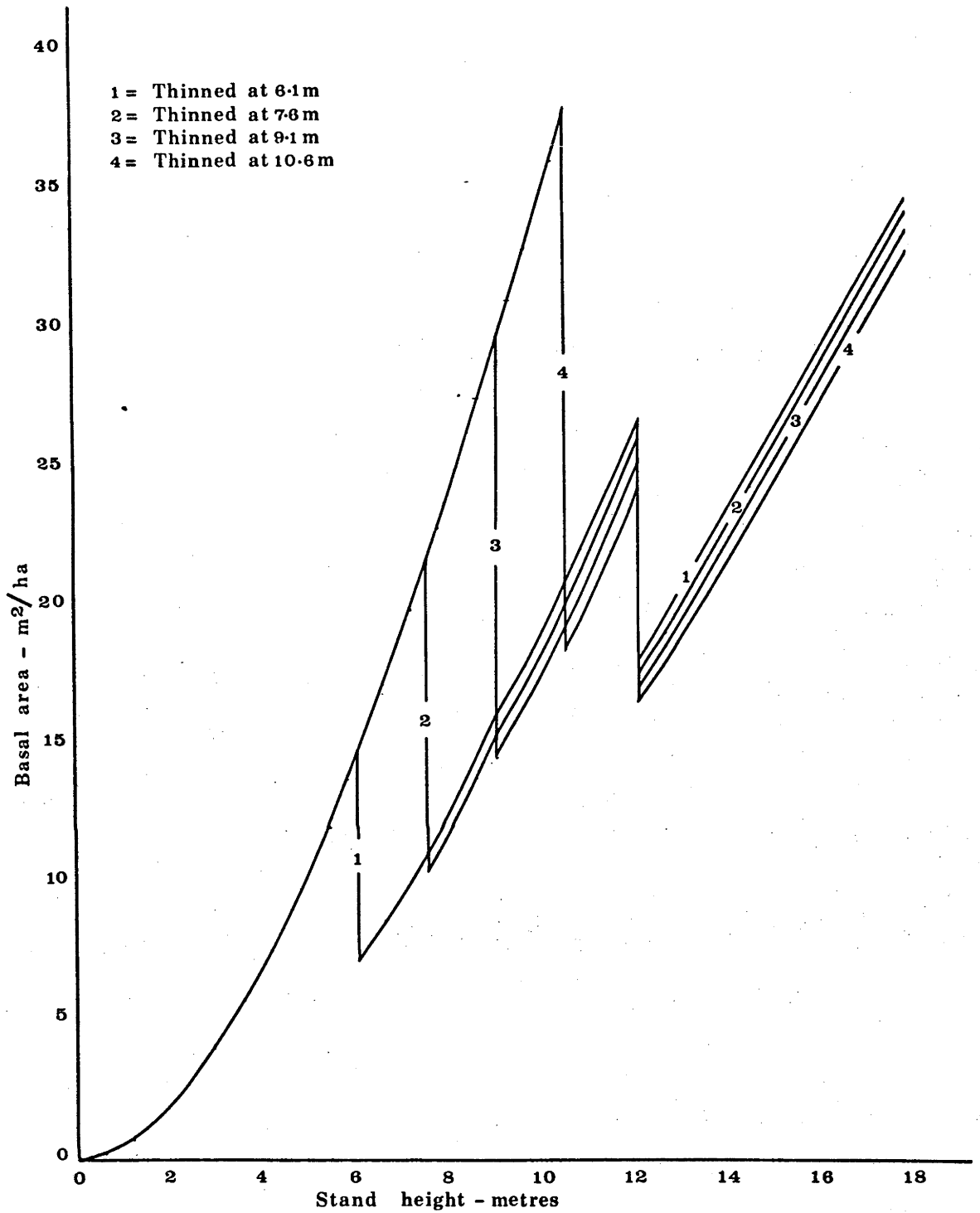
Figure 14   The effect of the timing of thinning to 247 stems per hectare on basal area growth

A number of studies (Armitage 1970, Sutton 1970 c, 1973) have established than an individual tree may change its crown status as the stand ages. Trials by the New Zealand Forest Research Institute have shown that severely pruned trees are capable of immediate response to release by heavy thinning. With severe pruning but without heavy thinning to follow, up to 84 % of pruned stems may lose dominance, compared with 44 % in lightly pruned or unpruned controls (James et al 1970). Most forestry organisations therefore prescribe a thinning after the first pruning treatment, which generally takes place when the first 6.1 m of stem upon which further pruning will be concentrated has formed. The objective is increment on pruned stems.

The effect of leaving varying numbers of stems after the first thinning was investigated by simulating thinnings to stockings ranging from 247 to 988 stems per hectare at stand height 6.1 m. Second thinning was to 247 stems per hectare at stand height 12.2 m. The pruning schedule and initial stocking were as prescribed above, and rotation lengths ranged from 20 to 30 years.

The effect of the severity of the first thinning on clearwood yield is illustrated in Figure 15. Reducing the severity of the thinning restricted knotty core diameter and stand mean diameter at rotation age. The decrease in knotty core diameter more than outweighed the decrease in final log diameter, and clearwood yields increased as the thinning became less severe.

The model does not allow the effect of selective pruning on the growth of individual stems to be examined. If pruned trees become suppressed in less severe thinnings, then the increases in clearwood yields shown in Figure 15 may be less marked.
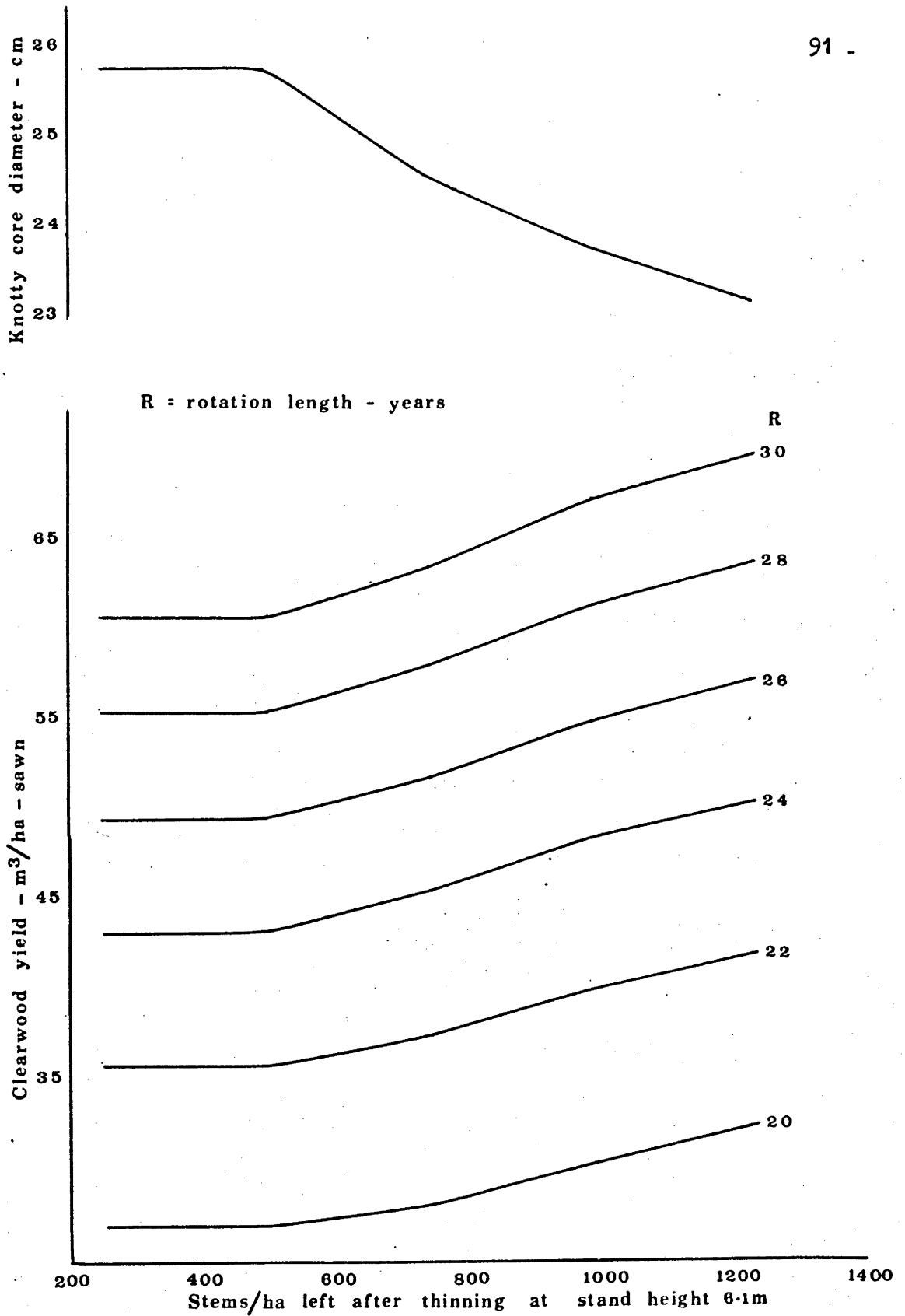
Figure 15   The effect of the severity of first thinning
            on clearwood yield and knotty core diameter.

There appears to be more latitude in controlling the first thinning compared with the second thinning. Clearwood yield in first thinning was not much affected by varying the residual stocking between 200 and 600 stems per hectare.

Heavy early thinning reduced clearwood yield. Although the stand mean diameter at rotation age was increased by thinning heavily and early, the increased knotty core diameter more than outweighed the former effect and clearwood yield was reduced as a result.

The Effect of Initial Stocking on Clearwood Yield

To investigate the effect of initial stocking on clearwood yield, the basic regime was simulated with initial stockings from 500 to 2 500 stems per hectare.

The effects of initial stocking on clearwood yield and knotty core diameter are illustrated in Figure 16. Decreasing the initial stocking from 2 500 to 1 500 stems per hectare gradually decreased clearwood yield and knotty core diameter increased quite rapidly. Decreasing initial stocking further below 1 500 stems per hectare had a much greater effect on clearwood yield, but the effect on knotty core diameter did not change much.

These results indicate that above an initial stocking of 1 500 stems per hectare there is a considerable degree of flexibility in deciding upon an initial stocking and the choice will be dictated by the expected survival rate rather than any considerations of expected clearwood yield. However if initial stocking falls below 1 500 stems per hectare clearwood yields will be decreased.
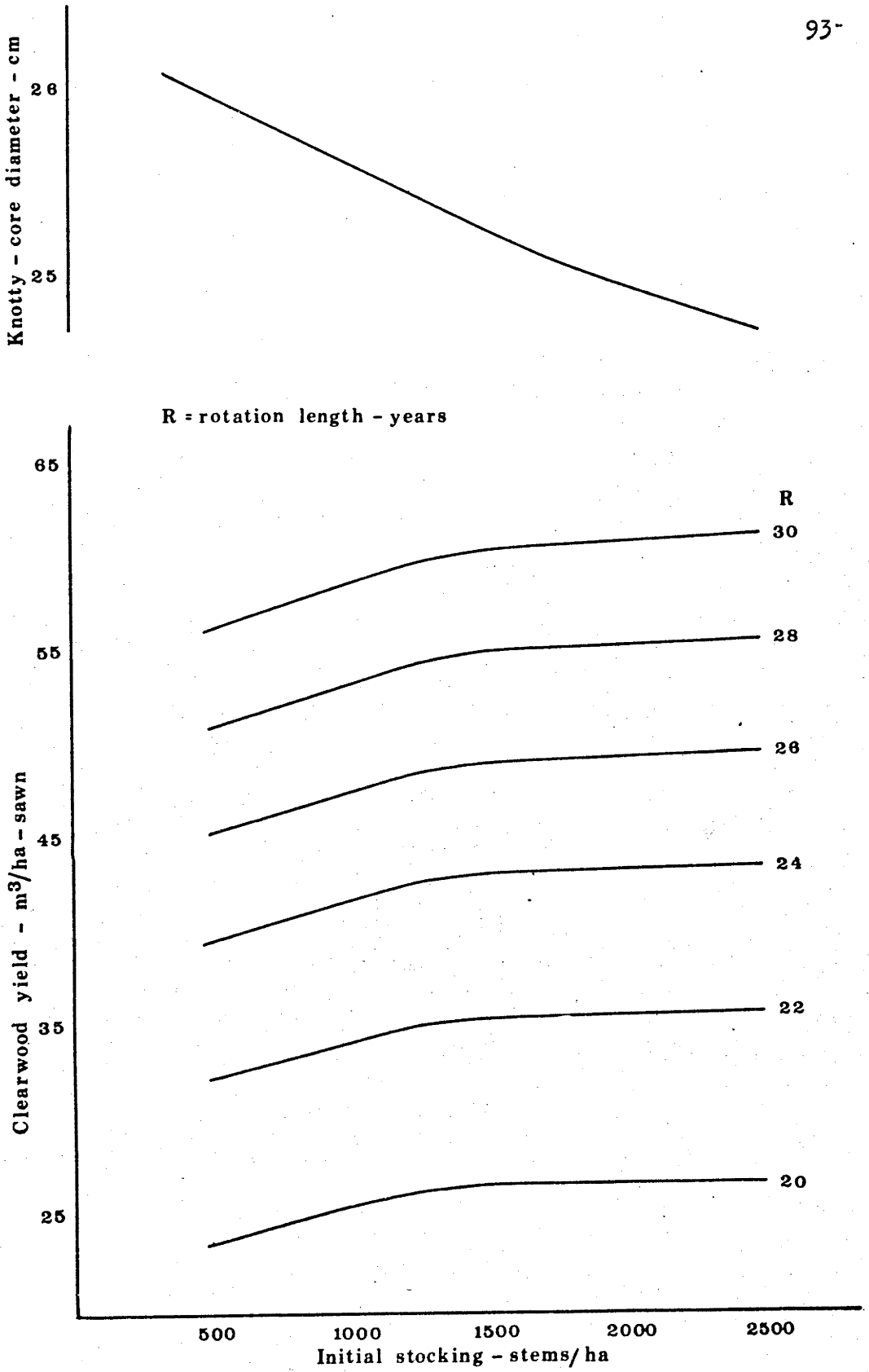
Figure 16   The effect of initial stocking on clearwood yield and knotty core diameter

