THE RELATIVE ECONOMIC IMPORTANCE OF STEM STRAIGHTNESS, BRANCH DIAMETER AND STEM DIAMETER IN *P.RADIATA* BREEDING

A thesis submitted by Richard Gregory Benyon for the degree of Doctor of Philosophy of The Australian National University, Canberra, April, 1989.

I, Richard Gregory Benyon, certify that this thesis, including the planning and organisation of the study, compilation, analysis and interpretation of the data and writing up of the results is entirely my own work. Assistance given in the collection of data, has been noted in the acknowledgements.

R G Benyon

R.G.Benyon, April 1989.

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without whom it would never have begun, let alone ended
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Abstract

In the 1950's it was recognised that *Pinus radiata* D.Don exhibited genetic variation in many traits. As a result several tree breeding programs were begun to provide genetically improved stock as a basis for future plantations. Worthwhile gains were made during the first breeding generation using such simple techniques as intensive selection in plantations and grafting of 'plus' trees for clonal seed orchards.

If worthwhile gains are to continue in advanced generations the efficiency of selection must be maximised. This will entail the use of selection indices incorporating information about the relative economic importance of traits and estimates of phenotypic and genetic variances and covariances.

This thesis describes the development of a method to calculate economic weights for three important traits (stem straightness, branch diameter and stem diameter) for use in selection indices. The suitability of subjective assessments of stem straightness and branch diameter in tree selection is also examined. Finally, an economic evaluation is made of a first generation *P.radiata* clonal seed orchard.

The thesis is based on an examination of the relationships between tree breeders' assessments of the three traits and stem economic value,using data collected from a saw mill study.

Sixty-five *P.radiata* stems from a 34 year old progeny test in the Australian Capital Territory were felled. Stem straightness had previously been assessed subjectively on these stems at ages 16, 25 and 34 (three times by two observers). Branch diameter had been measured at age 13 and assessed subjectively at ages 25 and 34. Stem diameter had been measured at ages 13, 25 and 34.

After the trees were felled, detailed measurements were made of sweep and the diameter of a sample of branches on logs cut from the stems. Data were also obtained from an additional 25 stems of an unimproved stock of the same age as the trees in the progeny test.

In the mill recovery study, 273 logs from the felled stems were sawn and the quantity and grade of timber recovered from each log determined. The relationships between value recovery from the logs and the accurate measurements of sweep and branch diameter were analysed. The results enabled the loss of value recovery from each log and stem, caused by sweep and large branch diameter, to be analysed. Economic weights for stem straightness were found by regression analyses of the relationships between the estimated loss of value recovery, caused by sweep in each stem, and the subjective assessments of stem straightness at ages 16, 25 and 34. In a similar manner, economic weights for branch diameter were calculated from regression analyses of the relationships between the loss of value recovery caused by branch diameter and assessments of this trait.

Economic weights for stem diameter at ages 13, 25 and 34 were calculated using regression relationships between value recovery from whole stems and stem diameter.

In the progeny test from which the sample logs were harvested, the economic weights showed stem diameter to be nearly 8 times more important, economically, than stem straightness and 5 or 6 times more important than branch diameter.

Smith-Hazel indices were calculated for tree selection in the progeny test, using phenotypic parameters calculated for all trees in the test at age 34, standard genetic parameters for *P.radiata* listed by Cotterill *et al* (1988) and the economic weights. The indices were also calculated using equal emphasis weights. The results of the analyses demonstrated that use of incorrect economic weights in index selection can result in serious reduction in economic gains. At all selection ages, the economic weighted index gave higher predicted economic gain than the equal emphasis weighted index. The difference was 82% at age 34, 63% at age 25 but only 2% at age 13. The importance of using accurate economic weights was dependent on the other parameters used in the selection index.

When stem straightness (judged subjectively by two observers on separate occasions) was given equal importance to other traits in the selection index, differences in the observers' scores caused large variation in predicted economic gains. At age 34, and placing equal emphasis on stem straightness, branch diameter and stem diameter, one observer's scores for stem straightness resulted in 20% more predicted economic gain than those of the second observer. The difference was less (8%) when the subjectively scored trait, stem straightness, was of low relative importance.

A separate study of stem straightness in *P.taeda* showed that while it is possible to calculate economic weights from subjective scores, a large amount of variation in stem economic value cannot be explained by variation in subjective scores. Stem straightness in 80 stems was scored using precise stem descriptions based on measurements of bends in felled stems. The precision of the relationship between loss of recovery caused by sweep and the subjective scores determined from these precise assessments was nearly double that of the relationship determined using a subjective assessment of stem straightness before the stems were felled.

In a separate *P.radiata* progeny test a comparison of stem diameter, stem straightness and branch diameter was made between seed orchard stock and an unimproved control. The differences were evaluated in economic terms using the economic weights determined in the first part of the study. It was predicted the seed orchard stock would be worth $9.70 per stem more at harvest age than the control, due to improved stem diameter and stem straightness. Allowing for losses of seed through lack of viability, culling of seedlings in the nursery and harvesting of trees before final clear felling, it was estimated the seed orchard seeds would return $0.97 per seed more than the control. Allowing for the costs of establishment, the seed orchard had positive net economic worth at a real discount rate of 8%.

If further studies were undertaken, involving a wider range of material than used in this study, more widely applicable economic weights for stem diameter, stem straightness and branch diameter in tree selection could be calculated. To do this, more accurate methods than presently used for assessing stem straightness and branch diameter on standing stems would be needed. However, given the practical constraints of time and resources available, it seems unlikely that such studies will be undertaken.

The results of the present study are probably broadly applicable to other *P.radiata* sites. The forest of which the study trees formed a part, appeared to be typical of the majority of *P.radiata* stands. Stem bends, although common, were mostly slight and there were few trees having excessively large diameter branches. It was estimated that in total, sweep had reduced the potential value of sawn recovery by only four per cent, *ie.* complete elimination from this site of all stems having sweep would result in a value recovery gain of four per cent. Similarly, it was estimated large diameter branches had caused a reduction in the potential value recovery of only two per cent.

Given the low observed economic importance of stem straightness and branch diameter in comparison to stem diameter, as demonstrated in this study, it is apparent that tree breeders should place less emphasis on the improvement of the former two traits in future breeding generations and greater emphasis on the improvement of growth rate. The relative economic importance of other traits, such as wood density and resistance to some diseases and pests that have recently threatened the health of some *P,radiata* plantations should also be determined.

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TABLE OF ABBREVIATIONS AND SYMBOLS

Notes: (1) For compactness and neatness in equations and tables, abbreviations have been written without periods (for example, sedub rather than s.e.d.u.b.). For consistency, the same practice has been followed in the text. (Both the period and no-period forms are to be found in the literature.)

(2) In a few cases where the absence of either periods or distinguishing type might cause confusion or irritation the term has either not been abbreviated or periods have been put in.

(3) Every attempt has been made to keep the notation consistent throughout the thesis but there may be some variations, whether by oversight or forced by the context.

(4) Well known scientific abbreviations like ANOVA have been omitted from the table.

(5) Symbols are listed alphabetically, with Greek letters at the end.

(6) The 'Reference' column shows where the symbol is defined or first used in a major way.

Symbol	Meaning	Units	Reference
bd_{av}	Index of average branch diameter of a log	mm	Chapter 10
bd_{max}	Index of maximum branch diameter of a log	mm	Chapter 10
C	Percentage Conversion, the percentage of log volume converted to sawn timber	%	Chapter 7
dbhob	Stem diameter over bark at height of breast (1.3m)	cm	Chapter 2
dum1...dum4	Dummy variables to represent different branch diameter classes in the regressions for volume of framing	–	Chapter 10
ew_{net}	Economic worth, net of all costs	$	Chapter 5
reject, F4,F5,F8,F11	Grades resulting from the stress grading of framing timber	–	Chapter 10
length	Length of a log	m	Chapter 6
lvr	Loss of value recovery of a log or stem	$	Chapter 5
lvr_{bd}	Loss of value recovery due to unfavourable branch diameter	$	Chapter 5
lvr_{sw}	Loss of value recovery due to unfavourable sweep	$	Chapter 5
P	Probability level in statistical tests of significance	fraction	Chapter 7
PT3	Progeny Test number 3 at Uriarra, A.C.T.	–	Chapter 6
R^2	Coefficient of determination in regression analysis	various	Chapter 7
sedub	Log small end diameter under bark	cm	Chapter 6
s.u.	Standard unit of quantity of sawn timber equal to that of a piece of 90mm x 35mm framing	–	Chapter 10
sweep	Stem or log sweep	cm	Chapter 4
sweep ratio	Ratio of sweep to diameter of log	fraction	Chapter 7
sw_1	Sweep in 1st plane (that in which sweep is worst)	cm	Chapter 7
sw_2	Sweep in 2nd plane perpendicular to 1st	cm	Chapter 7
t_1	difference in diameter between point of greatest sweep in 1st plane and small end of log	cm	Chapter 7
t_2	difference in diameter between point of greatest sweep in 2nd plane and small end of log	cm	Chapter 7

Symbol	Meaning	Units	Reference
V_s	Volume of sawn timber obtained from a log	m^3	Chapter 7
vub	Volume under bark of a log	m^3	Chapter 6
X	A generic independent variable	various	–
$X_{1i} \ldots X_{ki}$	Observed values of the k independent variables for the i^{th} individual	various	Chapter 7
Y	A generic dependent variable	various	–
Y_i	Observed value of the dependent variable for the i^{th} individual	various	Chapter 7
$B_0 \ldots B_k$	Coefficients of the general linear regression model	Y units /X unit	Chapter 7
b_{1bd}	Slope coefficient in regression relating loss of value recovery to branch diameter score	$/point scored	Chapter 5
b_{1ss}	Slope coefficient in regression relating loss of value recovery to stem straightness score	$/point scored	Chapter 5
e_i	Random error term in the general linear model	Y units	Chapter 7

Chapter One

TREE SELECTION AND GAIN EVALUATION TECHNIQUES USED FOR TREE BREEDING

Foresters and forest scientists have sought to improve the economic productivity of forest plantations since the planting of trees for wood production first began as a commercial undertaking. One method, the selection of specific individuals with outstanding characteristics to provide genetically improved offspring as a basis for future plantations (tree breeding), became recognised throughout the world in the 1950's as a potential tool for the improvement of forest productivity (Zobel and Talbert 1984).

1.1 *Pinus radiata* breeding programs in Australia

In Australia, major plantation species, such as *Pinus radiata* D.Don (radiata pine), exhibited genetic variation in many traits (McWilliam and Florence 1955, Fielding 1957). This is important because such inherent variation in an outcrossing wild species can be used to improve the value of plantations even if the heritability of the traits is only low to moderate. Several state and national forestry organisations commenced tree breeding programs in the 1950's, based on this variation.

By the end of the 1950's, breeding programs of *P.radiata* were under way in Australia and New Zealand (Fielding 1957, Thulin 1957, Simpfendorfer 1960). First generation seed orchards began providing seed for large scale plantings in the late 1960's and by the early 1980's genetically improved stock comprised about one sixth of all *P.radiata* plantations in Australia (Pederick and Eldridge 1983).

Initially, tree breeding efforts were devoted to solving technical problems, such as vegetative propagation and controlled crossing techniques, and to establishing progeny trials (Larsen 1956). *Pinus radiata* breeding started simply, inexpensively and in much ignorance. It involved simple, intensive selection of plus trees, propagation of these by grafting and establishment of seed orchards, isolated from plantations, from which improved seed was collected. Despite their simplicity, such techniques probably resulted in worthwhile genetic gains because *P.radiata* is a variable, outcrossing, wild species. Such genetic gains have been confirmed by: (1) estimates of expected gain based on low to moderate heritability, high selection intensity and large, phenotypic variation and (2) realised gains observed in yield trials (Pederick and Eldridge, 1983).

Now that early technical problems have mostly been solved and estimates of genetic parameters are available, breeding is more complex, with many alternative plans to choose from. As a result, tree breeding can be much more costly. Therefore, if breeding programs are to be cost effective, there must be rapid turnover of generations, efficient selection and precise knowledge of which traits to emphasise.

1.2 Additional data required to make *P.radiata* breeding cost effective

1.2.1 The need for information about the relative economic importance of traits

Pinus radiata exhibits genetic variation in many economically important traits (Fielding 1953). Efficient tree selection and proper planning requires information concerning the relative economic importance and heritability of traits and of any genetic correlation between traits. Economic gain is maximised if such information is combined in a single selection index (Matheson and Brown 1983, Cotterill and Jackson 1985, Cotterill *et al* 1988).

When *P. radiata* breeding commenced none of these data was available, however, the last two decades have seen estimates of genetic parameters obtained from numerous progeny tests (Shelbourne 1969, Bannister 1980, Cotterill and Zed 1980, Nicholls *et al* 1980, Dean *et al* 1983, Shelbourne and Low 1980). There are still comparatively little data concerning the relative economic importance of traits, despite a number of authors stressing its necessity (Australian Forestry Council 1974, Eldridge 1977, Cotterill and Jackson 1985, Barnes and Gibson 1986, Cotterill *et al* 1988). Consequently, tree breeders do not have all the information needed to make best use of efficient index selection, to measure the economic value of genetic gains already made or to accurately predict the economic value of future gains.

1.2.2 The suitability of subjective scoring systems for tree selection

Two important traits which can be improved by breeding are stem straightness and branch diameter. These are usually assessed or measured using simple subjective systems, however, there are obvious difficulties in relating such systems to variation in stem worth. Indeed this has only been attempted in one study for *P. radiata* in Australia (Brown and Miller 1975, Miller 1975). Furthermore, it has been demonstrated that subjective methods may be unreliable for variance estimation, raising doubts about the usefulness of such methods for planning breeding programs (Bannister 1979). Sensible design of breeding programs requires that improvements in these traits be economically quantifiable.

1.3 Thesis aims and outline

This thesis addresses questions about the relative economic importance of traits and the suitability of subjective assessments for tree selection in *P.radiata* breeding programs.

Specifically, the thesis:

1. Describes a method for quantifying relationships between net stem economic worth and stem straightness and branch diameter measurements or scores;
2. estimates the relative economic importance of these traits and stem size;
3. examines the reliability of subjective methods used to assess stem straightness and branch diameter; and
4. estimates the gain in plantation worth resulting from improvement in stem straightness, branch diameter and stem size made after one generation of breeding *P. radiata* .

The thesis is presented in three parts. Part One reviews the literature covering basic tree breeding methodology and the use of economic data in tree breeding programs (Chapter Two), methods used to assess stem straightness and branch diameter in breeding programs (Chapter Three) and the effects of stem straightness and branch diameter on costs and returns from plantations grown for wood production (Chapter Four).

Part Two describes the development and application of a method for determining the relative economic importance of stem straightness, branch diameter and growth rate. In applying the method the reliability of subjective scoring methods is assessed. The basic method is explained (Chapter Five) and collection of data used to apply it detailed (Chapter Six). Subsequently, the method is used to determine the relative economic importance of stem straightness, stem size (Chapters 7,8 and 9) and branch diameter (Chapters 10 and 11).

Part Three illustrates the use of economic weights in calculations of selection indices and shows how the weights were also used to evaluate the economic worth of a *P.radiata* seed orchard. Smith-Hazel selection indices are calculated using economic and 'equal emphasis' weights and the indices applied to one *P.radiata* progeny test. The effect of the different weighting methods on predicted genetic and economic gains is examined (Chapter 12). A comparison of stem straightness, branch diameter and stem diameter is made between trees of Tallaganda Seed Orchard stock and an unimproved control and the differences evaluated in economic terms using the economic weights from Part Two. The results are used to evaluate the economic benefits of the seed orchard (Chapter 13). The effects of observer differences and age of assessment on: (1) phenotypic parameters; (2) expected economic gains and (3) tree selection, are investigated (Chapter 14). Finally, the results are summarised and recommendations for further study made (Chapter 15).

Chapter Two

THE NEED FOR ECONOMIC DATA IN *P. RADIATA* BREEDING PROGRAMS

2.1 Introduction

This chapter examines the basic steps involved in present day *P. radiata* breeding programs and focuses on those parts of a program in which knowledge of the relative economic importance of traits aids in determining breeding strategies. Particular attention is given to tree selection, for it is in this step that economic data can be employed most effectively to maximise potential economic gains. The role of economic weights in the theoretically most efficient selection method, index selection, is explained and the current practices used for economic weight determination in the absence of detailed economic data discussed. Finally, studies that have attempted to evaluate the worth of existing tree breeding programs are briefly reviewed.

2.2 The basic steps in a *P. radiata* breeding program

Present day *P. radiata* breeding programs can be considered as a series of separate, but interrelated steps, which are repeated in a cyclic process. A single cycle is generally referred to as a breeding generation. Typically, one generation in *P. radiata* may take between 15 and 35 years to complete, depending on the complexity and size of the program and the efficiency of planning. Whatever the precise make up of a *P. radiata* breeding program, it always involves selection, gene multiplication and mating (Cotterill 1986).

2.2.1 Selection

In the first step of a generation, a few tens or hundreds of individuals are selected from the existing wild and domesticated populations of the species. The aim of selection is to find those trees whose offspring are most likely to have desirable genes. These selections are made simply on the basis of outward appearance (phenotypes).

2.2.2 Gene multiplication

In the second step the genes of the selected individuals are reproduced in quantity for distribution into new plantations. If any of the phenotypic variation apparent in the original population was caused by genetic variation, the new plantations will have a higher frequency of desirable genes than the original population from which selections were made and will, therefore, show improvement over the original population.

2.2.3 Mating

In the third step of a breeding generation, controlled mating between the selected trees is used to create new combinations of genes and expand the breeding population to allow for selection in the next breeding generation. A generation is complete when the new breeding population reaches an age at which selection for the next generation can commence.

2.2.4 Choosing a breeding strategy

Each step has several alternative procedures. The combination of procedures adopted in these three steps is commonly referred to as the breeding strategy.

The complexity of breeding strategies varies considerably, particularly in steps 1 and 3. The most complicated strategies usually realize the greatest genetic gains per breeding generation but also require the greatest amount of resources, information and planning. A breeding strategy should be chosen which best achieves the tree breeder's goals, yet satisfies any necessary constraints.

2.3 The need to define goals and evaluate strategies in economic terms

The broad goal in the breeding of any species grown commercially for wood production is to obtain maximum net economic benefit. Therefore the goal ought to be defined in terms of such standard economic criteria as maximum internal rate of return or maximum net present worth (Mishan 1971). In selecting a breeding strategy, tree breeders should evaluate the alternatives in terms of these criteria. In some species a single trait may be of overriding economic importance, for example, resistance to a particular disease (Sparrow 1979). In such cases the goal can be simply defined as maximum improvement in that trait. However, with most tree species, including *P. radiata,* the goal of greater economic worth is usually considered to be best achieved by modifying a multitude of traits, which may be interrelated and under varying degrees of genetic control. Accurate definition of goals and precise delineation of strategies demands information about :

(1) the relative economic importance of traits,

(2) genetic gain in important traits expected under each strategy, and

(3) the costs of particular strategies.

When tree breeding programs first began, tree breeders had none of the information needed to formulate goals in precise economic terms, nor to predict the outcomes of breeding strategies. Early tree breeding research was concerned with the practical aspects of breeding such as breeding systems and techniques of vegetative propagation, so choice of breeding strategy was limited to strategies requiring minimal information (Larsen 1956). More complex strategies could not be considered until the initial breeding generation was completed .

When *P. radiata* breeding programs in Australia and New Zealand began in the 1950's, tree breeders had very little information concerning the degree of inheritance of the observed variation within the species. Nor did they have precise knowledge of the relative economic importance of particular traits. It was believed the best approach would be genetic improvement in a number of traits considered intuitively as economically important (multitrait selection). Trees for breeding were selected by intensive visual searching in thousands of hectares of plantation. Even though this is the least efficient selection method (Cotterill *et al* 1988) worthwhile gains were made, as several studies have demonstrated, because the species exhibited a high degree of natural variation and the traits on which selections were based are slightly to moderately heritable (Wright and Eldridge 1983).

The first breeding generation of *P. radiata* has provided the information needed to evaluate the outcomes of alternative breeding strategies in future generations. Most of these data are related to genetic parameters and will enable prediction of genetic gains from alternative breeding strategies.

Tree breeders still cannot, however, translate predicted genetic gains under alternative breeding strategies into economic terms and, therefore, they are unable to base their choice of breeding strategy on economic criteria. This requires knowledge of the relative economic importance of the traits improved by breeding.

2.4 The importance of economic information in tree selection

Economic gains from breeding are maximised if there is direct input of economic information during tree selection. If tree breeders have reliable data concerning economic importance and genotypic and phenotypic parameters, they can combine this information to maximise the efficiency and effectiveness of tree selection. Conversely, without reliable data, the theoretically most efficient selection method may, in fact, be no better than more simple techniques. Efficient selection methods were developed by quantitative geneticists more than 40 years ago (Hazel and Lush 1942). Tree breeders still do not have all the necessary data to use them most effectively.

2.4.1 The most efficient selection method

Theoretical studies indicate that maximum economic gain is achieved if each tree considered as a candidate for selection is awarded a single value according to its perceived breeding value and trees with the highest value selected. This method is known as index selection. The most efficient selection index is one which combines information about the relative economic importance of traits with phenotypic and genetic information in a single index; the individuals with the highest index value are selected. An index of this form was developed by Smith (1936) for plant breeding and Hazel (1943) for animal breeding. Now commonly referred to as the Smith-Hazel index (Lin 1978), it is equally applicable to tree breeding (Cotterill et al 1988):

$$I = b_1X_1 + b_2X_2 + \ldots + b_nX_n \qquad [2.1]$$

where: I is the index value,

$X_1 \ldots X_n$ are the phenotypic values of traits 1 to n, and

$b_1 \ldots b_n$ are weighting coefficients applied to the n traits.

The vector of b's is calculated as:

$$[b] = [P]^{-1}[A][w] \qquad [2.2]$$

where: [P] is an n x n matrix containing the observed phenotypic variances of individual traits along the diagonal and phenotypic covariances between pairs of traits elsewhere,

[A] is an n x n matrix containing genetic variances of individual traits along the diagonal and genetic covariances between traits elsewhere, and

[w] is a column vector of relative economic weights (Cotterill *et al* 1988).

In the special case of genetic covariances being equal to zero, the index simplifies to the primary index:

$$I = w_1h_1^2X_1 + w_2h_2^2X_2 + ... + w_nh_n^2X_n \qquad [2.3]$$

where: I is the index value,

$X_1 \dots X_n$ are as above,

$h_1^2 \dots h_n^2$ are the estimated heritabilities of traits 1 to n, and

$w_1 \dots w_n$ are the relative economic weights for traits 1 to n.

If the heritabilities of all traits are the same the index simplifies further to the base index (Williams 1962):

$$I = w_1X_1 + w_2X_2 + ... + w_nX_n \qquad [2.4]$$

(N.B. In this case, unless all heritabilities are equal to 1, Equations 2.3 and 2.4 will give different values for I, however the relative weighting given to each trait will be the same.)

2.4.2 Selection in the absence of adequate information

Generally, *P. radiata* breeders have not had enough information to apply the Smith-Hazel index effectively. When breeding began in the 1950's, information about heritability and genetic correlations was unavailable; decisions about which traits were economically important and their relative importance were largely intuitive (Eldridge 1977). In Australia and New Zealand, *P. radiata* plantations were initially searched visually to reject or 'cull' trees obviously poor in at least one trait (a form of independent culling as mentioned in Section 2.4.4, p.16). In this way a few candidates with potential to be 'plus' trees were identified. An index employing economic weights determined largely by intuition and assuming equal heritability of traits and zero genetic correlation between them was then used to select a few dozen 'plus' trees from the remaining candidates. A typical example is the index used by the then Forests Commission of Victoria (Simpfendorfer 1960, Pederick 1967), a version of which is reproduced in Appendix 1. Other organisations recognised that the intuitive economic weights used may have been misleading and instead selected on an unweighted index for the trait perceived as most important, usually growth rate, with independent culling for other traits. An example is the method used by the CSIRO's Gippsland Research Station, where *P. radiata* plus trees were selected in the 1960's on an index for growth rate, with intuitively chosen independent culling levels on stem straightness, branch characters and stem cones (Eldridge 1977).

Progeny tests of first generation selected trees have enabled genetic and phenotypic variances and covariances to be estimated for many species. Genetic parameters for a number of *P. radiata* traits have been estimated by Bannister (1969, 1979, 1980), Nicholls and Brown (1974), Nicholls *et al* (1980), Cotterill and Zed (1980), Shelbourne and Low (1980), Bannister and Vine (1981) and Dean *et al* (1983). Cotterill *et al* (1988) present a table of standard genetic parameters for *P. radiata* based on averages from studies reported in the literature (Appendix 3, Section 3.3).

The relative economic importance of traits is still determined largely by intuition. Brown and Miller (1975) measured the relationship between sweep in *P. radiata* logs and the recovery of sawn timber, where sweep was defined as the degree of deviation of a log from straight. Miller (1975) showed trees classed by visual assessment as crooked tended to produce logs with the greatest degree of sweep, but did not attempt to develop relative economic weights for stem straightness and stem size. The Brown and Miller study appears to be the only one reported in the literature for *P. radiata* which attempts to relate assessments of a non-growth related trait to the volume of products obtained.

Spencer (1987) compared the quantity and grade of sawn timber and veneer recovered from *P.radiata* cuttings and seedlings. The results clearly demonstrated that monetary recovery was better from the cuttings. This was attributed to better stem form and branch quality. No attempt was made however, to relate the net economic worth of individual stems to assessments of specific traits and the economic importance of individual traits was not determined.

2.4.3 Methods used to estimate economic weights for selection indices

Cotterill and Jackson (1985) described three methods for estimating economic weights in selection indices. The first, 'partial regression', produces estimates of the true economic importance of traits, while the second and third, 'equal emphasis' and 'desired gain', are used when information about true economic weights is imprecise or unavailable and gives artificial economic weights that do not necessarily reflect the true economic importance of traits.

2.4.3.a Partial regression

Using the partial regression method, economic weights are estimated by relating net stem worth at harvest to the traits used for tree selection. Because selection usually takes place at a young age the regression incorporates relationships between juvenile and mature traits. The slope of the regression line relating net stem worth to the phenotypic value for each trait measures the trait's economic weight. That is, the economic weight is equal to the average change in net stem worth at harvest age accompanying a one unit change in the trait.

Cotterill and Jackson (1985) used data from 308 *P. radiata* stems to demonstrate the application of the technique. At four and a half years of age, stem height and diameter at breast height[1] over bark (dbhob) were measured and stem straightness and branch diameter scored out of 5. The trees were felled at age 11 and logs cut from each stem were classed by small end diameter and straightness either as one of five case log categories or as pulp. Net stem economic worth was calculated by subtracting harvesting costs from the price paid for the logs at road side. Due to the small size of the stems and the varying price paid for logs of different diameter, net stem economic worth was found to be determined largely by growth traits, especially tree height. Cotterill and Jackson stressed that the results applied only to the particular circumstances of the experiment and served mainly to demonstrate the method.

2.4.3.b Equal emphasis

When the real economic importance of traits is unknown, it is common practice to place equal emphasis on all traits (Cotterill *et al* 1988), in which case the weight for a particular trait is simply the reciprocal of the trait's phenotypic standard deviation:

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[1] Breast height is 1.3m above ground level

$$\text{i.e.} \quad W_1 = 1/S_1$$

$$W_2 = 1/S_2$$

$$\cdots\cdots$$

$$W_n = 1/S_n$$

where: W_1 to W_n are the economic weights, and

S_1 to S_n are the phenotypic standard deviations for traits 1 to n.

Emphasis can be changed by raising or decreasing the numerator. For example, if it were desired to give the first trait double the emphasis of the others the weights would become:

$$W_1 = 2/S_1$$

$$W_2 = 1/S_2$$

$$\cdots\cdots$$

$$W_n = 1/S_n$$

2.4.3.c Desired gain

Instead of expressing goals in economic terms, a tree breeder may wish to specify the characteristics of an ideal tree. For each trait the difference between the ideal and the current population mean is the desired gain. Actually, adverse genetic correlations may make it impossible to achieve the desired gains. Instead, a vector of weights can be calculated that will result in gains that are proportional to, but smaller than, the desired gains. These are called 'desired gain' economic weights. In each generation the gain desired for each trait would change as the theoretical ideal was approached. Therefore, desired gain economic weights need to be recalculated each generation (Cotterill and Jackson 1985).

When traits are adversely correlated, the weights that produce gains in the desired proportion may lead to small absolute gains. This could be the case if the ideal tree is a biological impossibility (Cotterill *et al* 1988). A Monte Carlo approach[1] has been used by some authors to investigate the influence of

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1 The weights of each trait are randomly set at different levels and the effect of varying the weight of each trait in turn while holding the others constant examined.

varying economic weights above and below the calculated economic weights for desired gain. Dean *et al* (1983) used this method to show that it is unlikely growth rate and the density of *P. radiata* juvenile wood can be improved simultaneously by current breeding methods.

Cotterill and Jackson's (1985) study compared Smith-Hazel indices calculated with economic weights determined by the three methods. The 'equal emphasis' and 'desired gain' weighting procedures gave similar results, i.e. both methods produced similar index coefficients, predicted genetic gains and selection of trees. Partial regression gave quite different results due, in part at least, to the strong emphasis placed on tree height.

2.4.4 Consequences of error in economic weights and genetic parameters

The Smith-Hazel selection index may only be the most efficient selection method when it is based on accurate estimation of parameters. There are two common error sources that may reduce the efficiency and effectiveness of the Smith-Hazel index. These are, error in the estimate of economic weights and error in the genetic parameters (heritability and genetic correlations).

Some authors have investigated the consequences of using incorrect genetic parameters or economic weights in selection indices. Others have conducted practical studies of the change in predicted gains for different methods of determining economic weights for selection indices. Others again have compared actual gains using several different selection methods: tandem selection (selection for one trait only each generation); independent culling (the rejection of trees falling below a set minimum standard in each of several traits); and index selection. Most studies relate to animal or plant breeding, where determinations of economic weights may be simpler than estimating genetic parameters.

Young and Weiler (1960), Williams (1962), and Harris (1964) present theoretical calculations which show the Smith-Hazel index may be less precise than the base index when economic weights are correct but genetic parameters imprecise because they are estimated from small samples. (Harris gives a rough minimum of 1000 individuals for reliable estimates of genetic parameters in animal breeding). Elgin *et al* (1970) measured real gains from five generations of alfalfa (lucerne) breeding. Imprecise estimates of genetic parameters resulted in slightly more gain with a base index than with a Smith-Hazel index. Cotterill (1985) compared expected genetic gains when a Smith-Hazel index and a base index were used to select *P. radiata.* Equal emphasis economic weights were used in both indices. He found that when adverse genetic correlations existed, the base index produced lower gains. When correlations were favourable there was little difference between the two.

All the aforementioned studies examine the consequences of using less efficient indices than the Smith-Hazel index in circumstances where estimates of genetic parameters are unavailable or imprecise. Far less attention is given in the literature to the consequences of using incorrect economic weights in a Smith-Hazel index when estimates of genetic parameters are reasonably accurate.

Studies by Dean *et al* (1983) and Cotterill and Jackson (1985) do provide some information concerning the effect of varying the economic weights used in selection indices. However, the need exists for more practical studies using reliable economic data. Such studies could demonstrate that one of two conditions holds:

(1) equal emphasis or desired gain weights are similar to actual economic weights and therefore use of either of the former produces estimates of gains close to optimum;

(2) equal emphasis or desired gain weights place too much emphasis on some traits and not enough on others, in which case their use may lead to lower estimates of economic gains than could be achieved if the correct economic weights were used.

Much of this thesis is devoted to determining which of these conditions holds. Obviously it is unlikely that equal emphasis or desired gain weights are ever exactly the same as the correct economic weights. Use of either of the former will almost always result in lesser estimates of maximum potential economic gain. One of the important results of this thesis is a demonstration of the reduction in potential economic gains that results from use of incorrect economic weights.

2.5 Use of economic data to evaluate gains already achieved by tree breeding

Many tree breeding programs have reached or are reaching the end of the first generation. Breeders need to determine if the money invested has been recovered and, thus, if breeding should continue into a second generation.

Many authors have attempted to demonstrate the benefits of particular breeding programs. Some have made direct comparisons between first generation improved stock and unimproved stock planted together in randomised experiments to demonstrate that genetic gains in the traits selected have indeed been realized. Others have attempted to place economic worth on these gains by equating the estimated discounted costs of tree breeding against the estimated discounted worth of the measured gains. Most of the latter studies have only evaluated the benefits of improved wood volume production, not of improved stem straightness, branch quality or wood quality.

Some authors have quoted gains in terms of the increased number of 'acceptable' stems per hectare (McWilliam and Florence 1955, James 1979, Pederick and Eldridge 1983). However, using such data to estimate the economic benefits of breeding is difficult.

More precise economic evaluations have been made by Perry and Wang (1958), Porterfield *et al* (1975), Reilly and Nikles (1977) and Wright and Eldridge (1985), all of whom estimate the net discounted economic worth or internal rate of return of breeding programs based on increased wood production from seed orchard stock. However, with the exception of Reilly and Nikles, none of these studies estimates the economic worth of improvements in other traits, including stem straightness and branch diameter. For an accurate evaluation of the economic worth of tree breeding, tree breeders need to take into account the effects of changes in all economically important traits.

2.6 Conclusions

While precise estimates of genetic parameters and predictions of genetic gain under different breeding strategies can now be made for *P.radiata* , there is still a need for information about the relative economic importance of different traits. Without both genetic and economic information, uncertainty remains concerning choice of breeding strategies for advanced generation breeding. From the first generation of improved stock a large amount of data concerning heritability of traits and genetic correlations between them has been accumulated. Techniques for predicting and maximising genetic gain are now well advanced. However, understanding of the relative economic importance of traits has hardly changed since tree breeding began on a large scale in the 1950's. To improve the efficiency and effectiveness of Smith-Hazel index selection, the quality of the estimates of economic weights must be comparable to the quality of the estimates of genetic parameters. The economic data needed for this will also be useful for demonstrating the economic worth of the genetic gains already achieved.

Chapter Three

METHODS OF ASSESSING STEM STRAIGHTNESS AND BRANCH DIAMETER IN TREE BREEDING

3.1 Introduction

Important in a consideration of the relative economic significance of traits are the techniques used to assess them. The more precisely a particular trait can be quantified the easier it is to appraise its economic importance. Measurements of traits must be accurate, reliable and repeatable to ensure that tree breeders can make precise predictions about responses to selection and subsequently the best choice of breeding strategy. Some traits, such as stem diameter and height, are measured using simple, repeatable, quantitative techniques. Methods and potential sources of error and bias associated with these are well known and documented (Carron 1968). With many other traits, including stem straightness and branch diameter, tree breeders have been forced to adopt simple, subjective methods because more precise, quantitative measures are excessively time consuming. Consequently various tree breeding organisations have used their own assessment procedures for these traits, resulting in a multiplicity of techniques for which accuracy and precision are largely untested. Some use quantitative instruments of varying complexity but more frequently simple subjective scales of judgement are employed based on brief observation of stems by one or more observers.

In adopting simple, subjective techniques tree breeders have devoted some time to considering the specific features of the rating scales used, such as the number of points on the scale and the method of 'anchoring'. They have paid less attention to the relationship between subjective scores and the economic worth of stems: something that needs to be done if economic weights are to be determined. This chapter reviews the commonly used assessment techniques for stem straightness and branch diameter, and describes potential error sources and discusses the consequences of these. Some of the methods described here are used later in the thesis in an evaluation of the economic importance of stem straightness and branch diameter.