The Effect of Site Index on Clearwood Yield

To investigate the effect of site index on clearwood yield, the basic regime was simulated on site indices ranging from 25 m to 33 m for rotation ages ranging from 20 to 30 years.

The clearwood yields obtained are illustrated in Figure 17. Site index had a marked effect on clearwood yield because of the effect on growth rate and hence stand mean diameter at rotation age. Over the range of site index investigated, clearwood yields on the highest site index were between two and four times greater than those on the lowest site index, depending upon the rotation length.

These results have significance in allocating land to forestry, and upon the allocation of land to produce different types of wood products within forests. Clearly a greater economic return from pruning can be expected on higher site indices.

The Effect of the Timing of Thinning and Pruning Treatments on Clearwood Yield

The diameter of the knotty core is an important determinant of clearwood yield. The timing of the pruning and thinning treatments would thus be expected to influence clearwood yield through an effect on stand mean diameter at the time of pruning and hence knotty core diameter.

The effect of the timing of pruning and thinning treatments on clearwood yield was investigated by scheduling the commencement of treatment at stand heights ranging from 4.0 m to 7.6 m. The treatments however were still imposed in the same relationship to each other as defined in the basic regime.
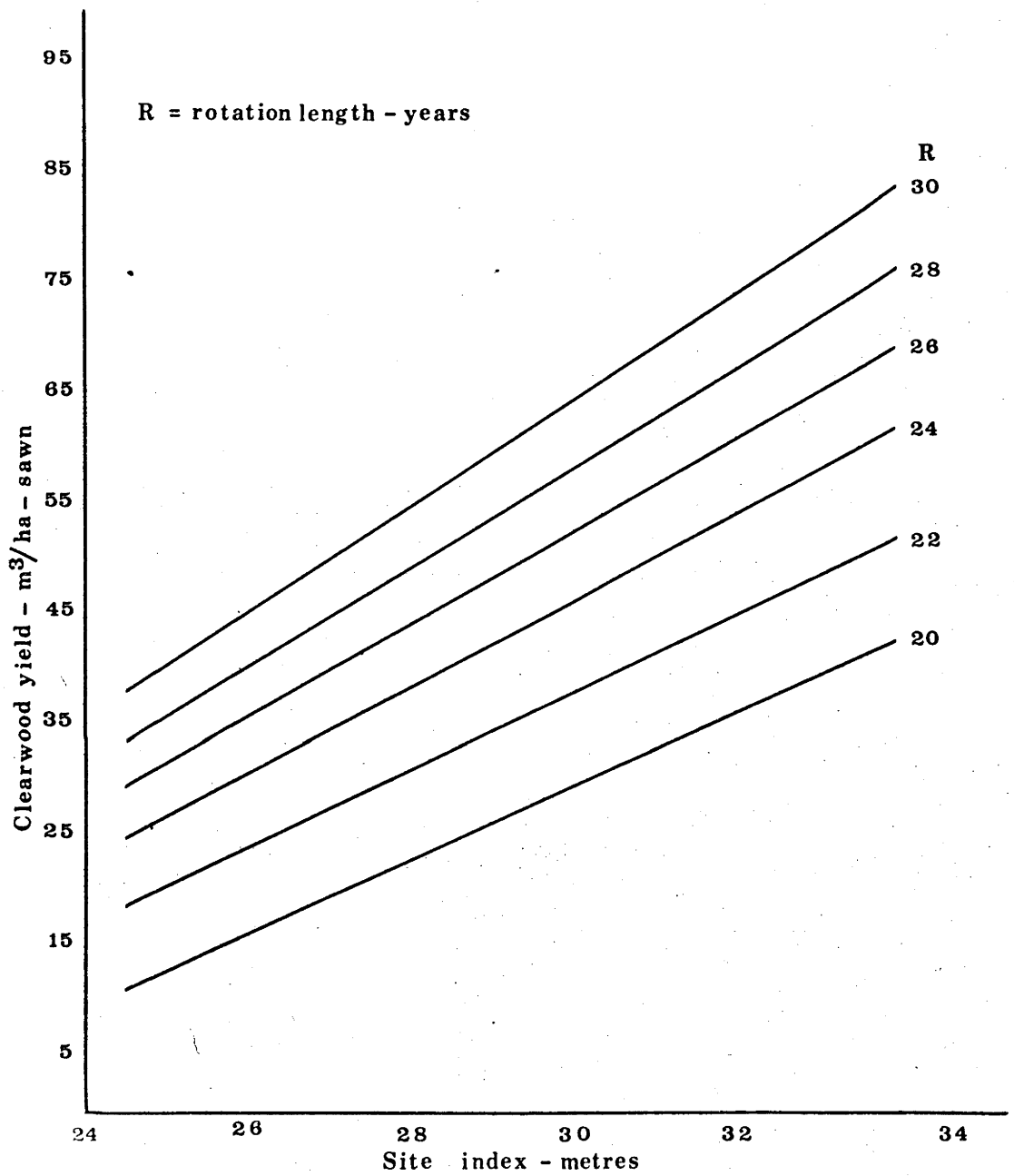
Figure 17   The effect of site index on clearwood yield

Clearwood yields and knotty core diameters are illustrated in
Figure 18. Delaying the onset of treatment progressively from
stand height 4.0 m to 7.6 m markedly decreased clearwood yield,
because stand diameter at pruning and hence knotty core diameter
was increased. The trends in Figure 18 indicate that advancing
the commencement of treatment before stand height 4.0 m will further
increase clearwood yield, and further decrease the knotty core
diameter. This anomalous result is due to the fact that the model
does not incorporate the effects of pruning on height growth. The
clearwood yields indicated in Figure 18 will be attained but at
progressively greater ages as the timing of the thinning is
advanced.

Figure 19 shows that early pruning causes substantial
reduction in basal area growth, and the increment lost is never
regained, resulting in reduced final log diameter.

The timing of pruning and thinning treatments is a critical
determinant of clearwood yield. Management must ensure that
operations are carried out at the prescribed stand ages.

Discussion

All the factors investigated affected the yield of clearwood.
Site index, the timing and severity of the second thinning, and the
stand heights at which the treatments are carried out were most
important in determining clearwood yield. The number of stems left
after first thinning and initial stocking were less critical.
Contrary to expectation, heavy early thinning reduced clearwood
yield if the pruning treatment did not commence until stand height
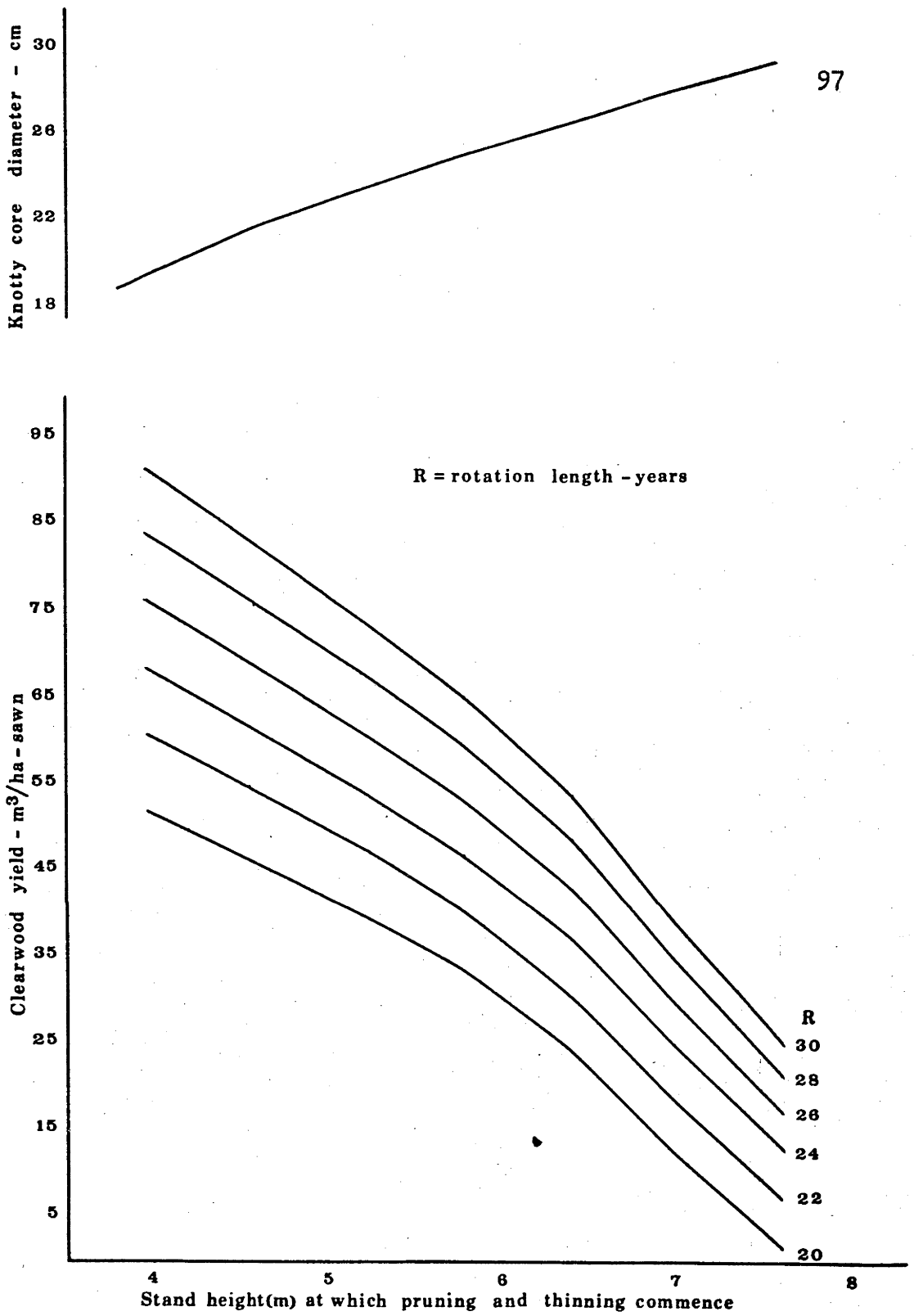
Figure 18   The effect of the timing of thinning and
            pruning treatments on clearwood yield and
            knotty core

20

98

pruning and thinning
commenced at 7·6 m M.T.H.

pruning and thinning
commenced at 4·6 m M.T.H.