3.2 Subjective methods

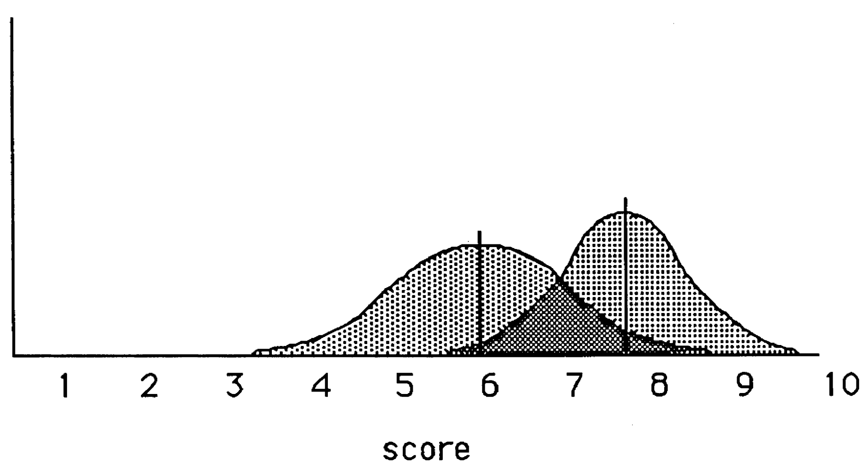
All subjective assessments of stem straightness and branch diameter use a rating scale. Stems are awarded points for each trait based on visual assessment. The method of 'anchoring' the scale, the number of points on the scale, and its suitability for making comparisons between experiments, may all vary.

3.2.1 Anchoring a subjective scale

The concept of 'anchors' is important in the use of subjective scales. A scale based solely on human judgement must be anchored to a common reference point so that the meanings of particular judgements are fixed (Guilford 1954). The more precisely the anchors can be defined the more likely it is that scores are consistent both between observers and by the same observer on different occasions.

Many commonly used subjective scales of stem straightness and branch diameter are anchored at their extreme limits. For example, a 10 point scale of stem straightness could be anchored with the description: 'a perfectly straight stem scores 10 and an extremely crooked stem scores 1'. Anchors of this kind are imprecise, making it difficult for observers to match trees consistently against them. An observer could experience difficulty identifying 'a perfectly straight stem'. Moreover, interpretation of 'an extremely crooked stem' and the subsequent rating of trees relative to this may well vary considerably between observers and also for the same observer over time. Trees which have stem straightness and branch diameter matching these extremes may rarely occur. Without anchors for direct comparison, observers cannot consistently locate individuals on the scale (Guilford 1954). Two independent observers could conceivably produce distributions of scores like those shown in Figure 3.1 for a single progeny test, especially if neither were able to classify any stem in the experiment as 'perfectly straight' or 'extremely crooked' for comparison.

Figure 3.1 Two possible distributions of scores on a 10 point absolute scale



Clearly the means and variances of the distributions differ. If different observers rated different parts of a progeny test, variation due to differences in their personal perception of individual stems could not be separated from environmental and genetic sources of variation.

3.2.2 Potential sources of error and bias

Lack of repeatability of subjective scales is not confined to tree breeding. Whenever assessment is based on simple observation and personal opinion, error and bias can occur. Subjective scales are frequently used in the human sciences and these disciplines have comprehensive and well documented studies on common error sources and methods for minimising their effects. Studies of rating scales used in psychology have found raters tend to be biased by prior beliefs, overall impressions and even the design of the recording sheet (Guilford 1954).

Guilford reviews common error types associated with rating scales. Five that might occur in subjective tree assessments are:

(a) the error of central tendency;

(b) the error of leniency;

(c) the halo effect;

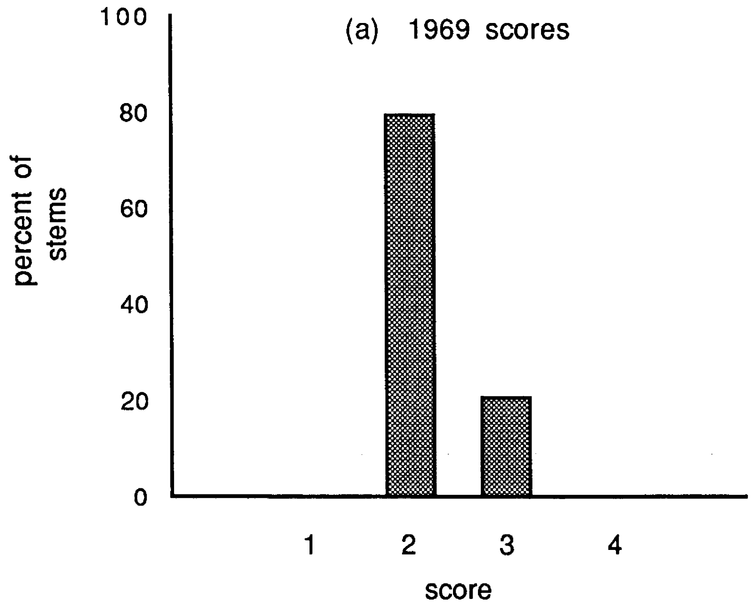
(d) logical error; and

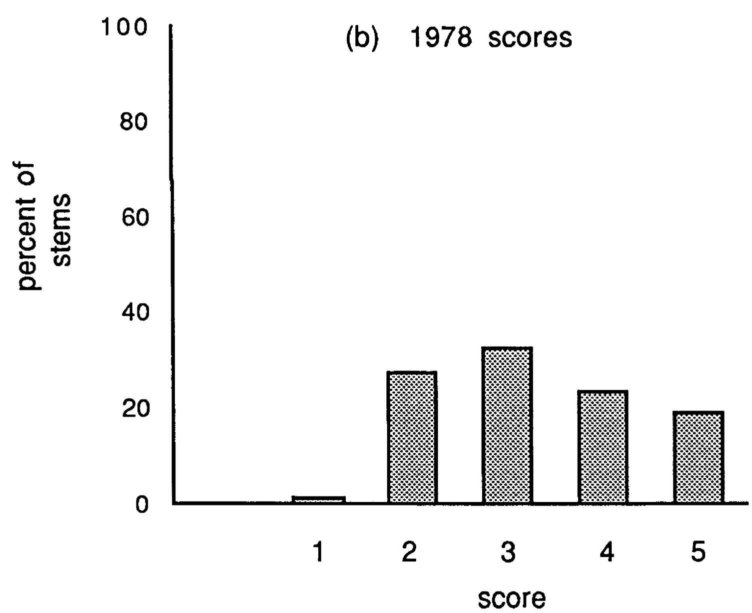
(e) error of proximity.

3.2.2.a The error of central tendency

This term describes the reluctance of an observer to use the extreme limits of a scale. As a result scores tend to cluster towards the mean or centre and variance is underestimated. If, for example, there were only four points on a scale of stem straightness, most stems would score '2' or '3' and the distribution would be binomial. In 1969 such a scale was used to score stem straightness in a test known as *P.radiata* Progeny Test No. 3 (PT3), established by the Commonwealth Forestry and Timber Bureau in 1952. The same test was scored again in 1978 on a five point scale. The distributions of scores from the two assessments are shown in Figure 3.2.

Figure 3.2 Distributions of the stem straightness scores in the 1969 and 1978 assessments of Progeny Test No. 3 (CSIRO unpublished data)





The 1969 assessment appears to exhibit evidence of the error of central tendency. In the 1978 assessment a deliberate attempt was made to spread the scores along the entire scale (CSIRO unpublished). Clearly the distributions of the scores are quite different. It is most unlikely the trees changed to such an extent in the nine years between assessments.

To avoid this kind of error, Guilford recommended an increase in the number of points on the scale, thus providing a wider range of choices and encouraging observers to spread their scores along the scale.

3.2.2.b The error of leniency

This refers to a tendency for observers to be biased by prior knowledge of the individuals being rated. If, for example, an observer was able to recognise families in a progeny test and knew how these had performed in other tests, the error of leniency would result in bias in favour of some families and against others, consequently heritability would be overestimated. In a study by Bannister (1979) five observers independently scored stem straightness in a *P.radiata* progeny test and the heritability of this trait was calculated using each observer's scores. Four of the observers had no prior knowledge of the families involved, however the fifth did have such knowledge. His estimate of heritability was 0.62, compared with 0.35, 0.42, 0.19 and 0.40 for the other four. The fifth observer's knowledge produced error of leniency.

Presumably this kind of error could be avoided by ensuring observers could not identify particular families in the field. However, this may be difficult if the manager or supervisor of the breeding program carries out the assessment, as is often the case, or if the trees and their progenies can be recognised. It is probably less likely where single tree or very small plots are used.

3.2.2.c The halo effect

This term describes a tendency for raters to be biased by an overall impression of each individual being rated. For example, in tree assessment, raters might give large, healthy looking trees good ratings for other traits as well. This kind of error leads to overestimation of positive correlation between traits.

Raters might also be influenced by the overall appearance of entire plots and tend to shift ratings for individual trees in the direction of the plot mean, resulting in underestimation of within-plot variance and consequently overestimation of heritability in experiments where families are grouped in large plots. This kind of error could also be avoided by the use of single tree plots.

3.2.2.d Logical error

Logical error occurs when, in the minds of the raters, traits seem logically related. For example it might seem logical for branch diameter to be positively correlated with stem diameter. In this case the correlation between rate of stem diameter increment and branch diameter would be overestimated. Logical error in tree assessment is difficult to avoid because observers, even if only scoring one trait at a time, cannot help noticing the appearance of other traits.

3.2.2.e Proximity error

A tendency to give similar ratings to traits that are in proximity to each other on the scoring sheet, or which are rated at the same time, is called proximity error. If, for example, branch diameter and stem straightness are judged at the same time, proximity error leads to spurious correlation between them. Proximity error in tree assessment might be avoided if each trait is assessed by a different observer, or if one observer assesses entire experiments or replicates several times, each time assessing a different trait.

3.2.3 Number of points on the scale

Guilford (1954) reviews studies of the optimum number of points on the scale and concludes there is no firm rule. Various studies in the human sciences have recommended scales comprising between 7 and 25 points, depending on the nature of the trait rated and the experience and interest of the raters.

The relationship between the number of points on the scale and the error of central tendency has been noted above. Cotterill *et al* (1988) have also suggested using an even number of points to reduce the error of central tendency, and recommend a 6 point scale. Raymond and Cotterill (1989) tried assessing branch characteristics on subjective scales of 3, 6 and 9 points. The 6 point scale was easiest to use and gave the highest heritability estimates.

3.2.4 Studies of errors in rating scales used by tree breeders

Bannister (1979) and Cooper and Ferguson (1981) attempted to measure observer error in visual scores of stem straightness. In Bannister's study, four inexperienced observers were given precise instructions as to how to score 'stem crookedness' on a ten point subjective scale. Together with their instructor they then scored and discussed a group of stems in an effort to standardise scores. Even so, after all five had independently assessed a *P.radiata* progeny test, the mean, variability and shape of distribution of the scores differed significantly within and between observers. For progeny test evaluation, Bannister recommended each tree be assessed independently by more than one observer.

In Cooper and Ferguson's study two observers with three and eight years experience, each scored 385 trees from four different control points (west, east, north and south) using a 9 point scale. The mean and variability of the distribution of scores differed between observers and scoring directions. Variation in straightness attributable to differences between clones increased from 37 per cent when one observer scored from one direction to 63 per cent when all scores (2 observers x 4 directions) were used.

Such inconsistencies make it difficult to interpret statistics involving variance estimates and to determine economic weights. Nonetheless in practice, many tree breeding programs rely on information collected by subjective assessment.

3.2.5 The use of subjective scores to assess stem straightness and branch diameter

Tree breeders have used a variety of subjective scales for assessing stem straightness and branch diameter in selection and progeny tests. These can be divided into two broad types: those which anchor the scale to absolute values, facilitating comparison between experiments, and those which anchor the scale relative to local extremes within the experiment. For the latter, variance is not comparable between experiments.

3.2.5.a Absolute scales

On an absolute scale, stems are rated against the extreme absolute limits of the character. The scale is fixed for all forest stands and therefore variance can be compared between stands provided the scale is applied consistently to all stands. An example of the method in its simplest form is the four point scale of stem straightness used to produce the first frequency distribution in Figure 3.2, for which the scores awarded were: 1 - excellent, 2 - good, 3 - poor, 4 - very poor (CSIRO unpublished data). The meanings given to points on the scale are rather vague; it is quite likely such a scale leads to the error of central tendency as Figure 3.2 indicates.

However, scales of this type usually comprise 5 to 10 points. Examples of the routine use of stem straightness or branch diameter scales of 5, 9 or 10 points, anchored at both ends to absolute extremes, include Burdon (1971 and 1975), Bannister (1980), Shelbourne and Low (1980), Cotterill and Zed (1980) and Dean *et al* (1983). Only Bannister notes the number of independent observations per stem (5) and the number of observers taking part.

Slee (1968) anchored a 10 point scale using fairly precise descriptions of points in the range 5 to 10 on the scale, based on the severity and number of bends observed in the stem (Table 6.1, p.63, lists the precise descriptions). The scale was effectively a six point scale, as the bottom 4 points were seldom used, with the advantage that very poor individuals could score lower than the usual minimum. The anchors were sufficiently precise to enable scoring to half points but this was not usually practised in routine applications. When the trees in experiments at different localities are of similar size this method probably enables valid comparison of variance between locations, especially if all scoring is conducted by the same observers.

3.2.5.b Relative scales

The stem straightness and branch diameter of some species, including *P.radiata* , tend to change markedly with environment. On any one site, the range of variation in these characters may be small relative to overall, absolute variation, say 2 points on a 5 point absolute scale. Therefore, the error of central tendency will probably occur.

For analysis of variance it is advantageous if scores have a normal distribution rather than being clustered in a narrow range (Dean *et al* 1986). One solution might be to use an absolute scale with many points, forcing observers to discriminate more finely. However, as an alternative, some tree breeding organisations use relative scales to assess stem straightness and branch diameter. To use such scales in a particular experiment all trees are quickly examined and the worst and best stems located. These serve as anchors for the lower and upper limits of the scale. On a 5 point scale, trees that are similar to the average of the experiment score 3, and those that are below average and above average score 2 and 4 respectively. Trees approaching the worst and best in the experiment score 1 and 5 respectively.

The purpose of using this kind of anchoring is to ensure the overall distribution of scores in any one experiment is approximately normal in shape. In Australia, the genetics research working group (Research Working Group No.1) of the Australian Forestry Council (1974) recommended the use of 5-point relative scales. Cotterill *et al* (1988) and Raymond and Cotterill (1989) recommend a similar system, but include a 6th point on the scale to avoid the error of central tendency. Trees near average are classed as either slightly below average (3) or slightly above average (4).

3.2.5.c Absolute versus relative scales

Relative scales are considered better than absolute scales for the purpose of heritability estimation (Dean *et al* 1986). However, relative scales are less suitable than absolute scales for the calculation of economic weights. Absolute variation in traits probably differs from forest site to forest site and breeding generation to breeding generation. Therefore partial regression economic weights determined for a particular trait on a relative scale will also differ between sites and breeding generations. Thus, if correct economic weights are to be used in Smith-Hazel index selection, these have to be recalculated for each site and each breeding generation when traits are assessed subjectively on relative scales.

By comparison, where a repeatable absolute scale is used, the relationship between subjective scores at a given age and stem economic worth at harvest can be estimated and partial regression economic weights determined. The economic weights are applicable at all sites in the forest in all breeding generations. If it is desired to use a relative scale of assessment and partial regression economic weights it may be possible to calibrate the relative scale with an absolute scale or measure at each site and in each breeding generation.

It is likely problems will always be encountered when any type of subjective assessment method is used. Those organisations that use subjective scales have been concerned mainly with the method of anchoring scales and the number of points on the scale. A few authors have investigated the repeatability of subjective scores within and between observers and all recommend that more than one independent observation be made per trait on each tree assessed (Shelbourne and Stonecypher 1971, Bannister 1979, Cooper and Ferguson 1981). There have been no studies of the precise relationship between stem economic worth and subjective ratings of stem straightness and branch diameter. Such a study will enable both the reliability of subjective scales to be determined and the relative economic importance of traits to be judged.

3.3 Objective methods of measuring stem straightness

To avoid errors associated with subjective methods some organisations have experimented with the use of simple objective methods for assessing stem straightness. These vary in the complexity of measurements gathered, equipment needed and time required. A common feature is that bends are counted or measured against a straight standard such as a stick or rod. No studies using objective methods have taken the additional step of relating the straightness measurements obtained to economic value.

One of the first to use an objective measure of stem straightness was Perry (1960) who assessed a 2-year-old control pollinated progeny test of *P. taeda*. Bends were identified by holding a straight stick next to each stem. Three independent observers counted the number of bends in the entire length of stem. A 'crook index' was calculated as a function of the number of bends and the displacement caused by the worst bend near breast height. Later, Goddard and Strickland (1964) used a similar method to measure stem straightness on the same trees at age 7. On this occasion only those bends in the lower 5.4 metres of stem were counted. The correlation coefficient ($r = 0.83$) showed the age 2 index to be a good indicator of the age 7 index.

Others to employ a straight stick to identify and measure the severity of bends in the lower part of the stem have been Hans (1972), who developed an instrument to measure the severity of bends and stem lean accurately in the lower 3.7 metres of a stem, and Shelbourne (1963), who measured bends in the lower 4.7 metres of *P.kesiya* stems.

Barnes and Gibson (1986) also used a straight stick to identify bends in the lower part of a stem. However, instead of measuring the severity of individual bends, the straight stick was used to identify the number of straight 1 metre sections in the first 6 metres of stem. Crooked sections received a weight of 1, while straight sections received higher weights according to the total number of consecutive straight sections. Each 1 metre section was further weighted according to its position in the stem and then a total score derived for each stem by summing the combined straightness and nominal economic weights of each section.

A problem with the Barnes and Gibson method lies in the definition of 'straight ' and 'crooked'. They suggested calling a section crooked if deflection of the stem from the straight stick exceeded a predetermined amount. A deflection that marginally exceeded this amount had the same effect on a stem's score as a severe deflection. Further, no account was taken of stem diameter. In a narrow stem a deflection of a particular magnitude has a greater effect on stem value than the same deflection in a thicker stem. The method clearly needs some refinement if the scores obtained are truly to reflect variation in stem value; more realistic economic weights could be derived from a mill recovery study, for example. Further, the method is only suitable for rating the lower part of the stem. Sections above 6 metres must be rated subjectively.

A 'sinuosity index' similar to the crook index of Goddard and Strickland (1964) was developed by Adams and Howe (unpublished) for assessing stem 'sinuosity' in 13 year old Douglas Fir. Bends in the upper 3 interwhorl segments of stems were measured with a straight stick. For each interwhorl an index was calculated by multiplying the number of bends by the displacement of the worst bend. Heritabilities of the index from the upper or second interwhorls were only slightly less than the heritability of the mean index of all three interwhorls. A 4 point subjective assessment of sinuosity in the upper three interwhorls was also tried in their study. The estimated heritability of stem sinuosity was higher when calculated using the objective index. Adams and Howe concluded that their objective method is time efficient for the assessment of Douglas Fir progeny tests.