Basal area - m²/ha

Stand height - metres
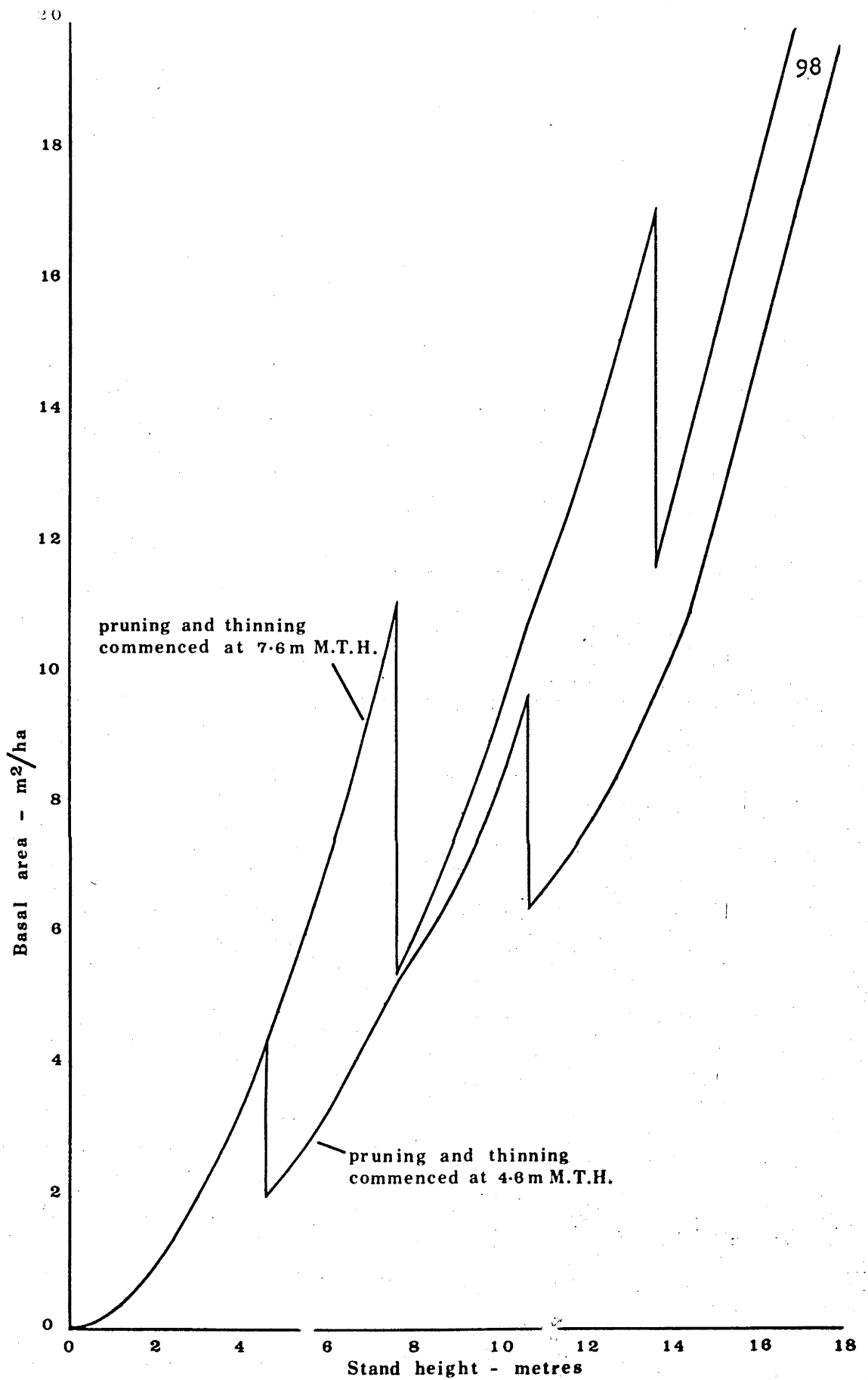
Figure 19   The effect of delaying the commencement of
               thinning and pruning treatments on **basal**
               area growth.

6.1 m. However, advancing the commencement of both pruning and thinning treatments to stand height 4.6 m yielded increased amounts of clearwood.

It is suggested that the following schedule would not be unreasonable if the object of management is to produce substantial volumes of clearwood:

(i)   establish 1 500 stems per hectare,

(ii)   prune 490 stems per hectare to 2.4 m at stand height 4.6 m,

(iii)   thin to 490 stems per hectare at stand height 4.6 m,

(iv)   prune 370 stems per hectare to 4.3 m at stand height 7.6 m,

(v)   prune 250 stems per hectare to 6.1 m at stand height 10.7 m,

(vi)   thin to 250 stems per hectare at stand height 10.7 m.

This schedule is similar to that advocated by Fenton (1972 a). It is unlikely to yield the maximum possible amount of clearwood because heavy early thinning increases knotty core diameter and reduces clearwood yield. Procedures do exist to enable the determination of the silvicultural strategy which will maximise clearwood yield using the model described in Chapter 4. Dynamic programming has been used by Schreuder (1971) to determine simultaneously the optimal thinning schedules and rotation lengths for even aged stands, and Watt (1968) has described simulation techniques to find the set of independent variables which will optimise an objective function. However, there was insufficient time available to enable the writer to attempt to use one or other of these techniques.

CHAPTER SEVEN

A STOCHASTIC ANALYSIS OF THE YIELD OF CLEARWOOD

Introduction

The analyses carried out in Chapter 6 assumed conditions of certainty: they assumed that the outcome predicted by the model occurred with a probability of unity. Most decision-making techniques in forestry have implicitly assumed conditions of complete certainty (Flora 1968). However, most decisions are in fact made under conditions of uncertainty.

Marty (1964) treated the decision to prune as essentially a decision under uncertainty. His approach consisted of specifying the range over which the determinants of the profitability of pruning such as growth rates, interest rates, pruning costs and clearwood prices were likely to vary, and analysing the profit function within these ranges. This approach has the disadvantage that it implicitly assumes uniform probability distributions for the determinants of pruning profitability. Thus the best and the worst outcomes were assumed to occur with a probability equal to that of the most likely outcome. This assumption is clearly invalid.

Thompson (1968) also considered the decision to prune as a decision under uncertainty. As sources of uncertainty he recognised future yields, future prices and the discount rate. He defined discrete future states of nature for these variables, allocated subjective probabilities of occurrence to each state and then applied Bayesian decision theory to calculate the profitability of pruning.

This method is theoretically sound but becomes cumbersome if a large number of variables encompassing a wide range of future states of nature are involved.

A method which has been widely used to assist decision making under uncertainty is the Monte Carlo method. Basically the use of the method involves specification of the probability distributions of the variables determining the outcome of a process. For each such variable, a random value from the distribution is selected and used in subsequent calculations, instead of the mean or median value used in the deterministic model. By repeating the simulation many times, the probability distribution of the outcome can be built up and used to guide a decision.

A good introduction to the Monte Carlo method is given by Jones (1972) and more advanced treatments have been written by Naylor et al (1966) and Churchman et al (1957). Monte Carlo simulation has been widely applied to problems involving stochastic processes whose analytical solution would be intractable, in fields as diverse as critical path network analysis (King 1953), queuing analysis for the design of production facilities (Tocher 1963), risk-investment analysis (Jones 1972) and nuclear physics (Meyer 1956). The method has been used in forestry decision making. Davis (1968) mentioned use of Monte Carlo methods in network analysis of controlled burning scheduling problems. Rudra (1970), Newnham et al (1970) and O'Regan et al (1966, 1967) have used Monte Carlo methods to simulate the structure of even aged stands.

The Yield of Clearwood as a Stochastic Process

The regressions upon which the simulation model described in Chapter 4 is based describe stochastic processes. On these grounds alone the decision to prune to produce clearwood embodies a degree of uncertainty. Uncertainty is also introduced into the model because a silvicultural treatment is unlikely to be applied exactly as prescribed.

The sources of uncertainty in the clearwood yield resulting from the regime advocated in Chapter 6 are:

(i)　　　the condition of the stand,

i.e. (a)　the initial stocking,

(b)　the ages at which the pruning treatments are carried out,

(c)　the number of stems pruned at each lift,

(d)　the ages at which the thinning treatments are carried out,

(e)　the residual stockings left after the thinnings,

(f)　the stand height at rotation age,

(ii)　　　the values of the dependent variables predicted by the

　　　　　regressions on which the model is based.

Probability distributions for the variables defining the silvicultural schedule were specified by means of the Beta probability distribution. The shape and position of the Beta distribution is specified by the mode (M), an upper limit (P) and a lower limit (Q) (Richmond 1968). The values of M, P and Q for each variable defining the silvicultural schedule were based subjectively upon the writer's experience and were given the values indicated in Table 8.

TABLE 8:   VALUES OF M, P AND Q FOR THE BETA DISTRIBUTIONS OF

VARIABLES DEFINING THE SILVICULTURAL SCHEDULE

Variable	Q	M	P
1. Initial stocking (s.p.h.)	1 376	1 500	1 624
2. First thinning			
(a) stand height (m)	4.3	4.6	6.1
(b) residual stocking (s.p.h.)	441	490	539
3. Low pruning			
(a) stand height (m)	4.3	4.6	6.1
(b) pruned stocking (s.p.h.)	441	490	539
4. Medium pruning			
(a) stand height (m)	7.3	7.6	9.1
(b) pruned stocking (s.p.h.)	333	370	407
5. High pruning			
(a) stand height (m)	10.4	10.7	12.7
(b) pruned stocking (s.p.h.)	225	250	275
6. Second thinning			
(a) stand height (m)	10.4	10.7	12.7
(b) residual stocking (s.p.h.)	225	250	275
7. Stand height (m) at rotation age (25 years) on site index 29 m	32.6	34.1	35.7

The distributions defined by these variables were thus
subjective probability distributions.   Variates were generated
stochastically from the Beta distributions using Fortran
subroutines ABSEL and RANBET written by Dr. A. B. Rudra of the
University of Melbourne.

For the regressions upon which the model is based, the probability distributions for each was specified by the expected value of the dependent variable and the standard deviation of the regression. A random variate (x) from a Normal probability distribution with expected value (EX) and stand deviation (S) is given by the following relation:

$$X = EX + S \times GRAND \tag{19}$$

where GRAND is a normally distributed random number with zero mean and unit variance.

The requirements for statistical inference in linear regression analysis, that the dependent variable is normally distributed with homogeneous variance, and that successive error terms $(\hat{Y}_i - Y_i)$ are independent are implicit in the use of equation 19.

The standard deviations of most of the regressions used in the model could be determined objectively, and these are given in Table 1 Appendix C. The standard deviations for equation set 15 relating diameter over stubs in each pruning lift to the stand mean D.B.H. at the time of pruning, and for equation 16 (a) relating the diameter of the largest branch on the low pruned section to the stand mean diameter at pruning could not be determined objectively. Normal probability distributions with expected values given by the appropriate equations, and standard deviations of 1.27 cm (0.5 in) were assumed, based on the writer's experience and appraisal of the data.

Mortality in stocking was assumed to be a deterministic process. The expected value of mortality over the period between

second thinning and rotation age is about 2 % and the use of a
deterministic estimate for mortality is unlikely to influence the
variance of the outcomes appreciably.   Clutter et al (1973)
stated that under certain conditions radiata pine stands may show
little mortality for a number of years, until density reaches a
point where very intense mortality occurs in a concentrated time
period after which mortality is again negligible.   Paillé et al
(1971) have described probability distributions for mortality of
individual Douglas fir stems, using relative tree size and position
in the canopy as independent variables.   Smith et al (1965) have
described the use of Poisson, Binomial and Negative Binomial
distributions to simulate individual tree mortality of Douglas fir.

Any attempt to simulate mortality in a stochastic fashion
should consider the spatial distribution of mortality as well as
its expected value over time and there is a complete lack of data
on the former aspect of radiata pine stand dynamics.

For equation 18 relating clearwood yield to tree basal area
and knotty core diameter, a Normal probability distribution with a
standard deviation of 0.07 m^3/tree derived from the analysis of
the sawing trial data in Chapter 4 was used.

Equation 13, relating the proportion of increment lost to
the proportion of green crown removed was used to calculate the
increment lost from pruning because an objective estimate of the
standard deviation from regression was available.

These modifications were incorporated into the simulation
model and the yields simulated using the University Univac 1108
computer.

Probability distributions were constructed for mean knotty core diameter and for stand mean diameter, total stand volume clearwood yield, and stocking at rotation age. The distributions of clearwood yield, knotty core diameter, stand mean diameter and total volume are illustrated in Figures 20, 21, 22 and 23 respectively. The distribution of stand stocking at rotation age is given in Table 1 Appendix D. The probability distributions for clearwood yields from rotation lengths of 20 years, 25 years and 32 years are compared in Table 9. One thousand iterations were required to produce reasonably smooth distributions.
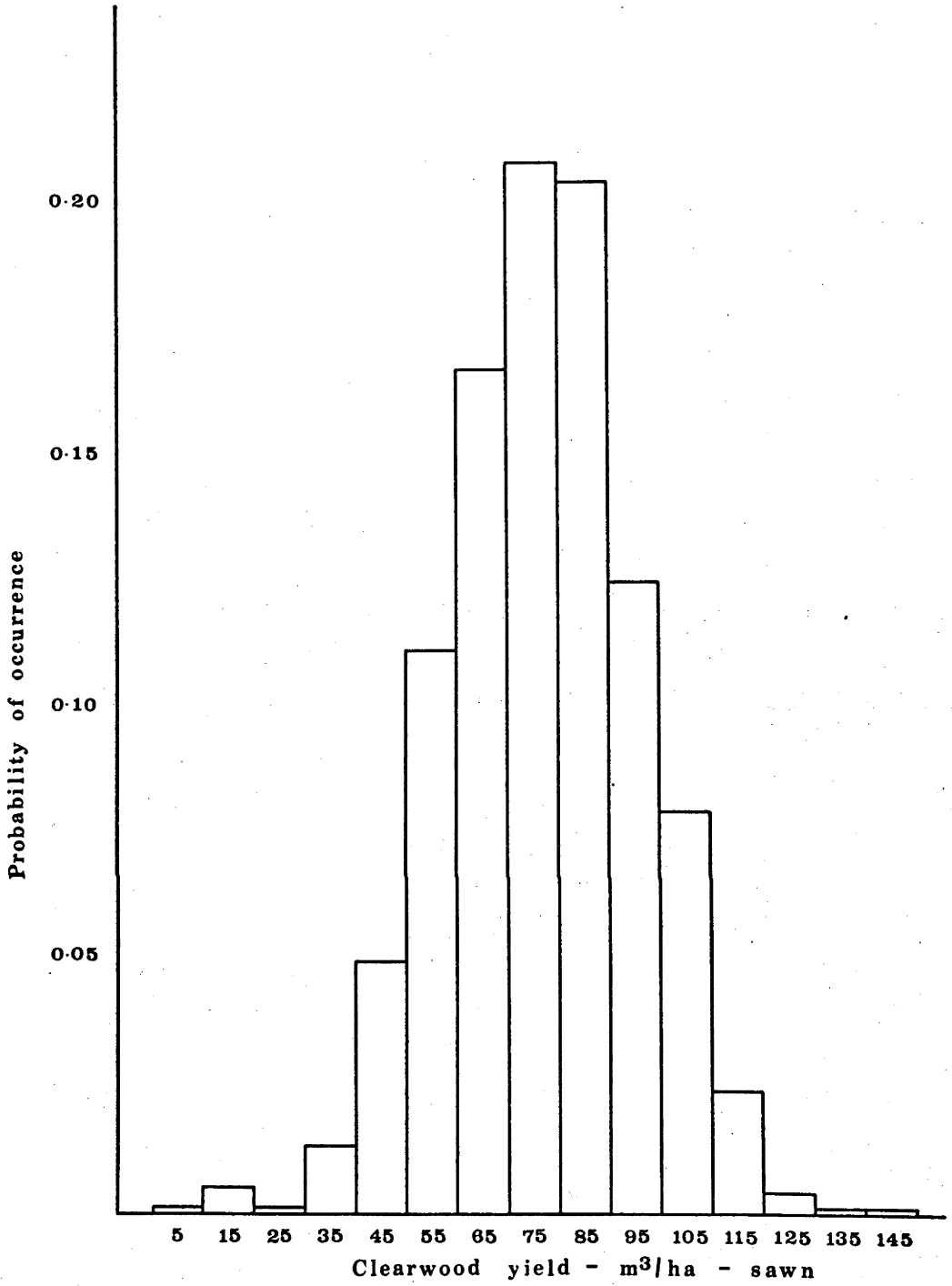
Figure 20   The distribution of clearwood yield
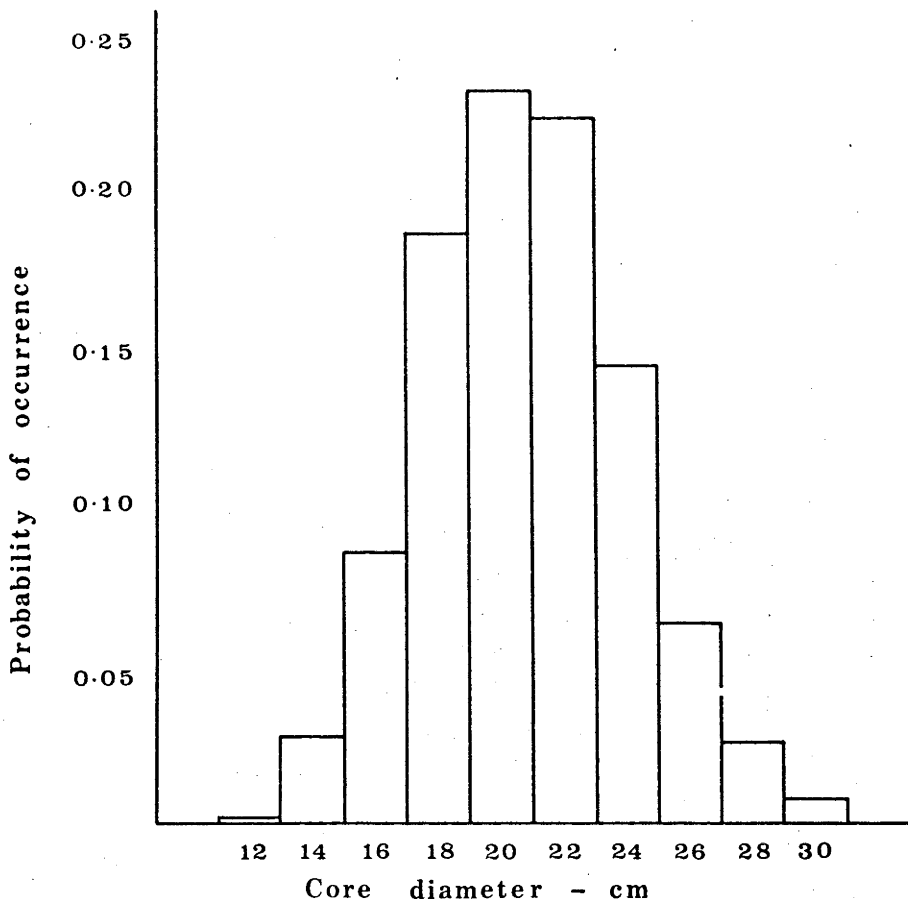
Figure 21   The distribution of stand mean knotty core diameter
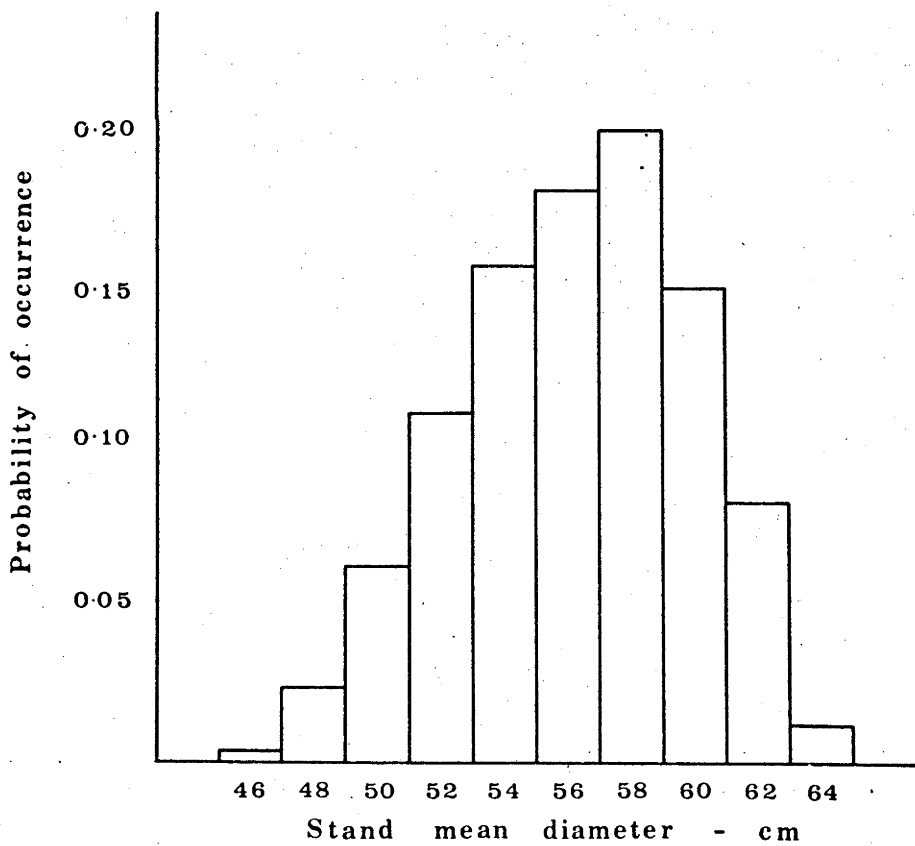
Figure 22   The distribution of stand mean diameter
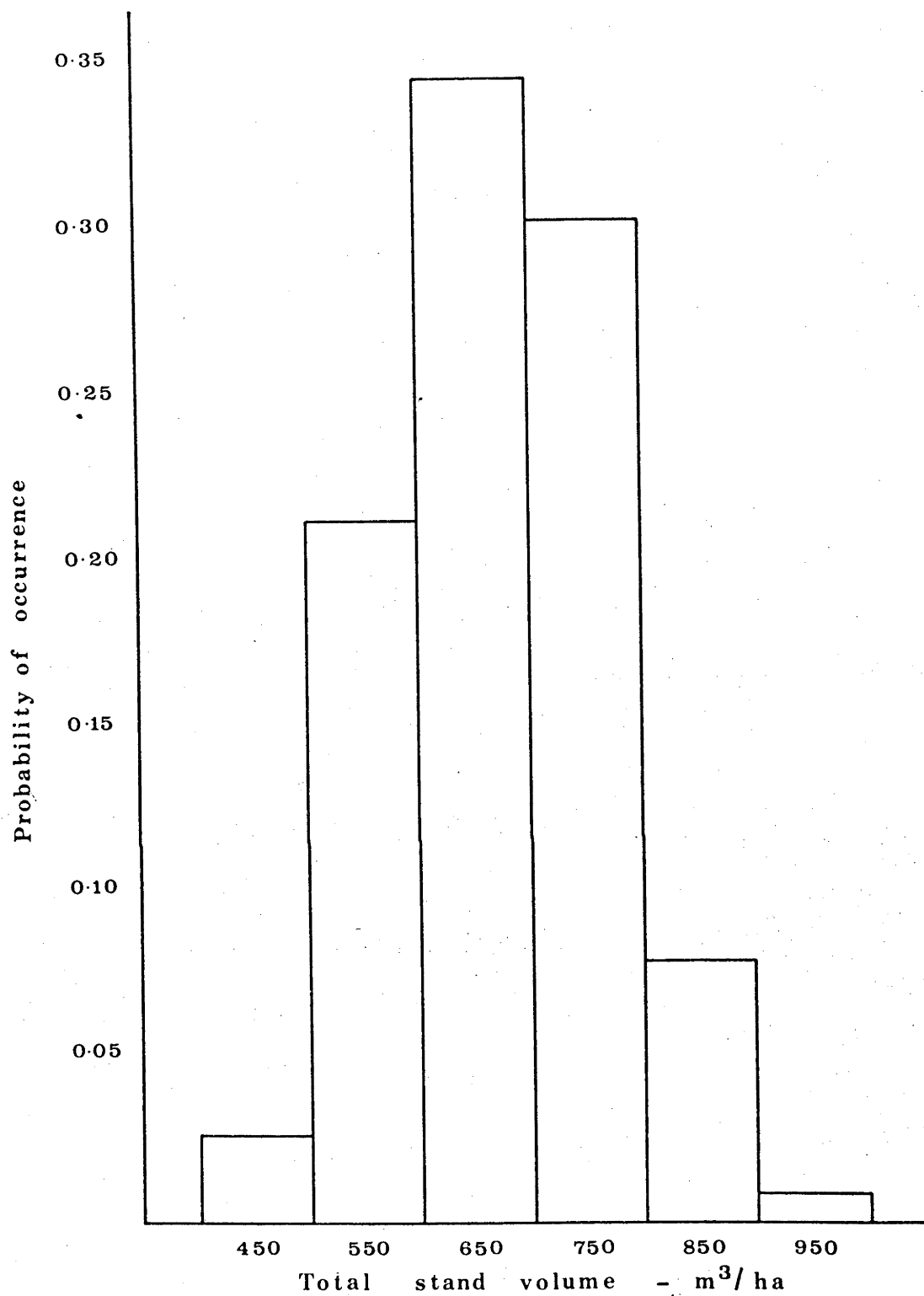
Figure 23   The distribution of total stand volume

TABLE 9 :   PROBABILITY DISTRIBUTIONS FOR CLEARWOOD YIELD AT AGES

20, 25 AND 32 YEARS ON A SITE INDEX OF 29 m.