Generally, only the lower part of a stem can be measured with a straight stick. It has been suggested that early in a tree's life bend formation in this part of a stem is strongly influenced by non-genetic factors such as the quality of planting and exposure to wind. As a tree ages, however, the formation of bends higher in its stem is controlled less by environmental factors and more by genetics. For example, the heritability of stem straightness in *P.taeda* has been shown to be less when calculated using an assessment of the lower few metres of stem in young trees than when assessment is based on a greater length of stem in older trees (Shelbourne and Stonecypher 1971). Thus, for estimating genetic parameters it may be desirable to judge stem straightness in a greater length of each stem than just the lower few metres, necessitating the partial use of a subjective method. In Hans' study (1972) the straightness of that portion of each stem higher than 3.7 m was assessed subjectively. While observer differences using his stick were not significant, there were significant observer differences in the subjective counts of bends above 3.7 m.

Shelbourne and Stonecypher (1971) used a plexiglass viewer to measure stem straightness in young *P.taeda* and compared the results with subjective scores for crook, sweep and combined crook and sweep where a crook was defined as a sharp bend and sweep as a gentle curve in the stem. The viewer was held at a fixed distance from the observer's eye and the edge of the stem lined up against a series of vertical lines on the viewer. As the distance from the observer to the tree was known, the lines measured the amount of displacement caused by stem bends. This method proved satisfactory except in young trees, where branches obscured the boles. Shelbourne and Stonecypher suggested it might be useful for the assessment of stem straightness in the lower part (below crown level) of older stems.

In an earlier study Shelbourne experimented with the use of photographs to measure stem straightness accurately. Trees to be assessed were photographed from two directions at right angles to one another. The horizontal displacement of each stem in three dimensional space was plotted from the two photographs and variables such as the sum of displacements per unit length of stem calculated. The method was found to be precise but too time consuming to be of practical use in progeny testing (Shelbourne 1966, Shelbourne and Stonecypher 1971). A similar method was used to study the inheritance of bole straightness in *Dalbergia sissoo* Roxb. (Vidakovic and Ahsan 1970) with apparently satisfactory results. In addition to being time consuming, photographic methods are costly in materials and may be physically difficult to use in forests grown at close spacings or which have persistent live branches on the bole.

Although some organisations have tried objective stem straightness assessment methods none have attempted to relate them to the economic worth of stems. Therefore, it is not yet possible to prove that any are superior to subjective methods in terms of the value of extra precision gained. Like subjective measures, an objective measure of straightness without an economic weight attached is useful for ranking families only on the basis of straightness, not in a Smith-Hazel selection index using several characters. Without an economic weight, it is not possible to demonstrate the economic importance of stem straightness and so the real benefits of different breeding strategies cannot be evaluated. Certainly, objective measures enable more precise and repeatable measures of stem straightness to be obtained, but the question remains as to whether the extra precision gained is worth the increased cost of measurement. Unless it can be shown that the economic benefits derived from the use of particular objective methods outweigh the increased cost of using them, such methods should not gain wide acceptance. Bannister (1979) has already shown that subjective methods are adequate for ranking families. The only benefit of using an objective measure of straightness is a likely increase in the precision of heritability estimates. However, until true economic weights are determined, heritability may not be a particularly useful parameter beyond demonstrating that a character is genetically controlled.

Chapter Four

A REVIEW OF PREVIOUS STUDIES CONCERNED WITH OR RELATED TO THE EFFECTS OF STEM STRAIGHTNESS AND BRANCH DIAMETER ON THE ECONOMIC WORTH OF STEMS

4.1 Introduction

Although no studies reported in the literature have actually attempted to relate tree breeders' assessments of stem straightness and branch diameter to stem economic worth, many are concerned with the influences these traits have on specific aspects of the production process, such as product quantity or quality. This chapter reviews these studies, some of which provided a useful background in the planning of the present study and interpretation of the results.

4.2 The influence of stem straightness on stem value

4.2.1 Harvesting, handling and transport costs

Surprisingly there do not appear to be any published studies that directly relate stem straightness to costs of harvesting individual stems, but it is a reasonable assumption that severe bends, or crooks, raise such costs. The worst bends may be so severe as to render portions of a stem unmerchantable, thus reducing the total quantity of products obtained. Furthermore, the presence of severe bends may necessitate use of manual harvesting procedures rather than a completely mechanised and cost efficient system. In high labour cost economies particularly this could increase unit logging costs.

When less severe bends occur, it may be necessary to cut logs to shorter lengths to minimise losses during processing, thereby increasing the amount of cross-cutting time required per stem. Some handling costs, particularly those associated with the picking up and moving of logs from one place to another, are determined by the number of logs handled rather than their length. Therefore, shorter logs will also cost more to handle per cubic metre or tonne.

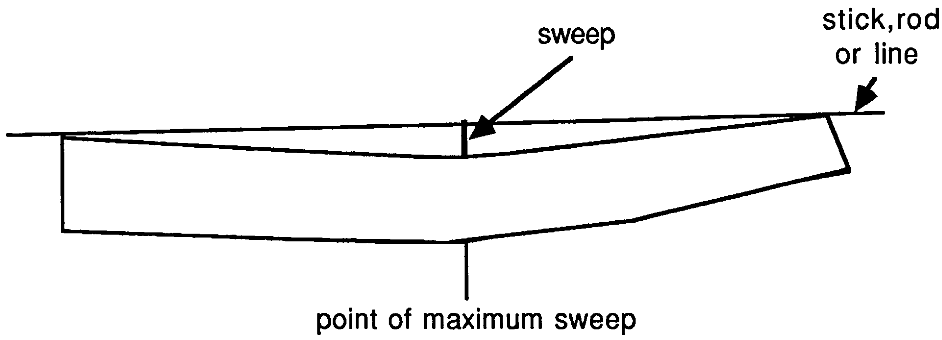
Finally, because crooked logs cannot be packed into as small a space as straight ones, fewer can be carried per truck and forwarder load, further adding to harvesting and transport costs. (Monks, Australian Newsprint Mills, Tasmania, pers comm.)

4.2.2 Quantity and quality of products obtained

4.2.2.a Sawn timber

Logs cut from non-straight stems contain sweep. In this study sweep is expressed as the deviation of a log from straight, caused by a bend. It was measured at the point of the maximum distance between the log surface and a straight stick, rod or line held against the log, as illustrated in Figure 4.1. Brown and Miller (1975) used the same method to measure sweep in logs that were later sawn in a mill study and concluded that, for the purpose of studying the effect of sweep on volume recovery, sweep was best expressed as a ratio of log diameter. In some studies sweep has been expressed in relation to log length (Whiteside 1982). However, Brown and Miller concluded that sweep expressed in this way was not the best indicator of potential sawn recovery from logs.

Figure 4.1 Side view of a log, showing sweep

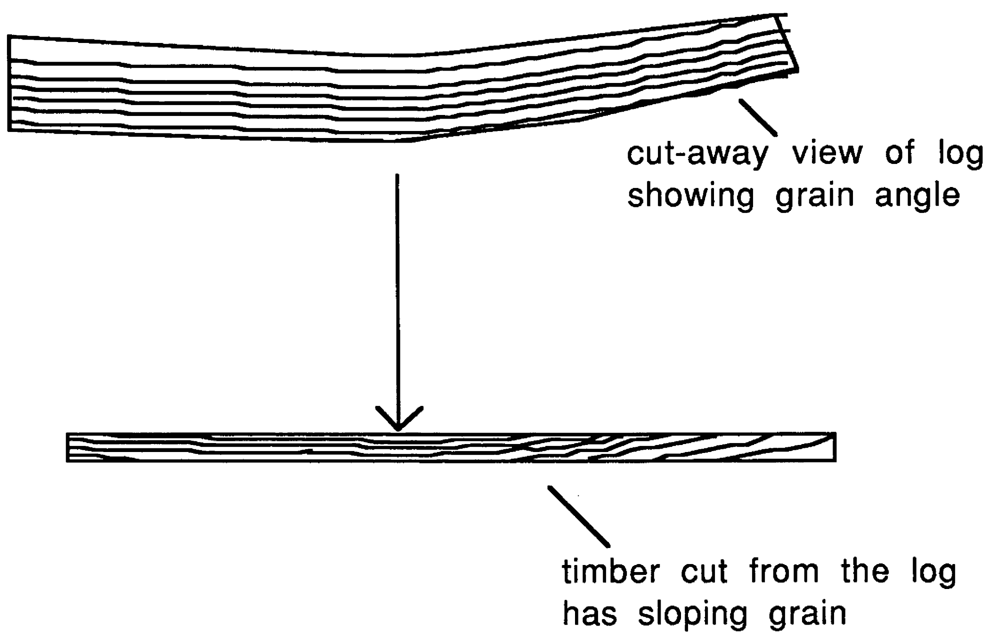


Sweep reduces the total quantity of timber sawn from a log. In Brown and Miller's milling study of 400 *P.radiata* logs, sweep had a significant and adverse effect on the quantity of timber obtained per log. Whiteside (1982) used computer simulations to predict the effect of sweep on the quantity of timber obtained from individual *P.radiata* logs, sawn in several different mills using various sawing patterns. Predicted sawn recovery was shown to be strongly correlated with measured sawn recovery after the logs were sawn in a separate mill study.

Regression equations developed from studies such as these can predict accurately the loss in value caused by stem bends and could be used to predict the increase in stem worth from improving stem straightness.

Sweep also influences slope of grain in sawn timber, as illustrated in Figure 4.2. Wood is an anisotropic material, that is, its properties vary according to the direction in which they are considered. For example, when in tension, *P.radiata* wood is more than 40 times stronger along the grain than across it, and in compression is 7 times stronger (Bamber and Burley 1983). Sloping grain is a defect in structural timbers and so the Standards Association of Australia specifies maximum allowable slope of grain in structural grades of *P.radiata* timber (Standards Association of Australia 1986).

Figure 4.2 An illustration of the effect of sweep on sloping grain in timber

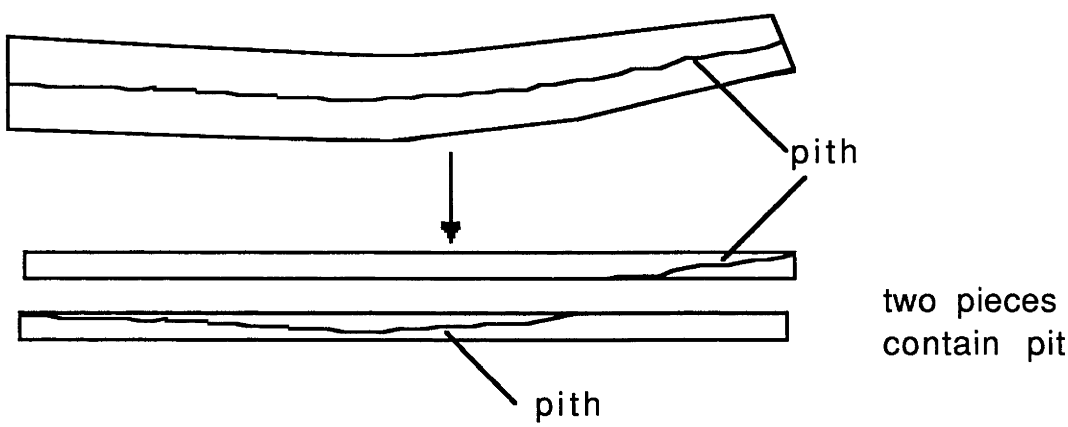


Another property of wood related to grain direction is the amount of shrinkage accompanying a decrease in moisture content. In *P.radiata* , wood shrinkage is about 20 times as much across the grain as it is along it (Bamber and Burley 1983). Timber cut from 'swept' logs will contain sloping grain. Such timber when dried will develop twist, spring, cup or bow (Balodis 1972), for which there are also maximum allowable values specified in the Standards Association of Australia's timber grading rules (Standards Association of Australia, 1986).

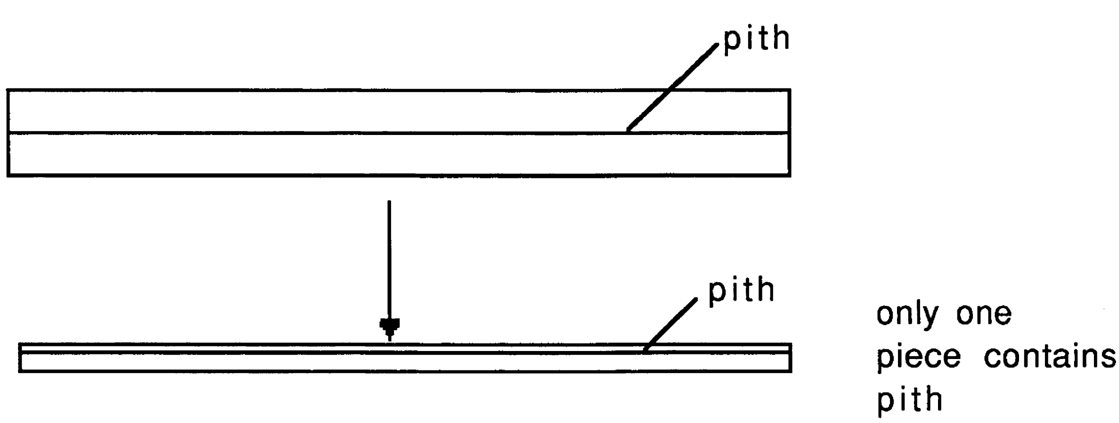
Softwood stems like *P.radiata* have a core of low density, juvenile wood surrounding the pith (Cown 1974). Pith and low density wood reduce timber strength (Grant and Anton 1984, Bier 1986a) and therefore reduce timber grade (Standards Association of Australia 1986). If a log is straight, and has straight pith as in Figure 4.3b, correct positioning of sawcuts can confine the pith to a single piece of timber. Since timber is graded on the worst defect (Standards Association of Australia 1986), even a small amount of pith necessitates downgrading. If the pith is not straight as is shown for the bent log in Figure 4.3a, more than one piece of timber will contain it.

Figure 4.3 An illustration of the effect of sweep on the number of pieces of timber containing pith

(a) Bent log



(b) straight log



The form of reaction wood that occurs in softwoods as compression wood causes a reduction in timber quality (Bamber and Burley 1983). Compression wood is highly lignified, with short tracheids that are round in cross-section with well developed intercellular spaces. It is dense and hard, but brittle. Severe compression wood makes timber difficult to saw, nail and finish, has low strength and causes excessive shrinkage which may result in twist, bow, cup and spring (Westing 1965, Nicholls 1982, Harris 1977). In softwoods, compression wood forms on the underside of stems and at the base of branches as a response to displacement from vertical or to the mass of the branch. Stem bends form as the stem rights itself by producing compression wood (Westing 1965). Therefore crooked stems would be expected to contain more compression wood than straight ones. This has been confirmed, although to a lesser degree than expected, by Shelbourne (1966), and Burdon (1975).

There are no reports in the literature of attempts to measure the influence of log sweep on timber quality. Because quality may be influenced by a multitude of factors (Standards Association of Australia, 1986) such studies would be far more difficult than the regression studies Miller and Brown (1975) and Whiteside (1982) used to show the influence of sweep on volume recovery.

4.2.2.b Veneer

Sweep also reduces the quantity of veneer obtained from logs. As with sawn timber, actual or simulated veneering studies can be used to quantify this relationship accurately. Zobel and Kellison (1978) demonstrated that an improvement in stem straightness improved recovery of veneer from individual stems. Although they presented no data, they claimed the average monetary worth per tree of veneer recovered from a sample of straight stems was approximately 13 per cent better than from a sample of stems of average straightness, providing indirect evidence that sweep reduces recovery from veneer logs. They did note, however, that the straight stems were slightly larger than the average stems, which may have resulted in a greater quantity of veneer being obtained from these and consequently greater monetary yield.

Compression wood is also associated with stems having non-circular cross sections and adversely influences peeling, drying, dimensional stability and glueing ability of veneer (Westing 1965, Nicholls 1982, Echols 1973). The quantity of veneer obtained from such logs is less than from logs of circular section of the same size (Ronan 1974).

4.2.2.c Posts and poles

Manufacturers of preservative treated posts and poles require straight logs. Any containing slight bends are rejected. Post sized logs are usually too small to be sawn; those that fail to meet the grade must be pulped, giving reduced value. In areas which do not support industries based on wood pulp, such as the A.C.T., small crooked logs are not used and, therefore, are valueless.

4.2.2.d Pulp and paper

As noted above, crooked stems tend to produce more compression wood than straight ones. Because compression wood has a low cellulose but high lignin content, total yield of paper from it is less than from normal wood and the consumption of pulping chemicals higher when using chemical or semi-chemical processes. Lignin may also reduce mechanical pulp strength by interfering with fibre bonding (Watson and Dadswell 1957, Corson and Lloyd 1982) and may increase power requirements for defiberisation. Blair *et al* (1974) compared the strength properties and yield of paper made from the wood of eight *P.taeda* families classed as straight and eight classed as crooked. Paper tear strength and yield were significantly higher in the straight stemmed families.

4.3 Influence of branches on stem worth

4.3.1 Impact on pruning and harvesting costs

The time taken to remove branches from stems during pruning or harvesting operations is related to branch thickness, angle to the stem and number of branches. Removal of branches during the stump operations phase of harvesting (trimming) in pine plantations is also very time consuming when using a chainsaw and more costly than felling or cross-cutting.

Branch thickness and angle are strongly correlated in *P. radiata, i.e.*, thicker branches are more steeply angled (Cotterill *et al* 1988). Therefore breeding for thin branches results in flatter branches and vice versa. Branch thickness and angle are, however, negatively correlated with the number of branches on the stem, so that an improvement in one results in a deterioration in the other (Fielding 1967). Breeders of *P.radiata* have been forced to choose between breeding for many, small, flat angled branches or fewer, thicker, steeply angled branches. It is generally accepted that the former is preferable to the latter (Bannister 1965).