Clearwood Yield	Probability of Occurrence at age:		
m^3/ha	20	25	32
5	0.005	0.001	0.001
15	0.015	0.005	0.001
25	0.055	0.001	0.005
35	0.127	0.013	0.002
45	0.248	0.050	0.005
55	0.254	0.112	0.013
65	0.185	0.168	0.038
75	0.084	0.209	0.078
85	0.022	0.205	0.109
95	0.005	0.126	0.164
105	-	0.080	0.221
115	-	0.024	0.159
125	-	0.004	0.127
135	-	0.001	0.056
145	-	0.001	0.017
155	-	-	0.004
Expected value	51.87	76.90	102.33
Variance	231.70	348.99	448.57
Coefficient of Variation	29.35	24.29	20.70

The deterministic estimates of the mean knotty core diameter,
stand mean diameter, total stand volume, clearwood yield and
stocking for the 25 year rotation are compared with the stochastic
estimates of the means and modes of the corresponding probability
distributions in Table 10.

TABLE 10.   COMPARISON OF DETERMINISTIC AND STOCHASTIC ESTIMATES
OF KNOTTY CORE DIAMETER, STAND MEAN DIAMETER, TOTAL STAND VOLUME,
CLEARWOOD YIELD AND STOCKING AT AGE 25 YEARS.

Variable	Deterministic Mean	Stochastic Mean	Stochastic Mode
Knotty core diameter (cm)	19.6	20.9	20.0
Stand mean diameter (cm)	50.9	56.2	58.0
Total stand volume (m^3/ha)	572.0	675.5	650.0
Clearwood yield (m^3/ha)	63.7	76.9	75.0
Stocking (s.p.h.)	242.0	241.2	245.0

Discussion

Table 9 shows that the expected value of the clearwood yield
increased as the rotation lengthens.   The variance of the outcome
also increased with rotation length, but the coefficient of
variation decreased.   Thus while the absolute risk of not obtaining
a particular outcome increases with rotation length, the relative
risk decreases.   The forest manager must firstly decide upon the
yield of clearwood he requires, and secondly upon the degree of
certainty with which he wants to obtain the required quantity.
Depending upon his attitude to risk taking, he could then specify

the rotation length which would maximise his utility using procedures such as the standard gamble technique described by Halter et al(1971).

The differences between the deterministic means of the variables in Table 10 and their corresponding stochastic estimates is due to the combination of probability distributions. In equation 9, relating stand basal area to stand height and stocking, and equation 13 relating the proportion of increment lost due to pruning to the proportion of green crown removed, the logarithm of the dependent variable was assumed to be normally distributed about the regression plane. If the logarithm of a variable is normally distributed, then the distribution of the antilog follows a positively skewed log normal distribution, and the mean exceeds the mode. Combining these distributions with symmetrical distributions will increase the expected value of the outcome.

The results presented for the Monte Carlo analysis in this chapter were derived under the assumption that the probability distributions employed in the model are independent of one another. Silvicultural treatments were simulated over a period of about five years and in practice they are usually implemented by different personnel skilled at each particular operation. The assumption that the probability distributions of the variables defining the schedule are independent is probably valid. The assumption that the probability distributions of the regressions comprising the model are independent is also probably valid. While basal area increment is correlated with height increment, height rather than age has been used as an independent variable to predict basal area increment and therefore the distributions of height increment and

basal area increment are independent.

Additional sources of uncertainty which were not incorporated in the model were the occurrence of fire, windthrow and insect and fungal attack. Windthrow and insect and fungal attack are uncertain causes of loss of yield, but their probabilities of occurrence over time, and their severity should not be difficult to estimate from historical records. The yield salvaged should also be considered. Chandler (1970) suggested that windthrow was correlated with silvicultural treatment and stand height. Soil type is also important (Wendelken 1966). Fenton and Dick (1972 a) have calculated the probability of fire loss in New Zealand for the periods 1952 - 72, 1962 - 72 and 1967 - 72 as 0.089, 0.032 and 0.019 respectively. Fire, windthrow, and insect and fungal attack will act to reduce the expected value of clearwood yield.

On the basis of the writer's experience, and the information available, the results represent the best estimates that can be made of clearwood yield under the defined conditions. The variability in the clearwood yield has important implications for the profitability of pruning. This aspect is considered in more detail in the next chapter.

CHAPTER EIGHT

THE PROFITABILITY OF PRUNING RADIATA PINE

Introduction

The difficulty in analysis of the profitability of pruning is
that clearwood is jointly produced with other forms of wood. There
is thus no rationale upon which to allocate a proportion of the
costs of afforestation to clearwood production. Similarly, the
definition of the returns to pruning simply as the value added to
otherwise knotty lumber ignores other benefits of pruning, such as
improved access and visibility, fire protection, reduction in
trimming costs at clearfelling (Whiteley 1971), or the
inter-relationships that pruning has with the production of good
quality logs on short rotations.

The difficulty of allocating the costs and benefits of
pruning led Fenton (1972 b, 1973) to state that the profitability of
pruning is not found by comparing pruned and unpruned logs of the
same age and size, but by comparing a pruned regime with its most
profitable alternative. This approach to the calculation of
pruning profitability involves the comparison of the profitability
of a pruned regime with all possible alternative management
strategies.

Most studies of the profitability of pruning (Brown, 1965,
1969; Marty, 1964; James, 1968; Thompson, 1968; Lewis, 1964;
Horton, 1966) have adopted a simple marginal approach. They have
assumed that the only benefit achieved by pruning is the marginal value

added to otherwise knotty lumber, and that the only costs associated
with the production of clearwood are the marginal costs directly
associated with pruning.

Both approaches to the evaluation of the profitability of
pruning were considered in this study.   Firstly using the marginal
approach, the discounted net worth (D.N.W.) of the pruning treatment
was analysed over a range of site index taking into account only the
direct costs and benefits of pruning.   Secondly the management
strategy which incorporates the pruning treatment was analysed
deterministically for one site index as a basis for the comparison
of this strategy with other alternatives.

The Costs of Pruning

Pruning costs are basic to the analysis of the profitability of
pruning.

The Kaingaroa Forest Work Study Unit has carried out time
studies of pruning operations in Kaingaroa Forest.   These have
involved intensive study of low, medium and high pruning operations
in radiata pine stands occupying a wide range of site index and have
included extremes of undergrowth and topographical conditions.
These studies have established that the costs of pruning depend upon:

(i)   The time taken to prune a specified length of stem, using
       specified pruning tools and a defined work method.   Under
       these conditions the D.B.H. of the stem at the time of
       pruning is a reasonably good and easily measurable
       variable from which to predict the pruning time,

(ii)   The time taken to walk between pruned trees while selecting the next tree to be pruned. The walk and select time depends upon ground conditions such as the amount of slash and undergrowth, the degree of slope, and the number of stems pruned per unit area.

(iii)   Other miscellaneous time elements such as the time taken to prepare equipment, rest and relaxation time, and access time from the point of set down to the work site.

(iv)   The rate at which the worker is paid consisting of the basic wage rate, plus institutional payments such as wet pay, sick pay, holiday pay, insurance, travel etc.

These elements have been combined to produce sets of time standards for all pruning operations which enable the costs of pruning to a particular prescription to be calculated if the independent variables pertaining to a particular stand are known. The Kaingaroa Forest Time Standards for pruning were used to calculate all pruning costs in this study. An example of their application to low pruning is given in Appendix E together with the assumptions made to enable their use.

A Stochastic Analysis of the Profitability of the Pruning Operation.

The basic assumptions made in the marginal approach to the analysis of the profitability of pruning were that:

(i)   the marginal costs associated with the production of clearwood were the direct costs of pruning only,

(ii)   the marginal benefits of pruning consisted only of the

value added to otherwise knotty lumber by upgrading from a lower grade to clear grade.

The probability distributions for the costs of pruning were specified by means of the Beta distribution described in Chapter 7. The values of the modes of the distributions were calculated from the Kaingaroa Forest Time Standards for pruning. The upper (P) and lower (Q) limits for the probability distributions were based on the writer's experience of pruning costs. The relevant values are given in Table 11.

TABLE 11: VALUES ($/ha) FOR THE MODE (M) UPPER (P) AND LOWER (Q) LIMITS FOR THE DISTRIBUTION OF PRUNING COSTS

Operation	Cost ($/ha)[1]		
	Q	M	P
Low pruning	37.60	47.0	56.33
Medium pruning	28.40	35.50	42.60
High pruning	22.08	27.60	33.12

[1] includes direct overheads

The probability distributions were assumed not to be significantly different over the range of site index (24.4 m - 33.5 m) considered.

The value added by pruning to lumber sawn from a pruned log is problematical as there is no information concerning the future slope and position of the demand curve for clearwood relative to the demand curves for other timber grades. The present (May 1973) differential between dressing and box grades is about $1.40/m^3 ($6.00/100 bd. ft.).

In considering the differential between timber sawn from pruned and unpruned logs a detailed knowledge of grade yields by widths is required for both log types and the differential should relate to the timber sawn from equivalent portions of pruned and unpruned logs. New Zealand studies (Brown 1965, 1969, Fenton and Brown 1963) have assumed a differential between dressing and clear grades. If it is assumed that clearwood will be preferred over lower grades, then these differentials may be conservative because an unpruned log grown at the wide spacings envisaged in the regime under consideration is likely to produce substantial quantities of timber below dressing grade in quality.

The price differentials for clear grade timber shown in Table 12 have been used in calculations of the profitability of pruning in the past.

TABLE 12: PRICE DIFFERENTIALS FOR CLEARWOOD

Source	Differential $/m³ - sawn	Comments
Brown (1965)	4.24 - 8.47	N.Z. P.radiata - above dressing grade
Brown (1969)	8.47	N.Z. P.radiata - above dressing grade
Marty (1964)	21.19 - 63.56	U.S.A. P.strobus
Thompson (1968)	21.19 - 42.37	U.S.A. Species not given
Jones (1968)	8.47 - 16.95	U.S.A. P.elliottii
Fenton (1972 a)	16.95	N.Z. P.radiata - approximate above dressing grade
Fenton & Brown (1963)	8.47	N.Z. P.radiata - above dressing grade
Horton (1966)	21.19	U.S.A. P.strobus
Reilly (1970)	23.7 - 29.63	U.S.A. Southern Pines - pers.comm.

On the basis of these figures a probability distribution for
price differential with a mode of $8.47/m³ a lower limit of $0.0/m³
and an upper limit of $16.95/m³ was specified for the analysis using
the Beta distribution. The differentials given by this
distribution were assumed to apply on the domestic market regardless
of future trends in the real price of sawn timber.

A third cource of uncertainty in the analysis of pruning
profitability was the choice of the discount rate. The interest
rate to use for public investment has long been the subject of debate
(Baumol 1968). However the correct rate to use lies between the
social rate of time preference, and the social opportunity cost rate
occasioned by the transfer of funds from the private to the public
sector. Dasgupta et al (1972) suggested that the former rate would
be about 4.5 % in a developed economy, while the latter should be in
the range 8 - 12 % (Seagraves 1970). A 1971 New Zealand Treasury
directive stated that the correct rate to use for projects in the
public sector of forestry is 10 %, but this may include an allowance
for inflation (Fenton and Dick 1972 a).