4.3.2 Influence of branches on product value

4.3.2.a Sawn timber

Branches leave knots in the timber which are a source of weakness. Where longitudinal tensile strength of timber is important, loose or bark encased knots effectively act as holes and even fully intergrown knots reduce timber strength. Sloping grain around knots is the major cause of this loss of strength (Bamber and Burley 1983). Consequently, when *P.radiata* timber is visually graded, the ratio of the area of a knot in the plane of the cross section to the total area of the cross section often controls the grade (Standards Association of Australia 1986).

The same effect is apparent when material is machine stress graded. Grant (1980), Whiteside (1982) and Bier (1986a) observed the relationship between the machine stress grades of sawn timber and branch diameter measurements on logs. Grades were correlated both with the average diameter of all branches and the average diameter of the few largest branches on each log.

Knots exposed at the timber surface are prone to checking, which can cause paint failure (Bamber and Burley 1983). Exposed knots also influence the appearance of the timber, which may dictate its value for uses in which appearance is important (Stern and Hattemer 1964). For some decorative purposes such as wall panelling, exposed knots do not necessarily decrease the value of the timber.

4.3.2.b Veneer

As with sawn timber, knots reduce the strength of veneer. An important feature in grading *P.radiata* structural plywood is the total width of knots in a 30cm length of face veneer (Standards Association of Australia, 1979). Bier (1986b) found veneer strength to be related to a branch diameter index. Zobel and Kellison (1978) report average veneer grade to be higher from trees with small diameter branches than from trees with average diameter branches.

4.3.2.c Paper

Branch wood contains higher proportions of extractives and compression wood than stem wood (Bamber and Burley 1983). As noted in Section 4.2.2.d (p.43), compression wood and extractives reduce pulp yield and strength. Blair et al (1974) observed that pulp yield and tear strength were significantly higher from eight *P.taeda* families classed as having thin branches than from eight families having thick branches. However, Corson and Lloyd (1982) found very little difference in paper yield and strength between groups of *P.radiata* trees having thick and thin branches.

4.4 The use of log yield models to determine the relative economic importance of traits

In recent years the Forest Research Institute (FRI) in New Zealand has researched and developed a set of computer based silvicultural stand models to aid in short and long term planning for *P.radiata* plantation management. One of the main aims of the research has been to investigate the effect of various silvicultural treatments on the net economic worth of plantations (Whyte 1988).

The original model (SILMOD) was developed in the late 1970s and early 1980s using knowledge and information collected over many years. This model takes basic information about site location, site quality, initial stocking, the silvicultural regime applied and the costs associated with these, in combination with market prices for various end products and produces estimates of product out turns and forest net present worth. The economic outcomes of varying the input parameters can be investigated (Whiteside and Sutton, 1983). In recent years the submodels and linkages between them have been improved and some erroneous assumptions eliminated (Whyte, 1988).

Based on the initial inputs and proposed timings of thinnings and prunings, the various submodels contained within SILMOD simulate stand growth, including the development of characteristics such as branching habit, defective core diameter, wood density, resin pockets, stem sweep and log diameter distribution. Other submodels predict the costs associated with stand establishment, pruning, thinning, harvesting and log transport. For any silvicultural regime the final yield of logs by size and quality is obtained. This information, along with the cost estimates form inputs for the "PREVAL" submodel (Whyte 1988).

PREVAL predicts the volume and grade of timber, veneer and pulpwood products obtained for specified mill types, sawing standards and market prices. With appropriate discounting applied to take account of the different times at which the various costs are incurred and revenues gained, the net present value of the forest under each set of site and silvicultural inputs is calculated (Whyte 1988).

The relationships between log parameters and product outputs were developed from milling studies and computer simulations of a range of mill types, in which the effects of each log parameter on the quantity and quality of products obtained were estimated by regression analysis (Whiteside 1982). If tree breeders' assessments of individual traits could be linked to the log parameters used in the PREVAL submodel, this program could be used to investigate the effect of varying processing and market conditions on the relative economic importance of traits, as well as enabling the effects on stem value of improving particular traits to be simulated.

4.5 Conclusions

Numerous published papers provide general indications of the influence of bends and branches on the quantity and quality of products obtained from trees and the costs of recovering them. Some effects have not been measured directly but can be inferred from known relationships between bends or branches and other features known to affect quality.

No published studies attempt to quantify accurately the relationship between stem straightness and branch diameter, as assessed by tree breeders, and the economic worth of stems. These relationships will be influenced by numerous factors outside tree breeders' control, including harvesting and processing techniques and market forces. Predictive models, like those developed by the FRI, in which tree breeders' assessments of traits can be linked to predicted stem worth could aid in the study of the relative economic importance of traits under a range of likely conditions.

Chapter Five

CONSIDERATION OF THE RELATIONSHIPS BETWEEN THE NET ECONOMIC WORTH OF A STEM AND CHANGES IN STEM DIAMETER, STEM STRAIGHTNESS AND BRANCH DIAMETER

5.1 Introduction

A major aim of this thesis is to evaluate the relationships between the economic worth (ew_{net}) of a stem and tree breeders' assessments of stem straightness and branch diameter. Evaluation of these relationships is essential to the determination of economic weights for use in indices.

The main problem in quantifying the relationships for economically important traits is the difficulty of determination of the ew_{net} of individual stems. Estimates are needed of the total market value of products obtained (value recovery) and the total cost incurred in growing, harvesting and processing each stem (costs).

A logical point at which to evaluate ew_{net} is at the exit of the processing mill. At this point all processing is complete, value recovery can be determined, and the costs likely to be influenced by heritable traits have been incurred.

At a sawmill, value recovery per stem can be measured if the log and the tree from which each piece of timber originated can be identified. If logs are colour coded on their ends before entry to the mill, the colours on individual pieces of timber can be recorded on completion of processing, and the quantity and grade of all products recovered per log calculated. Detailed tracking of timber through the mill is not necessary. By-products such as sawdust and off-cuts can be assumed to have negligible market value and ignored or, alternatively, their volume could be estimated simply by calculating the difference between log volume and the volume of marketable products obtained.

Costs per stem are more difficult to measure. Costs are incurred from the time young trees are raised in a nursery through to harvesting and final conversion to saleable products. Some costs are constant from tree to tree irrespective of final tree size, or other traits. In intensively managed plantations and forests of fixed land area, these include the capital cost of land or land rent and interest on loans, the costs of raising seedlings in a nursery, forest road construction, tree planting, fertiliser, weed control, protection and administration.

Other costs per stem vary according to stem size and straightness, and branch diameter. These variables include pruning, felling, de-limbing and cross-cutting during harvesting, transport to the processing mill, de-barking, milling, stacking, drying and finishing. To determine such costs accurately for individual stems would require continuous tracking of individual logs and pieces of timber through all stages of processing from harvest to the mill exit. Clearly this is a far more difficult task than the measurement of value recovery and will vary markedly on different sites and with different silvicultural management.

Although it is difficult to evaluate the precise relationship between value recovery, tree size and the trait score for stem straightness and branch diameter, the recovery per stem will be shown later in this thesis (Chapter 8) to bear a very close relationship to stem size. Derivation of a model to evaluate the relationship requires an initial consideration of the effect of stem size. The effects of changes in other traits can then be considered as modifications.

5.2 A method for estimating an economic weight for stem size (dbhob)

For growth traits such as dbhob the relationship with ew_{net} might be depicted graphically as in Figure 5.1. The dots would represent sample stems whose ew_{net} has been plotted against stem dbhob. The ew_{net} is the total market value of products obtained from a stem less the sum of all costs of growing, harvesting and processing it.

Figure 5.1 Possible form of the relationship between ew_{net} and dbhob

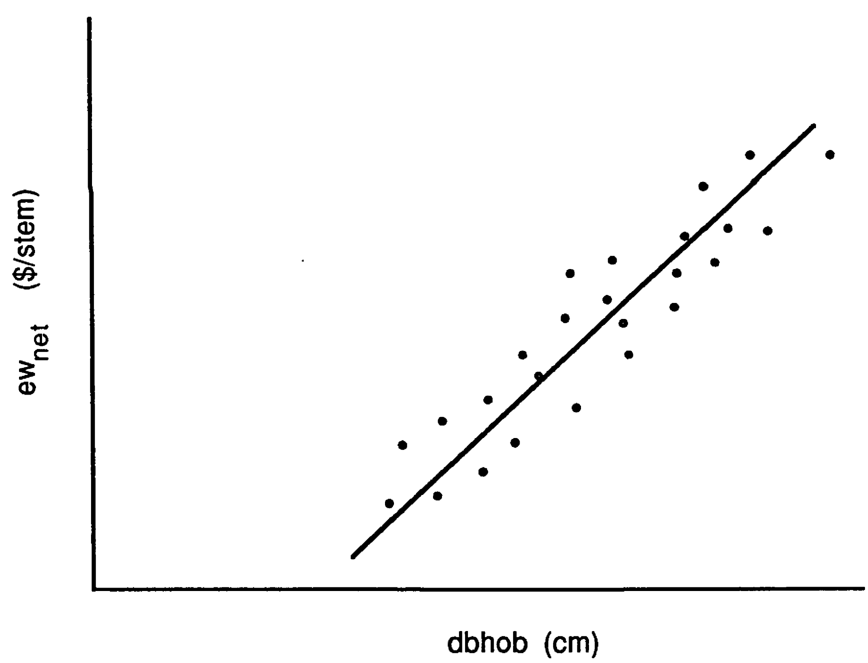


Figure 5.1 was not compiled from real data. In reality the relationship might be curvilinear. However, results from the saw-milling study on which much of this thesis is based indicated that in the range of dbhob from 25 cm to 45 cm the relationship between dbhob and the gross market value per stem was approximately linear (details are given in Chapter 8). If the relationship

between dbhob and growing, harvesting and processing costs is also linear over a similar range of dbhob then the assumption of linearity in the relationship between dbhob and ew_{net} will be valid as illustrated later in Figure 5.2.

The line in Figure 5.1 represents a least squares regression equation of the form:

$$ew_{net} = \alpha + \beta \times \text{dbhob}. \qquad [5.1]$$

The coefficient β in this equation measures the average change in ew_{net} in dollars, corresponding to a 1 cm change in dbhob. Thus, β is the economic weight for dbhob (a definition of partial regression economic weights was given in Section 2.4.3.a, p.14). The ew_{net} of any improvement in average dbhob resulting from tree breeding is equal to the genetic gain multiplied by β. For example, a genetic gain in average dbhob of 3 cm equates with a gain in ew_{net} per tree of $\beta \times 3$.

The way value recovery and costs are likely to vary with dbhob is shown in Figure 5.2.

In Chapter 8 it is shown that the relationship between value recovery and dbhob is approximately linear. Assuming the relationship between costs and dbhob is also linear, the best fitting linear regression equations are:

$$\text{value recovery} = \alpha_1 + \beta_1 \times \text{dbhob} \qquad [5.2]$$

and

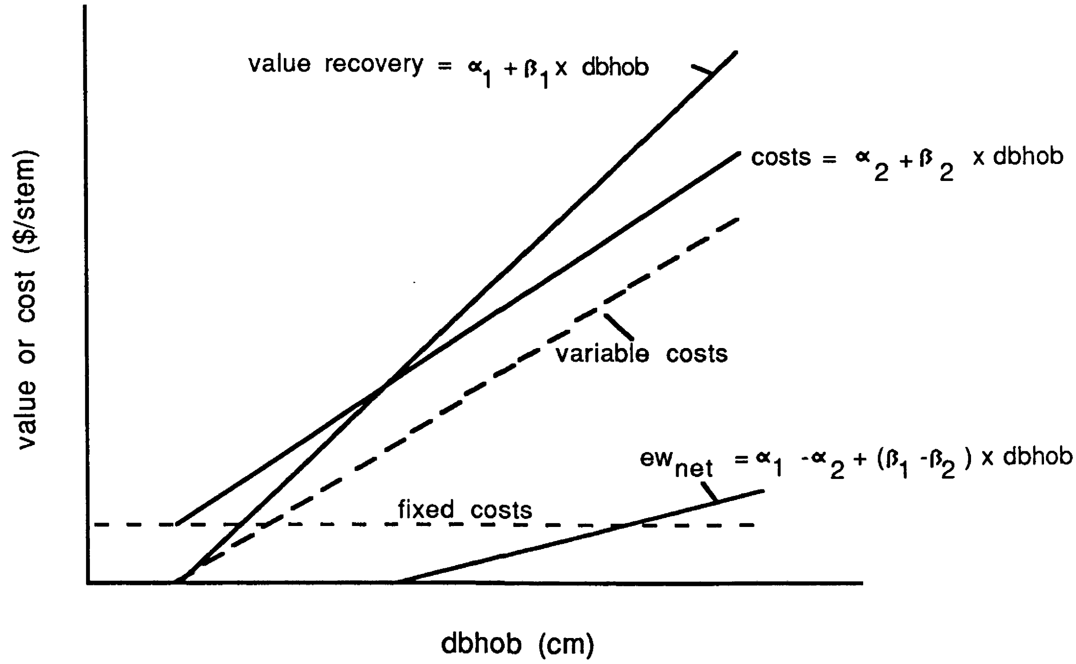
$$\text{costs} = \alpha_2 + \beta_2 \times \text{dbhob}. \qquad [5.3]$$

Since ew_{net} is equal to value recovery minus costs,

$$ew_{net} = (\alpha_1 - \alpha_2) + (\beta_1 - \beta_2) \times \text{dbhob}. \qquad [5.4]$$

Comparing this with Equation 5.1, α is equal to $\alpha_1 - \alpha_2$ and β in Equation 5.1 is equal to $\beta_1 - \beta_2$. The economic weight for dbhob is therefore equal to $\beta_1 - \beta_2$.

Figure 5.2 Possible forms of the relationships between value recovery and dbhob, and costs and dbhob



As noted previously, if value recovery per stem can be measured, β_1 can also be determined by plotting the relationship between value recovery and dbhob, but it is far more difficult to estimate β_2 due to the difficulty of measuring costs per tree accurately. An alternative and simple approach is to assume costs vary in direct proportion to value recovery:

$$\beta_2 = k \times \beta_1 \qquad [5.5]$$

where k is a constant with a value between zero and one (or larger for very small stems).

Over a small range of dbhob this assumption may be valid. The gain in average, harvest age dbhob obtainable through tree breeding may be in the order of 10 % to 30 % (Pederick and Eldridge, 1983). With such increases, the average diameter of logs harvested would also increase by about this much, if rotation lengths were held constant. With this increase in average log size it might be expected the ratio of variable costs to value recovery would decrease slightly, but this change would probably only be in the order of a few per cent.

Data are available from the literature that enable approximation of the constant k. For example, van Wyk (1983) has published theoretical costs and value recovery data for a modern radiata pine saw mill. Working at full capacity (two 8 hour shifts per day, 235 days per year), the mill would process 200 000 m^3 of saw logs for a gross value recovery of $21.28 million (N.Z. 1981 prices). Total costs, including royalties on logs, harvesting, transport of logs to the mill, labour, other operating costs, depreciation on saw mill capital and interest on loans, would be $17.80 million or 83.6% of total value recovery. Therefore, at this mill, k for average sized stems is 0.836 and β_2 is $0.836 \times \beta_1$. Thus, once β_1 is found using a recovery study, the economic weight, β in Equation 5.1, is equal to $\beta_1 - 0.836 \times \beta_1$, or $0.164 \times \beta_1$. In later chapters recovery data have been used to find β_1 for stem dbhob ($\beta_{1_{dbh}}$) and the economic importance of stem dbhob, that is, its economic weight, has been assumed equal to $0.164 \times \beta_{1_{dbh}}$. This estimate of β_2 was used in the study because it was considered to be the best available in the absence of cost data from individual stems, but in reality the relationship between costs and value recovery varies with tree size and mill type. Also, royalties paid by the miller to the forest grower were classed as costs. However part of the royalty may actually represent profit earned by the forest grower, in which case k is less than 0.836, if it is assumed the net worth of a tree is the sum of the growers profit and the millers profit.

5.3 A method to determine economic weights for stem straightness and branch diameter

The same approach has been used to calculate economic weights for stem straightness and branch diameter. Estimations were made of the coefficients β_1 in linear equations:

$$\text{value recovery} = \alpha_1 + \beta_1 \times \text{stem straightness} \quad [5.6]$$

and

$$\text{value recovery} = \alpha_1 + \beta_1 \times \text{branch diameter} \quad [5.7]$$

The β_1's ($\beta_{1_{ss}}$ for stem straightness and $\beta_{1_{bd}}$ for branch diameter) measure the average change in value recovery per stem which would be expected if the average subjective score or measure in a population of stems, changed by 1 point or unit.

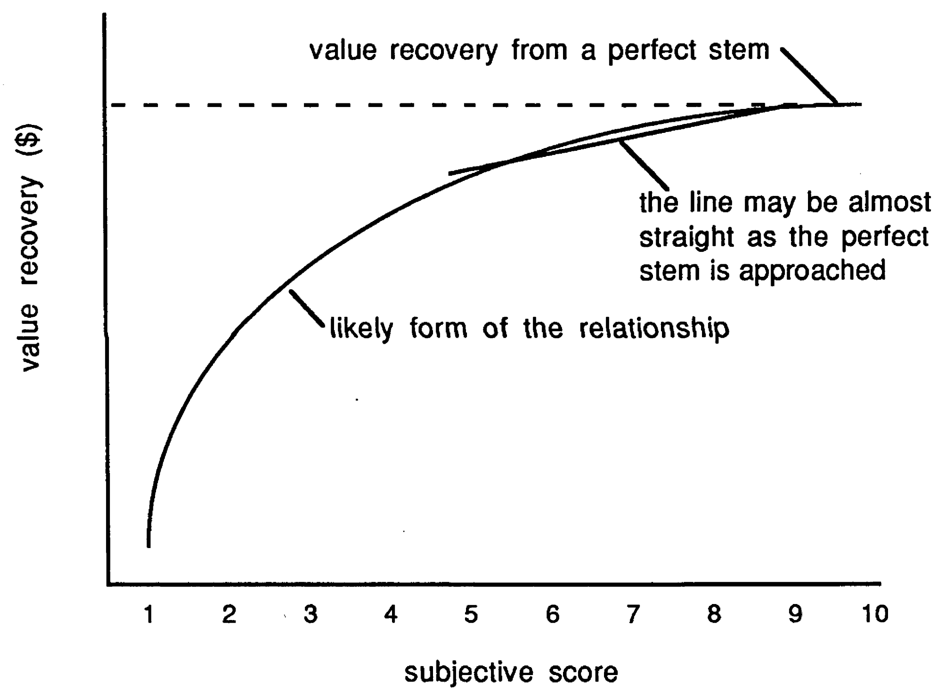
5.3.1 Measurement of $\beta_{1_{ss}}$ and $\beta_{1_{bd}}$ in theory

The relationship between value recovery and a trait such as stem straightness or branch diameter can be depicted graphically (Figure 5.3) . In compiling Figure 5.3 it has been assumed the traits were scored subjectively on ten point scales with a ten awarded to straight stems or stems with very thin branches and a one awarded to very crooked stems or stems with very thick branches. There is probably a score towards the lower end of this scale below which value recovery is zero (*ie.* a stem so poor the value of products recovered is less than the sum of all costs). No stem can score higher than 10 so this represents the maximum value recovery obtainable from any stem with respect to the trait involved (*ie.* a perfectly straight stem or one having branches so small in diameter as to have no effect on value recovery or costs). Individual trees may attain maximum possible recovery at a lower score than 10, in which case the relationship becomes a straight line parallel to the X-axis. The relationship may also approximate a straight line in other parts of the scale.