For this analysis the approach advocated by Fenton and Tustin
(1972) was adopted, and a range of interest rates was specified.
A probability distribution for interest rate was defined by means of
the Beta distribution with a mode of 7 % and upper and lower limits
of 10 % and 4 % respectively.

The final source of uncertainty was the stand height at
rotation age. A rotation age of 25 years was assumed since it is
difficult to specify a probability distribution for rotation length
outside the context of a particular management situation. Stand
height at rotation age was specified by the Beta distribution with a

mode on each site index given by the expected value of height
on the appropriate height age curve and upper and lower limits
set at $\pm 5\%$ of the mode.

The probability distributions specified above were
integrated into the clearwood simulation model and the D.N.W.
of the pruning operation simulated for a single rotation on
site indices of 24.4 m, 29 m and 33.5 m.

The probability distribution for the D.N.W. of pruning
on a site index of 29 m is illustrated in Figure 24 and
compared with the distributions for other site indices in
Table 13.
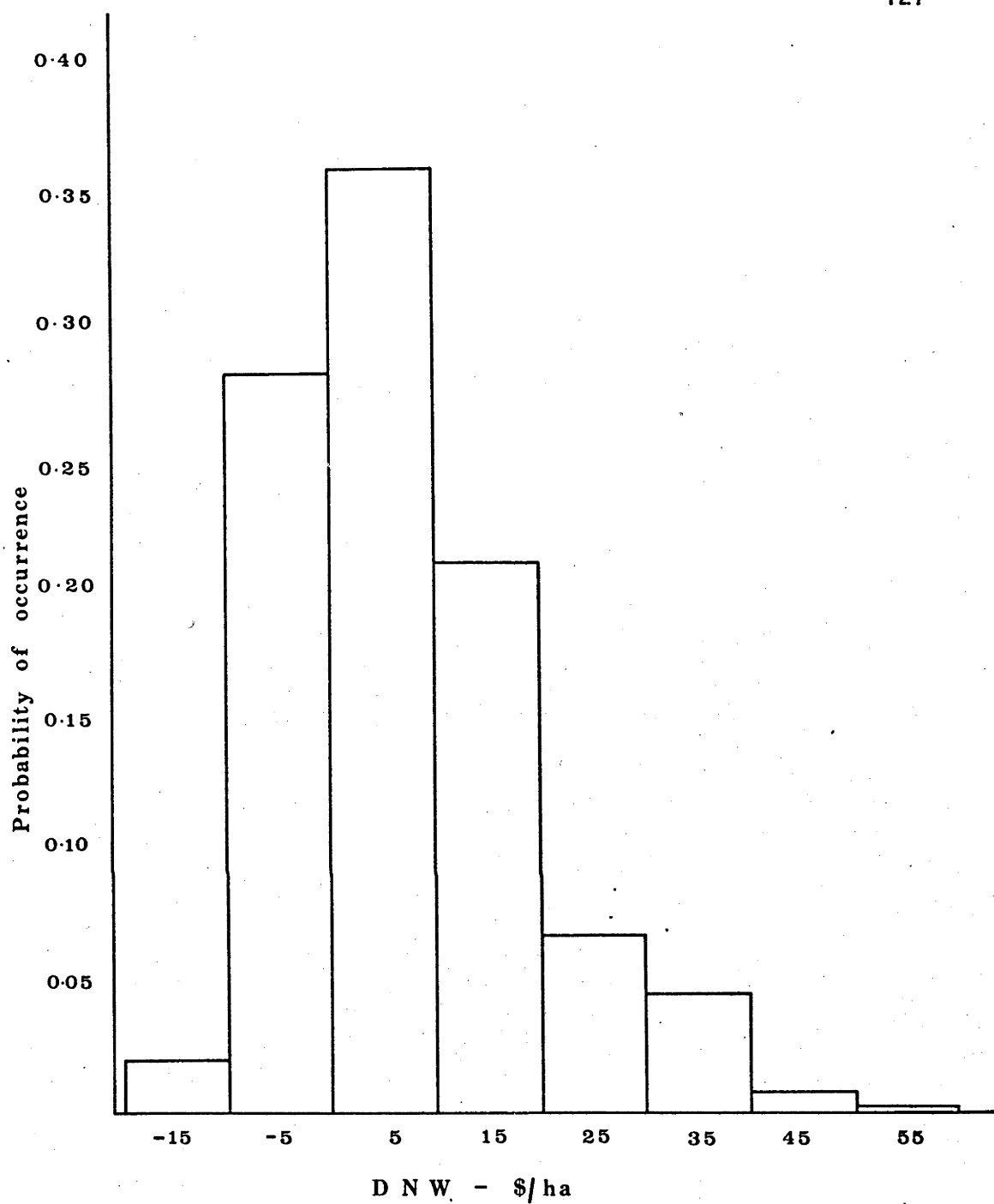
Figure 24   The distribution of the discounted net
              worth (D.W.W.) of the pruning operation

TABLE 13:   PROBABILITY DISTRIBUTIONS FOR THE D.N.W. OF PRUNING ON

SITE INDICES OF 24.4 m, 29 m AND 33.5 m (AGE 25 YEARS)

D.N.W. (\$/ha)	Probability of Occurrence on site index: 24.4 m	29 m	33.5 m
- 15	0.026	0.021	0.015
- 5	0.433	0.283	0.194
5	0.371	0.359	0.269
15	0.128	0.214	0.233
25	0.032	0.068	0.143
35	0.008	0.044	0.079
45	0.001	0.007	0.037
55	0.001	0.004	0.022
65	-	-	0.005
75	-	-	0.001
85	-	-	0.001
95	-	-	0.001
Expected value	2.4	7.05	13.44
Variance	83.84	141.9	257.37
Coefficient of variation	381.5	168.94	119.36

Discussion

Table 13 shows that the expected value of the D.N.W.
increased as site index increased, as expected.   However the
variance of the outcome also increased as site index increased.
This means that the absolute risk of not obtaining the expected
value of the outcome increased with site index, although the risk

that the outcome will be negative decreased.

The probability that the cost of pruning will be recouped by
the value added to otherwise knotty lumber is 0.541, 0.656 and
0.791 for site indices 24.4 m, 29 m and 33.5 m respectively. The
value added to clear lumber by pruning is most unlikely to cover the
costs of pruning on site indices below 25 m.

The uncertain elements of fire, windthrow and insect and
fungal attack have been ignored. These will reduce the expected
value of the D.N.W.

The Profitability of a Short Rotation Sawlog Regime.

Very detailed profitability studies of short rotation sawlog
regimes with pruning have been carried out by Fenton and Sutton (1968)
and Fenton (1972 a), and compared with other management alternatives
in Fenton 1972 b, c and d. These deterministic studies indicated
that pruned short rotation sawlog regimes are likely to be more
profitable than unpruned 'export' log regimes and very much more
profitable than pruned long rotation sawlog regimes incorporating
production thinning.

The purpose of the analysis carried out here was to determine
the profitability of a short rotation sawlog regime with pruning,
using the yields predicted by the simulation model, and to test its
sensitivity to the price of clearwood. The calculations were
carried out deterministically as the lack of data precluded a
stochastic study.

(i)   Calculation of returns

Total volume yields were predicted for rotation lengths
ranging from 20 to 30 years using the deterministic model
described in Chapter 4.   Duff's (1954) taper tables were used
to segregate volume into 5.5 m (18.0 ft.) log lengths and these
were assumed to be sawn to lumber using conversion factors derived
from a relationship between S.E.D. and D.B.H. established from
data presented by Fenton et al (1971).

Sawn timber grades were allocated in log height classes
using the results of sawing trials from Fenton et al (1971) with
the exception that clearwood yields were predicted from the
simulation model.

The current (May 1973) wholesale domestic price list for
Waipa State Sawmill (New Zealand) was used to value the sawn
outturn using the average prices for all widths within grades, and
otherwise ignoring the effect of piece width on price.   Clearwood
prices were assumed to be $4.24, $8.47, $12.71 and $16.95 per
cubic metre above dressing grade, giving a total price of $54.87,
$59.11, $63.35 and $67.58 per cubic metre respectively for
clearwood, in each of four analyses.

(ii)   Calculation of costs

Establishment, releasing, Dothistroma pini Hulbary aerial
spraying costs and log loading and transport costs were established
in communication with S. J. McPherson (Forester N.Z.F.S.).   The
silvicultural costs of the three prunings and two thinnings were
calculated using the Kaingaroa Forest Time Standards for pruning
and thinning.   Sawing, felling and snigging costs were those
described in Parkes (1972) for Australian conditions, relating

cost to log dimension. The costs derived appeared to be similar to current average costs in New Zealand (S. J. McPherson, pers.comm., Brown 1973) but detailed New Zealand data concerning these costs were not available in the literature. All costs are given in Appendix F.

(iii) Derivation of Stumpage Price

The total value of the sawn timber in each log was expressed on a per unit gross log volume basis, and sawing, hauling, loading, felling and snigging costs were deducted to derive a residual stumpage price for standing timber.

The stumpage prices for varying clearwood prices, and the stand diameter, height and merchantable volume for rotation lengths ranging from 20 to 30 years are given in Table 14.

TABLE 14: STUMPAGE PRICES ($/m³) FOR VARYING CLEARWOOD PRICES AND ROTATION LENGTHS (SITE INDEX 29 m)

Age (yrs)	DBH (cm)	Height (m)	Merchantable Volume (m³/ha)	Clearwood price ($/m³) 54.87	59.11	63.35	67.58
20	48.8	29.0	395.1	7.27	7.75	8.23	8.72
22	51.9	31.3	467.5	8.55	9.06	9.56	10.07
24	54.2	33.3	527.2	9.72	10.25	10.77	11.29
26	56.3	35.0	584.3	10.60	11.13	11.66	12.21
28	58.2	36.6	636.9	11.29	11.70	12.23	12.76
30	59.8	38.1	685.2	11.68	12.31	12.74	13.28

(iv) The Profitability Calculation

Profitability calculations in forestry are usually based upon the Faustmann Formula, or a modification of it. The traditional

formula is (Hiley 1956) :

$$\text{L.E.V.} = \frac{Y_n - C(1+i)^n - \sum_{b=1}^{b=n-1} P_b (1+i)^{n-b}}{(1+i)^n - 1} \quad (20)$$

where :

L.E.V.	=	land expectation value,
Y_n	=	net revenue at rotation age,
C	=	cost of establishment,
P	=	silvicultural costs in year b,
e	=	annual maintenance costs,
i	=	interest rate,
n	=	rotation length.

The Faustmann formula has a number of limitations. It assumes that a single representative area of forest land can be effectively identified and that all costs and returns associated with the area can be satisfactorily isolated. Constant interest rates, prices and site productivity over time are also assumed. A more serious limitation is that the model assumes that the marginal costs and the marginal products of the productive factors are constant, and that the factors of production are in perfectly elastic supply. In fact the supply of productive factors will not be perfectly elastic and their marginal productivity will decrease due to the law of diminishing returns. Apart from these limitations, the formula has a tendency to exaggerate the value of land for forestry because the time stream of capital expenditure on forest overheads is not adequately incorporated (Grainger 1968). Nevertheless, the Faustmann model can be safely used to make inferences about the relative profitability of different management strategies (Grainger 1968) and the Faustmann land expectation value (L.E.V.)

was used in this sense as a criterion of relative profitability in this study.

The cost data of Appendix E and the return data of Table 14 were used in equation 20 to calculate the L.E.V. for various clearwood prices and rotation lengths on site index 29 m.

The effect of clearwood price and rotation length on L.E.V. at interest rates of 7 % and 10 % is illustrated in Figures 25 and 26 respectively. The effect of interest rate on the L.E.V. for a 25 year rotation, assuming a premium for clearwood of $8.47/m^3 is illustrated in Figure 27. The internal rate of return is 13 %.

Discussion

Figure 27 shows that interest rate is the most important determinant of relative profitability. This has been a feature of all profitability calculations for sawlog silviculture in New Zealand (e.g. Fenton 1972 a, d, Fenton and Tustin 1972, Fenton and Dick 1972 a, b, c). Interest rate had a much greater effect than rotation length on relative profitability over the range of interest rates and rotation lengths evaluated.

Interest rate was more important than clearwood price in determining relative profitability, over the range of clearwood prices and interest rates evaluated.

The effect of clearwood price on profitability over the range of prices evaluated may not be significant in view of the variation in clearwood and total volume yields established in Chapter 7. A t 7 % interest rate a 19 % increase in clearwood price caused a 19 % increase in L.E.V. At 10 % interest rate,
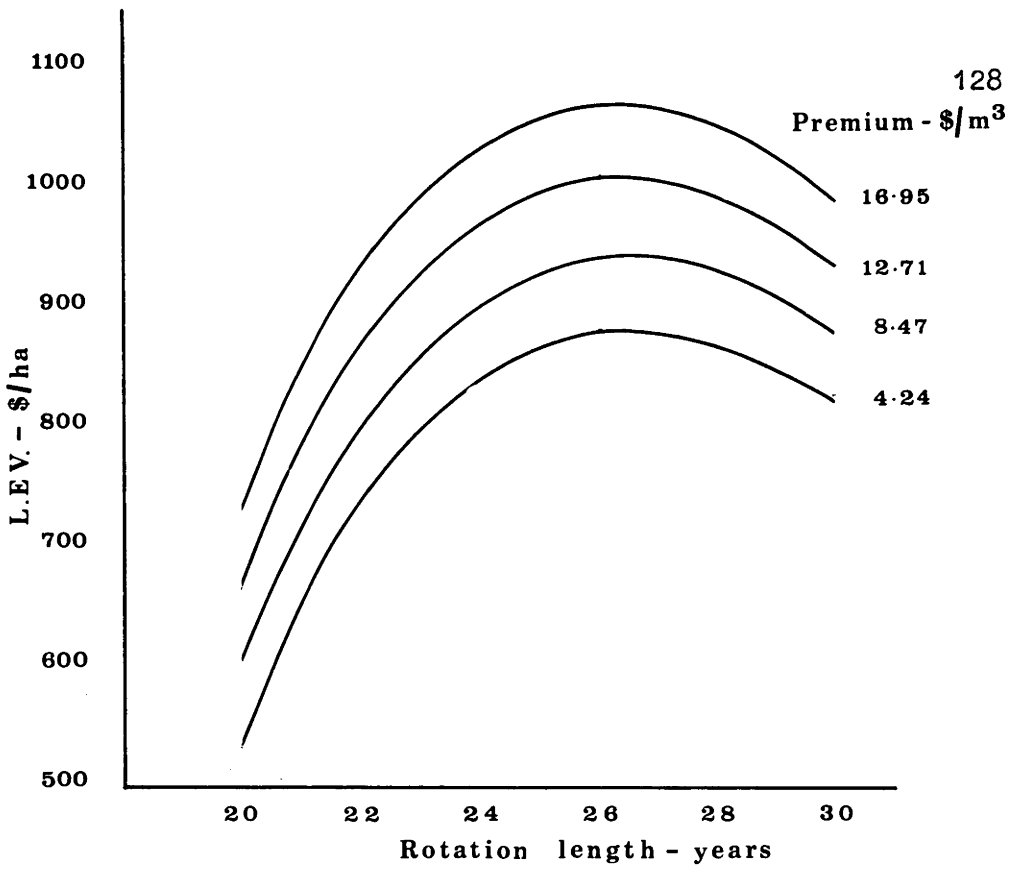
Figure 25   The effect of the premium for clearwood on the land expectation value at 7% compound interest
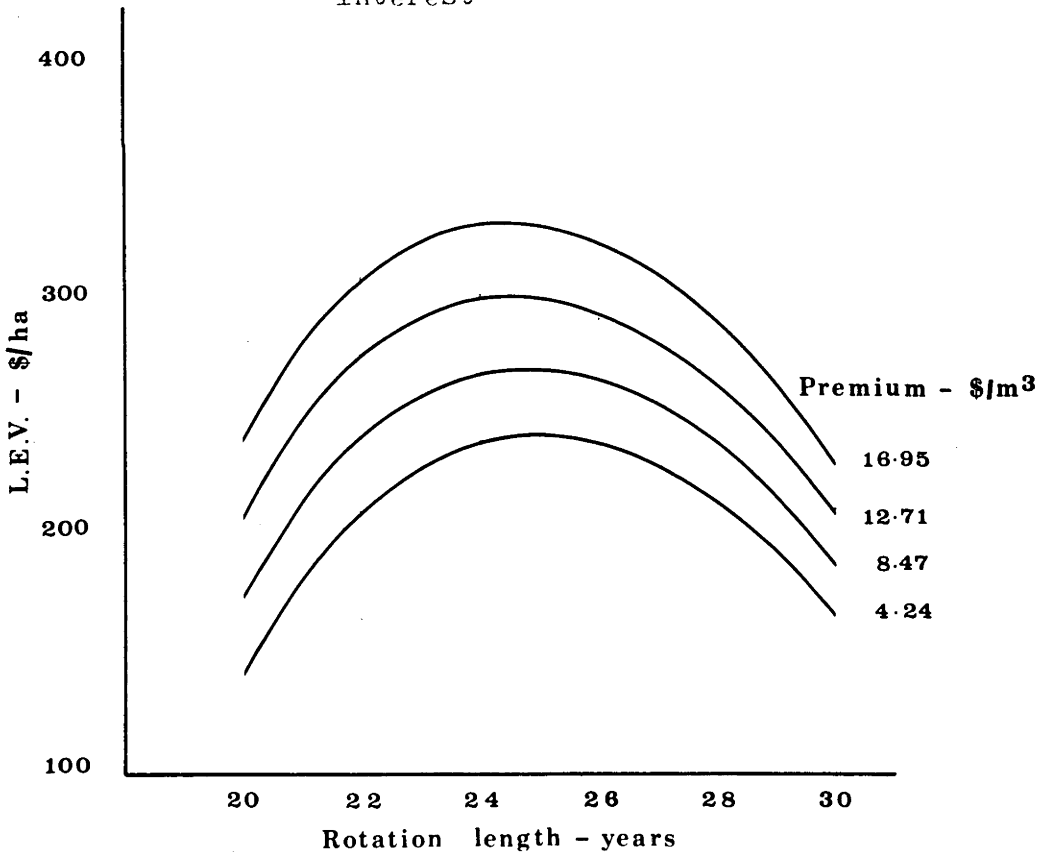
Figure 26   The effect of the premium for clearwood on the land expectation value at 10% compound interest
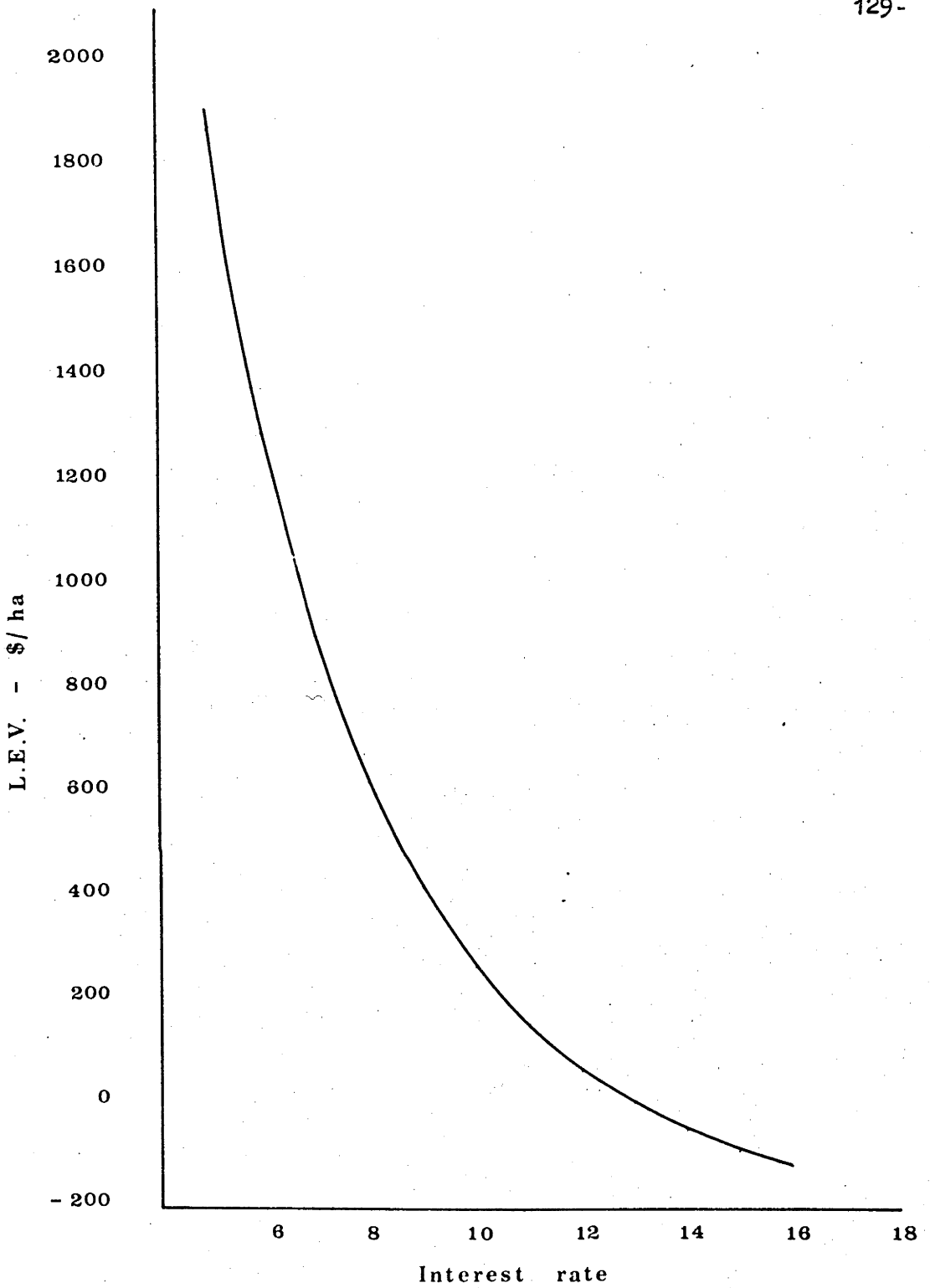
Figure 27   The effect of interest rate on the land
expectation value of a 25 year rotation
with a clearwood premium of $8.47/m^3

the same increase in clearwood price caused a 27 % increase in

L.E.V. The effect of clearwood price on relative profitability

becomes more important at higher interest rates.

The slight difference between interest rates 7 % and 10 %

in the rotation length maximising L.E.V. is of no significance to

forest management.

Short rotation sawlog regimes including pruning are likely

to be profitable on site index 29 m at interest rates of up to 13 %.

The results of this deterministic study, when considered in

conjunction with the stochastic analysis of the profitability of

pruning show that pruning the butt log of radiata pine is most

likely to be a profitable investment on site indices of 29 m and

above.

CHAPTER NINE

CONCLUSIONS

The decision to prune radiata pine in New Zealand's State
Forests was initially the result of the comparison of its wood
properties with those of the high quality clear timber of
indigenous species. The outbreak of mortality associated with
Sirex noctilio in the late 1940's led to the practice of thinning
to waste at an early age, and this reinforced the decision to
prune to control branch induced defects.

The future demand and price of radiata pine clearwood was
not explicitly considered in the decision to prune. It was
implicitly assumed that the superior qualities of radiata pine
clearwood would ensure that it could be sold at a profit sufficient
to justify the allocation of resources to pruning.

A deductive analysis of the nature of demand for clearwood
suggested that demand will be highly price elastic. Thus the
cost of supplying clearwood to the market relative to the price
of substitutes will be an important determinant of future clearwood
consumption. Potential clearwood producers should examine how to
supply the future quantities demanded by the market most
efficiently.

The yield of clearwood from a pruned log is essentially a
function of the diameter of the log, the diameter of the knotty
core, and the sawing pattern used to convert the log to lumber.
Unfortunately the growth of radiata pine in New Zealand is
insufficiently well understood to enable the characteristics of

each individual log in a stand to be predicted. A yield model constructed to predict the yield of clearwood was thus based upon stand averages, rather than the characteristics of individual trees. Future research should be oriented to the collection of data describing the growth of individual stems.

The yield of clearwood is also dependent upon the management strategy adopted. The thinning and pruning treatment imposed upon the stand, and the site index and rotation length were important determinants of clearwood yield. Clearwood production was less sensitive to the initial stocking. A 25 year sawlog rotation with heavy thinning and severe green pruning can be expected to yield about 75 m^3/ha of clearwood on a site index of 29 m. However considerable variation about the expected value of the clearwood probability distribution can be anticipated and clearwood yields may range from 5 m^3/ha to 145 m^3/ha.