In reality, stems vary in many traits and therefore it is difficult to separate the variation in value recovery which can be attributed to stem straightness or branch diameter from other sources of variation. However, over a large number of stems the general forms of the relationships are probably as illustrated in Figure 5.3 . In Chapters 8 and 11 sawmill recovery data show that the

relationships are as depicted among stems scoring between 6 and 9 points on 10 point subjective scales in the case of straightness and 3 and 5 points on 5 point scales in the case of branching.

Figure 5.3 Form of the relationships between value recovery and either stem straightness or branch diameter



The shape of the line below a score of 6 in Figure 5.3 is not based on real data. There must be a score at which stem straightness or branch diameter are so poor the ew_{net} of stems is zero. From extrapolation of analyses presented in Chapters 8 and 11, linear relationships across the entire range of scores did not cross the X-axis (indicating zero ew_{net}) within the possible range of scores. Therefore, the regression line depicted in Figure 5.3 must curve sharply downwards at some point below 6 on the 10 point scale shown.

5.3.2 Practical evaluation of the relationships between value recovery, stem straightness and branch diameter

In the present study a group of stems was felled and value recovery following sawmilling measured (details are given in Chapter 6). Simply plotting value recovery against subjective stem straightness and branch diameter scores revealed no clear relationships. An alternative procedure was developed that enabled more precise estimation of $\beta_{1_{ss}}$ and $\beta_{1_{bd}}$, employing the following steps:

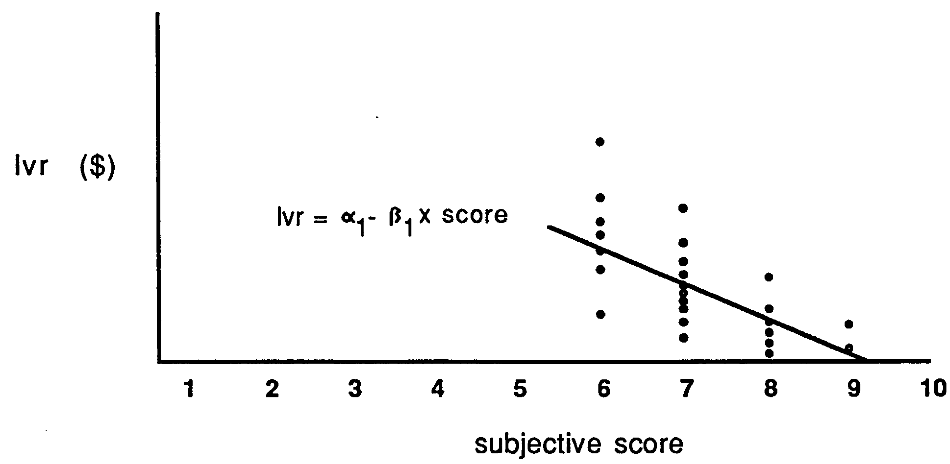
(1) In a sawmilling study, the relationships between value recovery and precise measures of the sweep of saw logs and the diameter of their branches were evaluated by regression analysis. For all logs measured in the study the linear equations so derived were used to estimate the value of recovery lost because the logs were not straight or because they had large diameter branches, that is, lvr_{sw}, the loss of value recovery caused by sweep and lvr_{bd}, the loss of value recovery caused by branch diameter.

(2) Whole-stem estimates of lvr_{sw} and lvr_{bd} were derived by summing the estimates for all logs from each stem.

(3) For each stem the lvr_{sw} and lvr_{bd} estimates were graphed against the subjective scores for these traits. The graphs are of the form depicted in Figure 5.4 . The negative slopes of fitted regression lines estimate $\beta_{1_{ss}}$ and $\beta_{1_{bd}}$ (*N.B.* The regression lines depicted in Figures 5.3 and 5.4 slope in opposite directions because in the former the Y-axis represents value recovery per stem, whereas in the latter it represents loss of value recovery per stem. For the same

reason the signs of the slope coefficients in Equations 5.6 and 5.7 differ from those in Equations 5.9 and 5.10).

Figure 5.4 Form of the relationships between lvr_{sw} or lvr_{bd} and subjective scores for stem straightness and branch diameter



5.3.3 Measurement of β_2 for stem straightness and branch diameter

The relationships between costs and stem straightness or branch diameter are difficult to evaluate. Only a few of all the costs listed previously are likely to be influenced by these traits.

As discussed in Chapter 4, straight stems with thin branches probably cost less to harvest and transport than crooked stems with thick branches. However it is more difficult to judge the effect of these traits on milling costs. At a saw mill for example, crooked logs are more difficult and consequently more expensive to debark and saw than straight ones. However, crooked logs produce less timber per log, so aggregate costs per log for operations such as drying, handling and planing will be lower from crooked logs of the same volume as straight logs.

Large knots can be removed from sawn timber and the short clear sections can then be finger jointed, in which case value recovery is maintained at the expense of increased processing costs and some reduction in volume recovery. Without finger jointing, processing costs of sawing will be unaffected by knots but value recovery will be reduced.

Such opposing effects make it difficult to judge the likely overall influence of stem straightness and branch diameter on costs. In reality, the relatively small changes in average stem straightness and branch diameter that can be achieved through breeding, perhaps less than one point per breeding generation on a ten point subjective scale, may have little effect on costs in comparison to their influence on value recovery, especially if most stems score in the upper part of a subjective scale, anchored to absolute limits.

5.4 Summary

In summary, for a group of stems, economic weights for dbhob, stem straightness and branch diameter have been estimated in this study using the following procedure:

(1) The equations below are evaluated by regression analysis:

$$\underset{\text{(per stem)}}{\text{value recovery}} = \alpha_1 + \beta_1 \times \text{dbhob} \qquad [5.8]$$

$$\underset{\text{(per stem)}}{lvr_{sw}} = \alpha_1 - \beta_1 \times \text{stem straightness score} \qquad [5.9]$$

and

$$\underset{\text{(per stem)}}{lvr_{bd}} = \alpha_1 - \beta_1 \times \text{branch diameter score} \qquad [5.10]$$

The β_1 coefficients in these equations represent $\beta_{1_{dbh}}$, $\beta_{1_{ss}}$ and $\beta_{1_{bd}}$ as defined previously. The values for the α_1's are not important because they are not used to determine the economic importance of traits.

(2) The economic weight for dbhob is assumed to equal $0.164 \times \beta_{1_{dbh}}$ (Section 5.2, p.54). It is assumed that stem straightness and branch diameter have no influence on costs and therefore the economic weight for stem straightness is approximately equal to $\beta_{1_{ss}}$ and for branch diameter $\beta_{1_{bd}}$, that is, $\beta_{2_{ss}}$ and $\beta_{2_{bd}}$ are assumed to be zero.

The following six chapters present the methods and data used to calculate lvr_{sw} and lvr_{bd} for groups of *P.radiata* and *P.taeda* stems and to evaluate the relationships between these values and subjective scores for stem straightness and branch diameter, thereby enabling the determination of $\beta_{1_{ss}}$ and $\beta_{1_{bd}}$. The data collected have also enabled evaluation of $\beta_{1_{dbh}}$.

Chapter Six

DATA COLLECTION FOR A *P. RADIATA* MILL RECOVERY STUDY

6.1 Material used

At the time the study was planned, *P. radiata* Progeny Test Number Three (PT3), Compartment 178, Uriarra, Australian Capital Territory, was scheduled for clear felling. The trees averaged 30.0cm dbhob (range 8.7 to 49.9) and 29.8m height (range from under 10 to 37.7). The original experiment was established in 1952 by J. M. Fielding and A. G. Brown of the then Commonwealth Forestry and Timber Bureau, using the progeny of 20 controlled crosses (families) of a number of selected 'plus' trees. The families were planted in five replications in randomised blocks of 10 trees per plot. The specific pedigrees and design of the experiment are not relevant to the present study.

The advantage of using trees from PT3 was the availability of data from measurements and assessments over several years. This provided an excellent opportunity to study the relationships between value recovery from individual trees (determined from a mill study) and several different assessments of stem straightness and branch diameter.

When the present study commenced in late 1985, three quarters of the original trees had died or been removed in thinnings carried out in 1974 and 1979. As a consequence many families were poorly and erratically represented and no meaningful interfamily comparisons were possible. Accordingly the trees used for the study were selected to encompass the range of stem straightness and branch diameter types available.

The range of material was further increased by including trees of routine stock of the same age planted adjacent to the progeny test. These trees were generally more crooked and had bigger branches than those in the test.

It is likely that a selective thinning in 1979 had removed the trees with the most crooked stems and perhaps some of those with the largest branches. Thus, the sample of trees felled in the study does not include the worst stems *P. radiata* can produce on the site. Only a few trees with severe deformities (forks, ramicorns, basket whorls) were left in PT3 after the 1979 thinning.

6.2 Measurement of standing trees

One hundred and ninety five merchantable trees in the experiment and eighty trees of routine stock from the neighbouring plantation were labelled and their dbhob and height measured. Stem straightness was assessed using the scale described in Table 6.1.

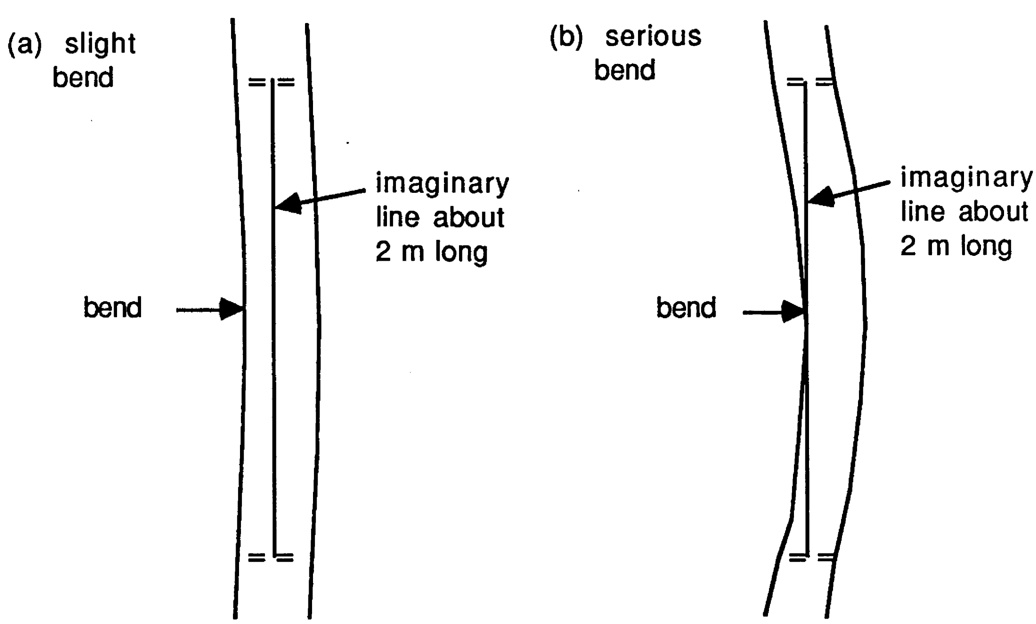
Three assessments were made of the progeny test trees, two being by one observer (the author) with an interval of several days, and the third by a second observer. The trees of routine stock were assessed once, several weeks after the assessments in PT3.

Table 6.1 Stem straightness assessment scale

Score	Description
10	No bends
9	One or two slight bends
8	A few slight bends
7	Several slight bends or one serious bend
6	Two or three serious bends, numerous slight bends or an equivalent combination of slight and severe bends
5	Several serious bends or combinations of slight and serious bends
4	Numerous serious and slight bends but a merchantable log can still be recovered
3,2,1	Correspondingly worse

To judge the severity of a bend, an imaginary line was drawn joining points at the centre of the stem about one metre either side of the bend. If the silhouette of the stem at the centre of the bend cut or approached this line the bend was classed as serious, otherwise as slight (Figure 6.1).

Figure 6.1 Method of judging bend severity



Branch diameter was assessed visually by estimating the diameter of the largest branches at the base of the green crown and awarding points according to the scale in Table 6.2. The number of branches and branch whorls judged was not precise. Generally the judgement was based on a total of 5 to 10 branches in 3 or 4 whorls.

Table 6.2 Scale used in assessing branch diameter

Score	Description
5	Branches up to 15 mm
4	Branches up to 30 mm
3	Branches up to 45 mm
2	Branches up to 60 mm
1	Branches up to 75 mm

Branch diameter of the progeny test trees was assessed twice by a single observer (the author). The trees of routine stock were assessed once on a separate occasion.

A number of traits including stem straightness and branch diameter had been assessed on each progeny test tree at various times by the CSIRO's Division of Forest Research, the successor to the Forestry and Timber Bureau and now the Division of Forestry and Forest Products. Two sets of stem straightness, branch diameter and dbhob data from the 1960's and 1970's have been included in this study. Details of the information collected on each occasion are summarised in Table 6.3.

In 1966 the diameters of the six thickest branches between 1.3 and 2.3 metres up the stem were measured to the nearest millimetre using calipers and the mean of the six measurements recorded. The measurements were over bark, 5 cm out from the stem. Stem dbhob was also measured in 1966.

Table 6.3 Summary of data collected from the trees in PT3

Trait	Year assessed	Assessment method
Stem straightness	1969	Subjectively for butt sweep and stem straightness on 4 point absolute scales
	1978	Subjectively on a 5 point scale anchored relative to the best and worst stems in PT3
Branch diameter	1966	Mean diameter (over bark) of the 6 thickest branches between 1.3m and 2.3m, measured 5cm out from the stem
	1978	Subjectively on a 5 point scale anchored relative to the best and worst stems in PT3
Stem diameter	1966	Measured over bark at 1.3m
	1978	Measured over bark at 1.3m

In 1969 butt sweep and stem straightness above the butt region were assessed subjectively as separate traits using 4 point absolute scales. The anchors for the butt sweep scale were:

1 - no butt sweep;
2 - slight butt sweep;
3 - moderate butt sweep;
4 - severe butt sweep;

and those for the stem straightness scale were :

1 - excellent;
2 - good;
3 - fair;
4 - poor.

Most stems scored either 1 or 2 for butt sweep and 2 or 3 for straightness. For the present study the scales have been reversed to facilitate easier comparison with the rating scales used in 1978 and 1986, and added together to give a single overall score for stem straightness. The relationship between the original and the transformed scales is shown in Table 6.4.

Table 6.4 Transformation of scores for stem straightness

Sum of the two original scores	Transformed score	Stem description (types actually present in PT3)
2	7	No stems of this type recorded
3	6	Good stem, no butt sweep
4	5	Fair stem, no butt sweep, or good stem, slight butt sweep
5	4	Fair stem, slight butt sweep, or good stem, moderate butt sweep
6	3	Fair stem, moderate butt sweep
7	2	No stems of this type recorded
8	1	No stems of this type recorded

In 1978 stem straightness and branch diameter were each scored subjectively on 5 point scales anchored relative to the best and worst trees in PT3. The meanings of the scores were thus:

5 - similar to the best trees in PT3;
4 - better than the average for PT3;
3 - about average for PT3;
2 - below average;
1 - similar to the worst in PT3.

Stem dbhob was also measured in 1978.

6.3 Measurements following felling

Sixty five progeny test trees and 25 trees of routine stock were felled for a recovery study. Felling, trimming, crosscutting and measuring of the logs were carried out over a two week period in March 1986. As each tree was felled and trimmed the length of the stem was measured and a 50mm thick disc of wood cut from its base. A decision was then made, using the criteria shown in Table 6.5, as to the types and lengths of logs to be cut. Stems were crosscut to best advantage taking account of severe bends and deformities such as forks, basket whorls, ramicorns and felling damage. In order of preference, portions of stems were selected to be veneer logs, long saw logs, short saw logs, posts, pulp and non-merchantable. Virtually no post logs were recovered. Logs were tagged at both ends with numbered log marking tags.

Discs of wood about 50mm thick were taken from between the logs. The tree number and the disc's position in the tree were marked on each disc and the discs taken to the Forestry Department, ANU. The original intention was to measure wood density in each disc. However, time constraints prevented such a study. The discs also facilitated measurement of the end diameters of each log and the calculation of log volumes under bark. The widest and narrowest under bark diameters on each wood disc were measured to the nearest millimetre. Sectional area was calculated from the mean of the two diameters. Log volume (vub) was calculated by multiplying the mean of the small and large end sectional areas by log length (Smalian's Formula).