Previous yield prediction systems in New Zealand have not considered the production of yield as a stochastic process, and the probability of obtaining the expected value of the outcome has been virtually ignored. The analyses carried out in this study also showed that total volume production, which is an important determinant of the profitability of afforestation may also vary widely. Most calculations of the profitability of pruning and of afforestation in New Zealand may be criticised on the grounds that they have failed adequately to consider uncertainties.

The profitability of a pruning treatment is difficult to analyse because clearwood production jointly uses the factors of production required to simultaneously produce other forms of wood.

The costs and benefits of pruning cannot be allocated objectively. A marginal analysis of the profitability of pruning which incorporated uncertainties in yields, costs and prices and the discount rate indicated that the costs of pruning are unlikely to be recouped by the value added to sawn timber by pruning on site indices below 24 m to 29 m. The expected value of the D.N.W of pruning increased as site index increased, but the risk of not obtaining the expected value also increased.

The lack of data precluded a stochastic analysis of a sawlog regime which included pruning, but a deterministic analysis indicated an internal rate of return of 13 % for a 25 year rotation length on a site index of 29 m. The profitability of the regime is relatively insensitive to clearwood price. Interest rate is the most important variable.

It seems probable, on a marginal profitability basis, that pruning on low site indices is not justified. While the New Zealand Forest Service is committed by past pruning to supply increasing quantities of clearwood for the next 30 years, it should attempt to determine levels of clearwood consumption and price after the year 2000. Clearwood production goals can then be set which will ensure efficient allocation of resources. The clearwood production goals presently implicit in the New Zealand Forest Service pruning policy require revision.

APPENDIX A.   ANALYSES OF VARIANCE.

Table 1

$$\ln BA = -4.87 = 1.85 \ln H + 0.48 \ln S$$

BA   = stand basal area (m^2/ha),

H   = stand height (m),

S   = stocking (stems per hectare).

Source	D.F.	M.S.	F.
Regression	2	0.5876	326.47***
Residual	63	0.0018	
Total	65		

$r = 0.92$

Table 2

$$\ln Y = 0.179 + 0.818 \times \ln X$$

Y   = proportion of original basal area remaining after thinnings,

X   = proportion of original stocking remaining after thinning.

Source	D.F.	M.S.	F.
Regression	1	0.883	213.44***
Residual	42	4.14×10^{-4}	
Total	43		

$r = 0.91$

Table 3

$$D = 1.13 + 367.6 \times \sqrt{\frac{1}{S}}$$

D = potential green crown depth (m),

S = stocking (stems per hectare).

Source	D.F.	M.S.	F.
Regression	1	217.21	69.62***
Residual	29	3.12	
Total	30		

r = 0.84

_____

Table 4

$$\ln Y = 0.83 \times 2.147 \times \ln X$$

Y = proportion of annual basal increment lost,

X = proportion of green crown removed.

Source	D.F.	M.S.	F.
Regression	1	3.71	23.2***
Residual	16	0.16	
Total	17		

r = 0.77

_____

Table 5

$$DIB2 = -1.22 + 0.33 \times DBH$$

DIB 2 = the diameter (cm) of the largest branch in the medium pruned section,

DBH = diameter breast height (cm).

Source	D.F.	M.S.	F.
Regression	1	4.14	31.85***
Residual	12	0.13	
Total	13		r = 0.85

Table 6

$$DLB \; 3 \; = \; -1.80 \; + \; 0.32 \; x \; DBH$$

DLB 3 = diameter of the largest branch in the high pruned section (cm),

DBH = diameter breast height (cm).

Source	D.F.	M.S.	F.
Regression	1	4.55	20.68***
Residual	9	0.22	
Total	10		

$r = 0.84$

Table 7

Analysis of covariance - Sawing trial data (Imperial units)

Source	D.F.	S.S.	M.S.	F.
Separate regressions	5	54501.6		
Single regression	1	56242.7		
Gain	4	8258.8	2064.71	6.37***
Residual	107	32731.0	324.07	

Table 8

$$Y \; = \; - \; 0.1157 \; + \; 1.1989 \; X$$

Y = clearwood yield (m^3),

X = tree basal area (m^2).

Source	D.F.	M.S.	F.
Regression	1	86.19	88.04***
Residual	37	0.979	
Total	38		

$r = 0.84$

APPENDIX B

VARIABLES USED IN THE FLOW CHART.

1   AK   = largest knotty core diameter (cm).

2   AKCD(I)   = the diameter (cm) of the knotty core in the I th
                  pruning section (I = 1,2,3 for low, medium and
                  high pruning respectively).

3   B   = basal area (m^2/ha) of an unthinned and unpruned
                  stand of stocking S and height H.

4   BA   = current basal area (m^2/ha) of the stand at
                  height H and stocking S.

5   BTEMP   = temporary variable name for stand basal area.

6   B1   = basal area (m^2/ha) of a specified number of
                  stems (S^+) at stand height H.

7   CWYLD   = clearwood yield (m^3/ha).

8   D   = green crown depth (m).

9   DBH   = mean diameter (cm).

10 DELTAB   = the difference in basal area (m^2/ha) between a
                  thinned and/or pruned stand and an unthinned and
                  unpruned stand of equivalent height and stocking.

11 DIB(I)   = the diameter (cm) of the largest branch in the
                  I th pruning section (I = 1,2,3).

12 DOS(I)   = the diameter over stubs (cm) of the largest pruned
                  whorl in the I th pruning section (I = 1,2,3).

13 H   = stand height (m).

14 INC   = basal area increment between stand height H
                  and stand height (H + 1).

15 K(I)   = the knotty core diameter (cm) in the I th pruning
                  section (I = 1,2,3).

16 M   = basal area loss (m^2/ha) associated with mortality
                  in stocking.

17 N   = mortality (s.p.h.) in stocking associated with a
                  unit increase in stand height.

18	OD(I)	= the radial growth required to occlude in the I th pruning section (I = 1,2,3)
19	PCR	= the proportion of potential green crown removed in pruning to height P
20	LOSS	= the factor by which the basal area increment in a pruned stand must be multiplied to allow for the effect of pruning on increment
21	RS	= relative spacing per cent
22	S	= stand stocking (s.p.h.)
23	S^+	= temporary variable name for a particular value of S
24	VOL	= total stand volume (m^3/ha)
25	Z(I)	= intermediate values used to calculate mortality in stocking (I = 1,2 .. 5)

APPENDIX C

STANDARD DEVIATIONS OF REGRESSIONS

TABLE 1:   STANDARD DEVIATIONS OF REGRESSIONS

Equation Number	Standard Deviation	Source	
5	0.103 m^2/ha	J. Beekhuis (pers. comm.)	
6	0.000523 m^2/ha	J. Beekhuis (pers. comm.)	
8	28.6 m^3/ha	J. Beekhuis (pers. comm.)	
9	0.80 m^2/ha	Table 1	Appendix A
10	0.02	Table 2	"
11	0.54 m	Table 3	"
13	0.40	Table 4	"
16 (b)	0.92 cm	Table 5	"
16 (c)	1.19 cm	Table 6	"

APPENDIX   D

PROBABILITY   DISTRIBUTION   OF   STOCKING   AT   AGE   25   YEARS

ON   A   SITE   INDEX   OF 29 m

TABLE 1:   PROBABILITY DISTRIBUTION AT AGE 25 YEARS ON SITE
INDEX 29 m

Stocking (s.p.h.)	Probability of occurrence
215	0.003
225	0.153
235	0.309
245	0.319
255	0.197
265	0.019

Expected value	241.11
Variance	106.97
Coefficient of variation	4.3 %

APPENDIX E

CALCULATION OF PRUNING COSTS

The assumptions made in calculating pruning costs were :

1. Contract labour would be used.

2. The basic wage rate including institutional payments and equipment allowance would be $5540 per annum, equivalent to $23.08/day.

3. Equipment used would be:

    (i) low pruning - No. 2 Porter Pruner, with hand held jacksaw for branches larger than 5.0 cm in diameter,

    (ii) medium and high pruning - ladder and jacksaw.

4. Undergrowth conditions would be medium (see Table 1).

5. Ten per cent of trees at low pruning would have branches greater than 5.0 cm in diameter requiring the use of a jacksaw.

6. Where pruning and thinning occur together, pruning would be carried out first, as is normal practice.

7. Average slope would be 10 degrees.

8. Pruning treatments would be as prescribed in the text.

    The application of the Kaingaroa Forest Time Standards for low pruning using these assumptions is described below:

1. Basic Prune Time

    Basic prune time (BPT) is given by the equation:-

$$\text{BPT (min./tree)} = 0.804 + 0.03 \times \text{DBH}$$

2. Time for branches greater than 5.0 cm in diameter:

    Standard 0.06 min./tree per 10 % occurrence

3. Walk and select time:

   The standard time is based upon the walk and select time
   for 741 s.p.h. (300 s.p.a.). The walk and select times
   for undergrowth conditions ranging from 'clean' to
   'extreme' are given in Table 1.

4. Crop density and slope allowance:

   This is a percentage allowance applied to the walk and
   select time to compensate for varying slope conditions and
   numbers of stems pruned. The allowances are given in
   Table 1.

5. Contingency allowance:

   This is a percentage allowance to the Total Basic Time
   (see calculation below) which has been calculated to allow
   for rest and relaxation time, time to prepare equipment,
   access time etc. The standard is 19 % plus 10 % for
   heavy slash, heavy undergrowth and slopes over 20 degrees.
   Example:

   <u>Stand data</u>

Stems pruned	: 490 s.p.h.
Average DBH	: 9.0 cm
No. of trees with branches greater than 5 cm diameter	: 50 s.p.h.
Undergrowth	: medium
Slope	: 10 degrees

   (i) Basic Prune Time (BPT):

   $$BPT = 0.809 + 0.038 \times 9.0 \qquad = 1.146 \text{ mins./tree}$$

   (ii) Time for branches greater than 5 cm diameter (BT)

   $$BT = 10 \times 50/490 \times 0.06 \qquad = 0.06 \text{ mins./tree}$$

(iii)   Walk and select time ($W + S$):

   (a)   Basic W & S $= 0.29$ min./tree

   (b)   Crop density and slope allowance $= 0.07 + 1.09$

                                                      $= 1.16$

therefore W & S $= 0.29 \times 1.16$ $= 0.336$ mins./tree

(iv)   Total Basic Time (TBT):

     TBT $= BPT + BT + W \& S$

            $= 1.146 + 0.06 + 0.336$ $= 1.542$ mins./tree

(v)   Total Time (TT):

     TT $= TBT + \text{allowances} (29\%)$

            $= 1.542 \times 1.29$ $= 1.989$ mins./tree

therefore Target (Trees per day (T.P.D.))

$$= \frac{480 \text{ mins./day}}{1.989 \text{ mins./tree}}$$

$$= 241 \text{ T.P.D.}$$

therefore Price per tree $= \dfrac{\$23.08/\text{day}}{241 \text{ T.P.D.}}$

$$= \$0.0958/\text{tree}$$

TABLE 1 :   LOW PRUNING STANDARDS

A.   Walk and select time (mins./tree)

Clean conditions	0.16
Light undergrowth	0.23
Medium undergrowth	0.29
Heavy undergrowth	0.39
Extreme undergrowth	0.75

B. Crop density allowance

Stems per hectare	Allowance %
670 - 790	0
570 = 669	5
490 - 569	9
250 - 489	10

C. Slope allowance

Degrees	A llowance %
0	0
5	2
10	7
15	13
20	23
25	37
30	60

APPENDIX F

COST DATA

1. Silvicultural Costs

Operation	Year	(Cost/ha)[3]
Establishment [1]	1	160.62
Release (hand)	2	42.00
Aerial Spray [2]	3	11.12
Low prune	4	47.00
Thin to waste	4	24.14
Medium prune	6	35.50
High prune	7	27.60
Thin to waste	7	8.65

1 : includes sites preparation, roading, tree stocks and planting

2 : includes chemical and flying costs

3 : includes direct overheads

2. Sawing Costs

Log centre diameter (cm)	Cost ($/m^3$)
25.4	26.69
38.1	23.52
50.8	22.46
63.5	22.24

3. Felling and snigging

Log D.B.H. (cm)	Cost ($/m^3)
25.4	3.53
38.1	2.38
50.8	1.98
63.5	1.85
76.2	1.77

4. Annual maintenance   - $8.65/ha

5. Loading and transport (25 miles)   - $2.12/m^3

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