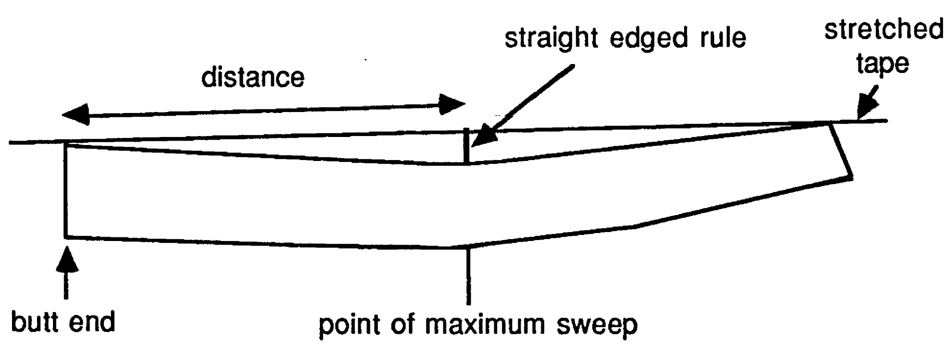
Table 6.5 Log classification criteria

Log type	Lengths (m)	Min sedub (cm)	Restrictions
Veneer	5.20	25.0	Must be reasonably straight (judged subjectively)
Saw log	3.65, 4.25, 4.55, 4.85, 5.15, 5.45, 5.75, 6.10	15.0	
Post for preservative treatment	2.0 or longer	7.0	Must be straight
Pulp wood	2.0 or longer	7.0	

The lengths of all logs and non-merchantable sections of stem were recorded and the plane of the worst bend in each saw log and veneer log located by eye. The amount of sweep in the log caused by the bend was measured by stretching a cloth tape between the ends of the log so that the tape touched the bark at both ends in line with the plane of the bend. A graduated straight edge was used to measure the gap between the tape and the outer bark surface of the log to the nearest 5mm. The distance from the butt end of the log to the point of maximum sweep was measured to the nearest 50mm (see Figure 6.2). The sweep at a point 90 degrees around the circumference of the log to the major sweep was also measured in the same way.

The trimming of branches from the felled stems exposed a cross-section of each branch at the log surface. For each branch whorl, the lengths of the shortest and longest under bark axes of the cross-sections of the two branch stubs uppermost as the log lay were recorded. As branches below the green crown had died and broken off many years before some branch stubs had become occluded, so branch diameter could not be measured on all logs.

Figure 6.2 Measurement of sweep in saw and veneer logs



Some 285 saw logs and 70 veneer logs were measured in the forest. With the exception of three saw logs that were left behind, and one with a severe fork, all were harvested and delivered to the A.P.M. Wood Products Pty. Ltd. integrated mill at Hume, A.C.T. (now Brown and Dureau Pty. Ltd.), where they were debarked and separated.

6.4 Log identification for processing at the mill

During sawmilling, pieces from many logs become mixed together. The saw logs from the study were processed in a single batch in a routine milling operation. To enable identification of timber from individual logs the log ends were painted in different colours. In a test of several brands prior to commencement of the main study, British Paints Nu-Vinyl Matt paints were found to be the most suitable as the colours remained clearly visible, even after the timber had been kiln dried at 120° C dry bulb temperature.

In order to have a unique colour code for every log it was necessary to paint each log end with a combination of two colours. By using six colours and an unpainted alternative, enough combinations were obtained for all logs. Each end was either painted with a base coat of one of the six colours or left unpainted. After the base coat dried a second colour was applied in a random pattern of spots using a 15mm wide artist's brush. The unique colour codes were matched to the log and tree identification numbers assigned earlier.

The veneer logs were coded using painted stripes rather than spots to enable the forwarder driver and log yard personnel to distinguish them from the sawlogs. Plate 6.1 illustrates the clarity with which the colour codes could be identified on the timber ends.

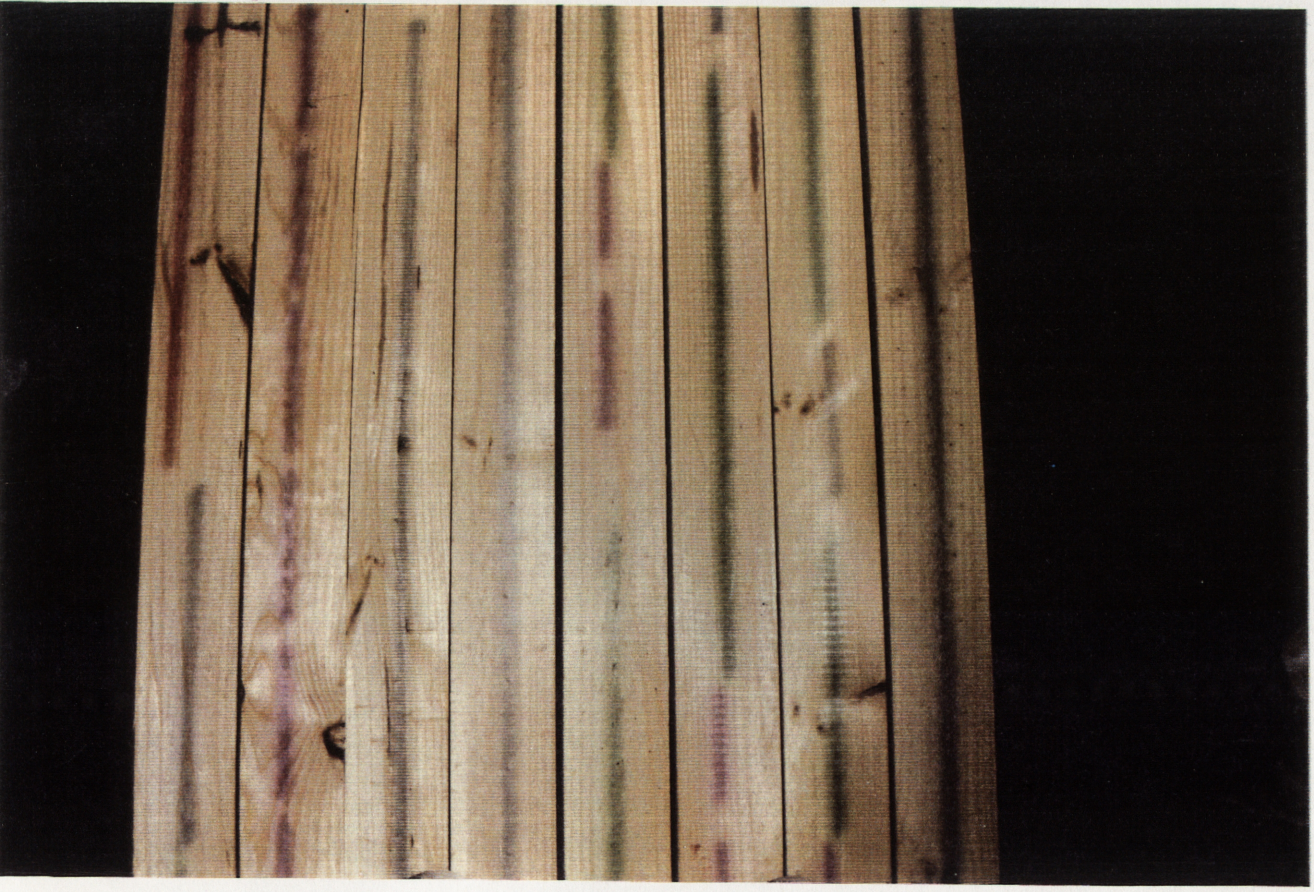
6.5 Data collection for the saw mill recovery study

Figure 6.3 illustrates the flow of logs and products through the saw mill, showing points of measurement.

Before being sawn, the saw logs were squared up in a chipper canter (Figure 6.3). Each log passed through the machine on a conveyor system, the operator estimating log diameter and setting the appropriate cant dimensions to

Plate 6.1 Stack of framing timber showing colour codes

Plate 6.2 Stack of framing timber , illustrating machine stress grades

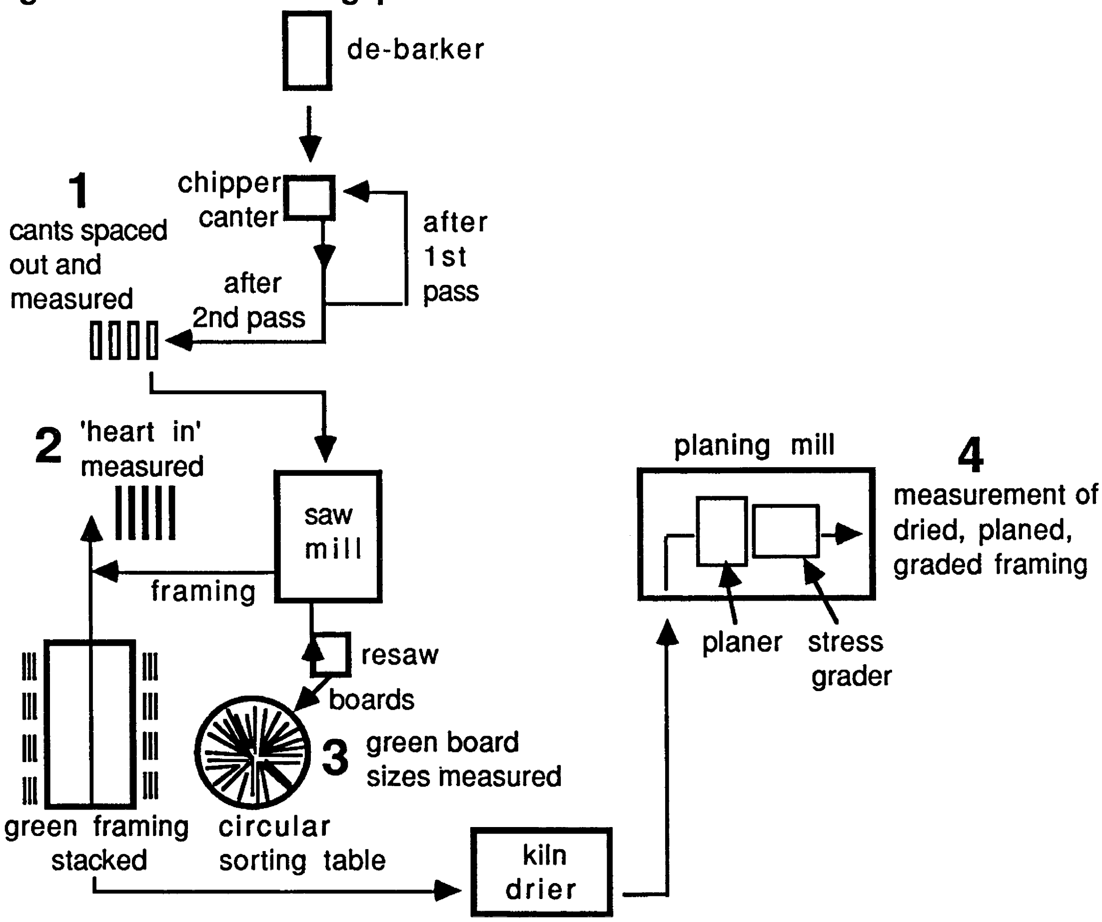


the nearest 25mm as was his normal practice. The first pass through the chipper canter gave a log two parallel, flat sides. Logs were then returned to the head of the machine, rolled 90 degrees and passed through again to make them almost square in cross-section.

The squared cants from the study were removed from the outfeed conveyor, laid out on the ground and the cross-sectional dimensions of each recorded, along with identifying colour codes (point 1 in Figure 6.3). The paint on a few ends had been scuffed during debarking and these were retouched. Two logs measured at this stage had very small cant widths in one direction, compared with their small end diameter and cant width in the other direction. It was obvious the operator had not changed the setting from the previous log. These two logs were subsequently excluded from the analysis. A further five cants were broken when the loader ran over them while attempting to spread the cants on the ground for measurement, and these were also excluded from the study.

Normally the mill produces light structural timber (framing) of various lengths and sections plus a small amount of board timber. The main framing sizes produced are 90mm x 35mm and 90mm x 45mm in section (finished sizes when dried and planed). The mill also produces lesser amounts of framing timber of other sizes (70mm x 35mm, 70mm x 45mm, 120mm x 35mm, 120mm x 45mm, 140mm x 35mm and 140mm x 45mm). On any one day the mill will be aiming specifically at producing a majority of one of the common framing sizes but will also produce many of the other sizes in order to make full use of each cant and to fill orders.

Figure 6.3 Monitoring points in the saw mill



1. The squared cants were measured and colour codes recorded.

2. Colour codes of the 'heart in' framing were recorded.

3. Colour codes and dimensions of the board sized timber were recorded.

4. Colour codes, dimensions and machine stress grades of the framing timber were recorded.

All the saw logs from the study were sawn in a single morning using standard sawing patterns. On that day the mill was aiming to produce a majority of 90mm x 35mm framing timbers. A lesser proportion of timber from the study ended up as 90mm x 45mm, 120mm x 35mm and 140mm x 35mm. Pieces containing wane were re-sawn into 70mm x 35mm and 70mm x 45mm framing timber or various sizes of board. Not all wane was excluded; however the presence of wane was recorded in a subsequent assessment. One structural piece of framing broke during sawing. The grade of this piece could not be measured and therefore the log was excluded from the analysis.

Pieces of potential structural timber containing pith in most of their length are normally rejected from the green chain by visual assessment by mill staff. The colour codes of these "heart-in" rejects resulting from the logs under study were recorded (point 2 in Figure 6.3).

During normal green mill operations, small framing timber and boards resulting from resawing pass from the recovery saw to a circular sorting table. Pieces resulting from the logs under study were removed from the sorting table and their colour codes, dimensions (green) and length of waney end noted (point 3 in Figure 6.3). The dried volumes of the boards were later estimated by adjusting green dimensions to nominal dried, finished sizes.

Framing timber was kiln dried at the mill at 120°C dry bulb temperature, planed, and machine stress graded according to Australian Standards 1748 and 1749 - 1978 (Standards Association of Australia, 1978). Normally, graded pieces would have been docked to final length but to preserve the colour coding, pieces from the study were taken from the main stream before docking. The colour code, cross-sectional dimensions and length of each piece were noted (point 4 in Figure 6.3). The stress grade was indicated by a continuous line of coloured dye sprayed on the wide face of each piece as illustrated in Plate 6.2. Each grade was identified by a different coloured dye in accordance with Australian Standard 1613 - 1974 (Standards Association of Australia 1974). After each piece had passed through the grader the following data were recorded:

1. log colour codes

2. cross-sectional dimensions
3. length overall
4. length of each grade within the piece, and
5. length of wane (if any).

The measurements collected are summarised in Table 6.6.

Table 6.6 Summary of the data collected for saw logs

Location	Data collected for each log
Forest	- length - sweep - diameter of the two uppermost branch stubs in each branch whorl - log identification number - colour code
Laboratory	- end diameters under bark (measured on wood disc collected from the log ends)
Sawmill	- cant widths - colour codes on the 'heart in' framing, board timber and machine stress graded framing - green dimensions and length of waney end in the board timber - finished dimensions, machine stress grades, length of waney ends and presence of pith in the dried, planed framing timber

Afterwards, it was found two logs had received identical colour coding by mistake. Since both were the same length it was impossible to distinguish timber from the two logs. Therefore, these were excluded from the analysis.

During processing, 40 pieces of framing timber (of the 800 sawn from the coded logs) and 10 boards (of 350) lost their colour code because one end was docked, broken, or lost through wane. The identity of some of these was determined by using the colour code on the remaining end in combination with the length of the piece and the known recovery of other pieces. Given the cant widths and pieces known to have been recovered from each of the remaining logs it was possible to infer the sawing pattern, particularly for logs that produced a cant size from which only a few pieces could be recovered. Using this method the number of unidentified framing timbers was reduced from 40 to 10 and the number of unidentified boards from 10 to 9. The consequence of non-identification of the remaining pieces is that recovery was underestimated in at most 19 logs, or 7% of those sawn. The unidentifiable timber accounts for 1.5% of the total volume of timber sawn.

6.6 Data collection for the veneer mill recovery study

The flow of material through the veneer mill is shown in Figure 6.4. The veneer logs were cut into 2.6m bolts and each bolt was peeled on a 2.6 metre lathe (2.4m nominal), set to produce 2.5mm thick veneer. Observers stationed at each end of the lathe on the log deck (point 1 in Figure 6.4) recorded the log identification number from the tag. A third person measured the round-up diameter of the bolt with calipers.

As the veneer passed from the lathe to the drier a fourth person used a spray can to apply a continuous line of coloured paint about 5 cm in from the edge (point 2 in Figure 6.4). A new colour was used for each new bolt. A sequence of six colours was repeated to ensure all veneer exiting the drier could be identified as being from the one bolt. An observer at the drier exit recorded the colour seen on the veneer (point 4). Another observer measured the diameters of the peeled cores as they passed off the line (point 3).

Each length of veneer was cut into 1200mm wide sheets and these graded as cross band, D or C grade by the operator, grade C being the best. These grades were recorded (point 5).

Figure 6.4 Monitoring points in the veneer mill

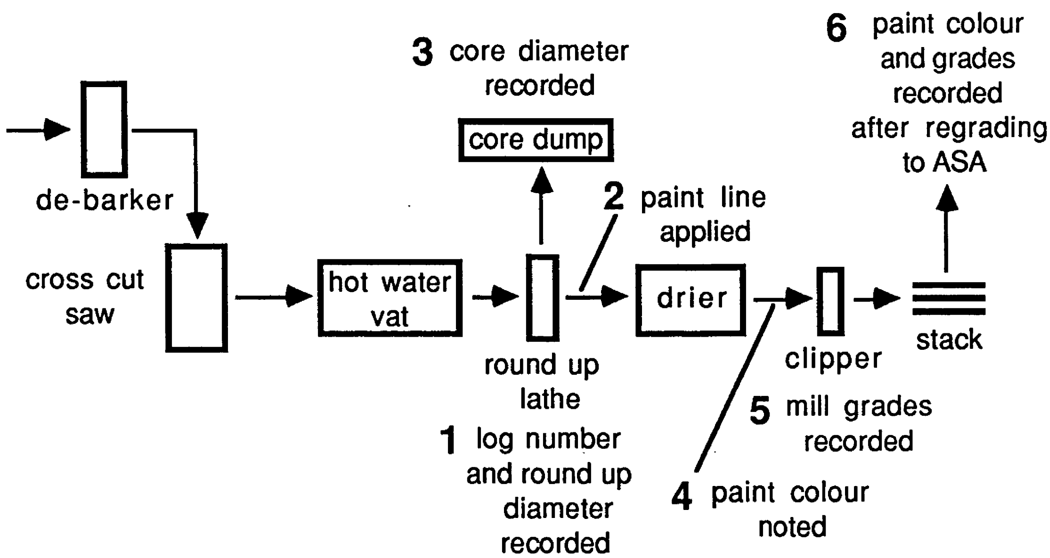


Table 6.7 Summary of the data collected for veneer logs

Location	Data collected for each log
Forest	- length - sweep - diameter of the two uppermost branch stubs in each branch whorl (*i.e.* uppermost on each log as lying on ground) - log identification number - colour code
Laboratory	- end diameters under bark (measured on wood disc collected from the log ends)
mill	- log identification number from tag - round up diameters of the two bolts - core diameter from each bolt - number of cross band, D and C sheets of veneer according to mill standards - number of cross band, D and C sheets according to Standards Association of Australia Standard 2269-1979

Once all bolts had been peeled each veneer sheet was regraded to Australian standard 2269. The coloured paint applied after the lathe was used to identify veneers as being from different logs. Because the veneers remained in sequence the colours could be matched with the log numbers and each sheet matched with a particular bolt (point 6 in Figure 6.4).

The measurements collected from the veneer logs are summarised in Table 6.7.

Chapter Seven

RESULTS OF THE *P. RADIATA* MILL RECOVERY STUDY; ANALYSIS OF THE EFFECT OF SWEEP ON PERCENTAGE CONVERSION TO SAWN TIMBER

7.1 Introduction

This chapter describes the analysis and interpretation of the data obtained from the 273 saw logs originating from PT3, whose identity was maintained during processing as described in the previous chapter. The data were used to derive a model relating log sweep and other parameters to the percentage of log volume under bark converted to sawn timber (percentage conversion). The model was used to calculate the loss of sawn volume from each log caused by sweep. The loss of value recovery caused by sweep was then calculated by multiplying the estimated loss of sawn volume (dried, dressed timber) by the average market price per cubic metre of timber recovered (Chapter 8). The analysis of the relationship between the branch diameter measurements and sawn timber grade recovery, and consequently the influence of branches, on value recovery is described in Chapter 10.

Previous milling studies indicated the existence of a negatively sloping linear or curvilinear relationship between sweep and percentage conversion (Brown and Miller 1975, Whiteside 1982). In this study, least squares analysis was used to fit regression lines relating the quantity of timber obtained from logs to an index of sweep and several other log parameters. The statistical package used was Statview (Brainpower Inc. 1985) on a Macintosh computer. This determined the coefficients of the model in which the dependent variable, percentage conversion, was expressed as a linear function of other log variables. The general model to which the data were fitted was:

$$Y_i = B_0 + B_1X_{1i} + B_2X_{2i} + \ldots + B_kX_{ki} + \varepsilon_i \quad [7.1]$$

where: Y_i is the value of the dependent variable observed on individual i,

$B_0 \ldots B_k$ are the true coefficients of the regression line,

$X_{1i} \ldots X_{ki}$ are the values of the k independent variables observed on individual i, and

ε_i is the random error associated with individual i.

7.2 Definition of the model

7.2.1 The dependent variable

The volume of sawn timber obtained from a log can be considered to be the product of log volume under bark and a conversion factor:

$$V_s = \frac{vub \times C}{100} \quad \text{i.e.} \quad C = \frac{V_s}{vub} \times 100 \quad [7.2]$$

where: V_s is total volume of sawn timber obtained from a log (m^3)

vub is log volume under bark (m^3)

C is percentage conversion

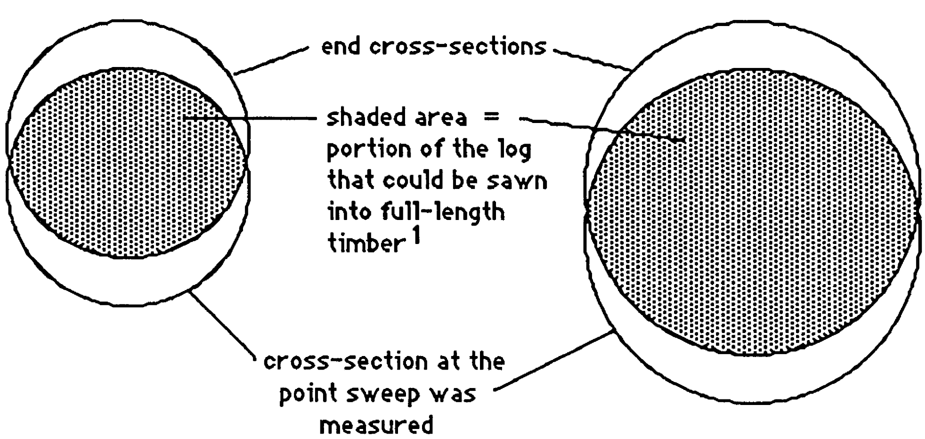
Sweep cannot influence log volume and therefore its effect must be on percentage conversion. For this reason, percentage conversion was used as the independent variable in the analysis; not volume recovery. In this study, V_s and vub were measured on each saw log (Chapter 6) and percentage conversion was calculated.

7.2.2 The independent variables

7.2.2.a Sweep and taper

Sweep, as defined in Chapter 4 and referred to throughout this chapter, can be expressed as the maximum deviation of the log surface from a straight stick, rod or line held against it. However, Brown and Miller (1975) argued it is better to express sweep as a ratio of log diameter when investigating its effect on percentage conversion. The reason for this can be illustrated by comparing end elevations of two logs which have the same sweep but different diameters, (Figure 7.1).

Figure 7.1 End elevations of two logs illustrating that the effect of sweep on percentage conversion varies according to log diameter



1. The proportion of each log that could potentially be sawn into full-length timber is equal to the shaded area divided by the area of one circle.

In Figure 7.1, the upper circles represent log end diameters and the lower circles represent the maximum displacement due to sweep. Assuming no taper, the amount of overlap represents potential recovery following sawing. Even though both logs have the same sweep, the proportional overlap of the circles is only 73.8% for the small log compared to 82.2% for the large log. Consequently percentage conversion will be higher from the large diameter log. Thus, percentage conversion is related to the sweep ratio, defined as:

$$\text{sweep ratio} = \text{sweep} / \text{sedub} \qquad [7.3]$$

Logs can have sweep in more than one plane. For this reason sweep in the logs harvested for the study was measured in two planes at right angles to each other (Section 6.3, p.67). A second sweep, in a plane perpendicular to that of a first sweep, has an effect approximately half that of the first (Brown and Miller 1975). To demonstrate this, the percentage overlaps of the areas of two and three circles, representing end elevations of non-tapered logs with sweep in one and two planes, have been calculated for a range of sweeps. The results are plotted in Figure 7.2. In the figure, each sweep is expressed as sweep ratio (Equation 7.3). It can be seen that when the two sweep ratios are in the range 0.1 to 0.2 the added effect of a second sweep on the area of overlap of the circles is about half that of sweep in one plane alone. Below 0.1 the added effect of a second sweep is proportionally more, and above 0.2 it is proportionally less.

Therefore, when sweep occurs in two perpendicular planes, percentage conversion from a non-tapered log can be approximated as:

$$\text{sweep ratio} = \frac{sw_1 + 0.5\,sw_2}{\text{sedub}} \qquad [7.4]$$

where: sw_1 is sweep measured in one plane (the larger of the two sweeps if they differ)

sw_2 is sweep measured in a plane perpendicular to the plane of sw_1, and

sedub is diameter under bark of a non-tapered log.

When a log is tapered the sawyer can reduce the effect of sweep by controlling the alignment, or direction in which the log passes through the saw. Figure 7.3 uses two end views of a tapered log having sweep in one plane, to illustrate how this can be done:

Figure 7.2 Influence of sweep in one and two planes on the potential conversion to full length timber

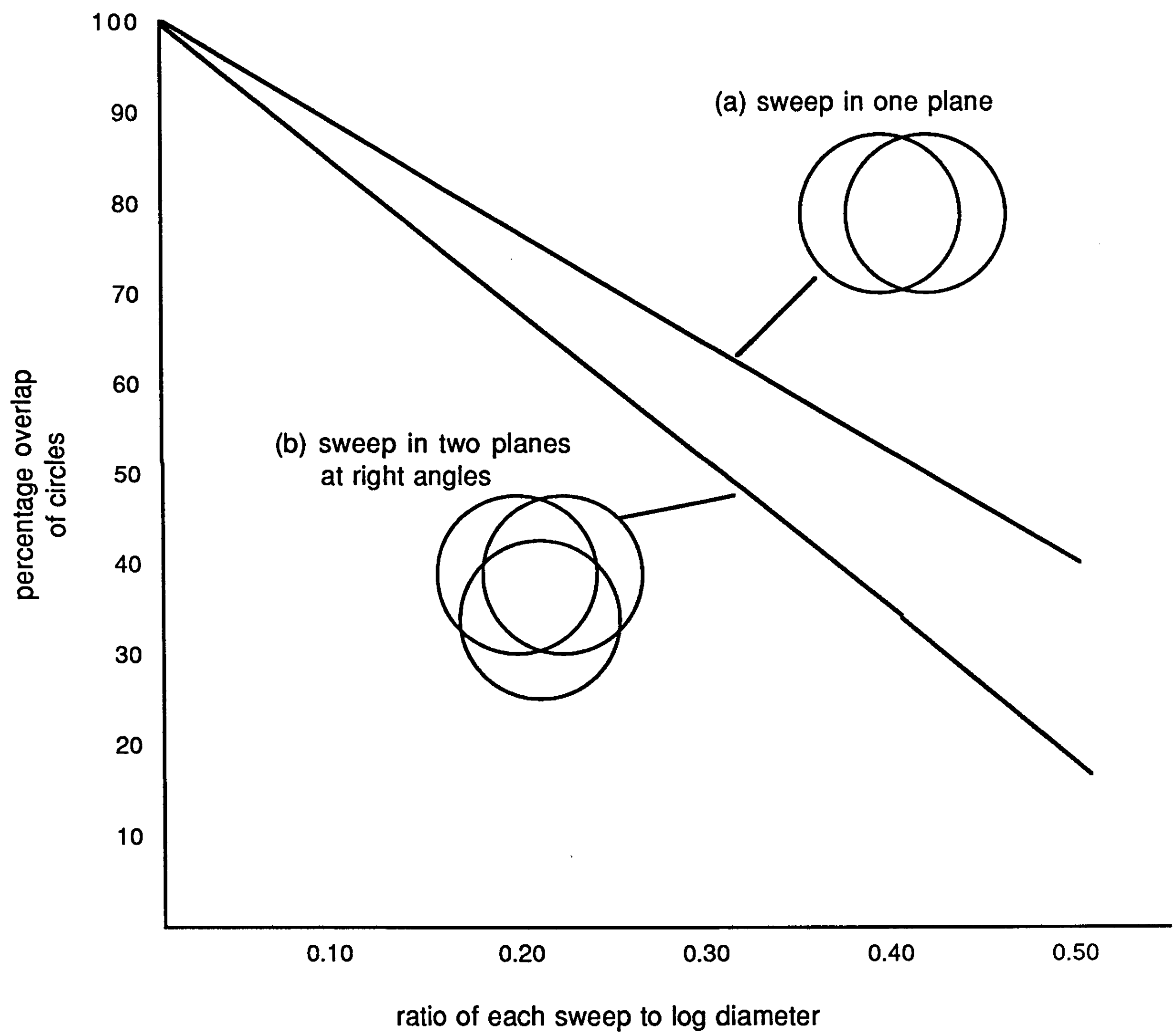
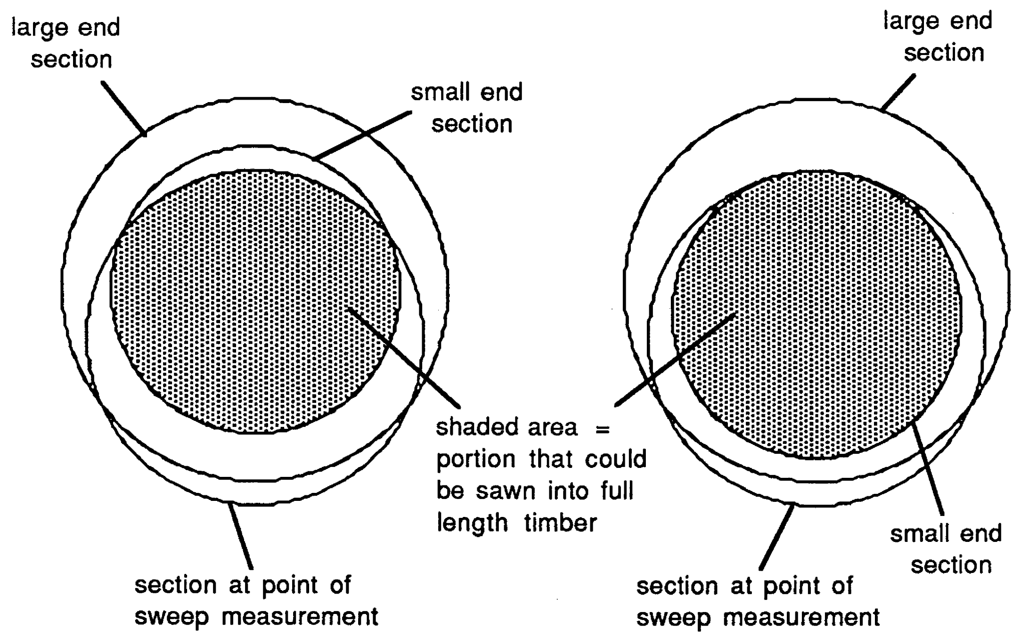


Figure 7.3 The direction of passage through the saw can lessen the adverse effect of sweep

(a) The log moves towards the saw in the direction of an imaginary line joining the centres of the two end sections

(b) Log orientation has been changed slightly to minimise the effect of sweep using the taper of the log to advantage



In Figure 7.3 (a), a log is drawn as if viewed from the saw. When an imaginary line joining the centres of the two end sections is parallel to the direction of movement through the saw, conversion will be reduced by sweep, as indicated by the fact that the small end section, as drawn in Figure 7.3(a), is not fully contained within the section at the point of maximum sweep. In Figure 7.3(b) the same log is drawn, still as if viewed from the saw but with the log orientation changed slightly so that the small end section of the log is projected through the section at the point of maximum sweep. The small change in the alignment has removed the influence of the sweep on percentage conversion. In theory, if sweep is less than half the difference between the diameter at the point of maximum sweep and sedub, correct orientation of the log through the saw will completely negate the effect of sweep on percentage conversion.

Because this relationship is vital to the calculations which follow, taper for the purposes of this thesis is defined as the absolute difference between log diameter at the point of maximum sweep and log diameter at the small end, in cm. (*n.b.* taper used in this way should not be confused with the more common definition of taper as the average rate of change in diameter per unit of log length.) Accordingly, using the thesis definition, Equation 7.4 can be adjusted to take account of log taper, using the following formula:

$$\text{sweep ratio} = \frac{(sw_1 - 0.5t_1) + 0.5(sw_2 - 0.5t_2)}{\text{sedub}} \qquad [7.5]$$

where: sw_1 is sweep measured in one plane (cm)

t_1 is the difference between log diameter at the point of sw_1 and diameter at the log small end (cm)

sw_2 is sweep measured in a plane at right angles to the plane of sw_1 (cm)

t_2 is the difference between log diameter at the point sw_2 and log diameter at the small end (cm)

sedub is small end diameter under bark (cm).

N.B. For some logs in the study $sw_1 - 0.5t_1$ or $sw_2 - 0.5t_2$ was negative. In such cases a value of zero was used

7.2.2.b Log diameter and length

Previous mill studies have shown that log diameter and length can influence percentage conversion (Brown and Miller 1975, Whiteside 1982). Sedub and length, were therefore included as independent, X variables in the regression study.

7.3 Unrepresentative data

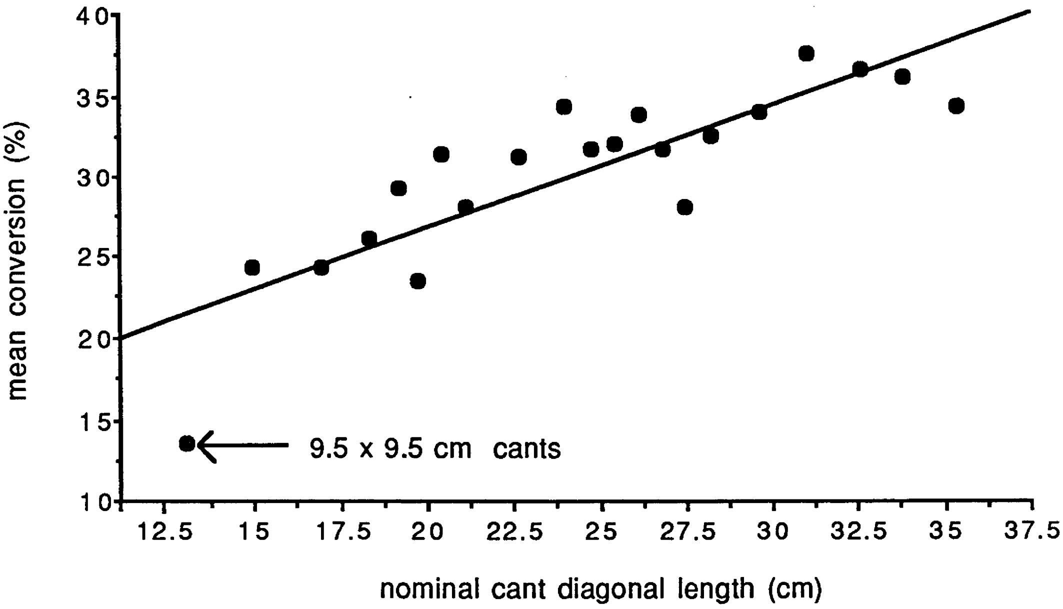
A number of logs were excluded from the analysis. Some were either left in the forest, broken during processing or processed incorrectly (Section 6.5, p.69).

In addition, nineteen small diameter logs that were squared to a very small cant size (9.5 cm × 9.5 cm nominal cross-sectional dimensions) were also excluded. These returned a much lower percentage conversion than predicted by a linear regression of mean conversion against cant size, measured as the nominal length of the diagonal of the cant cross section (Figure 7.4). In the figure the points represent the mean of all logs having a nominal cant diagonal length, in cross-section, equal to that indicated on the X-axis. The point indicated by the arrow shows the mean percentage conversion for the 19 logs having cant dimensions 9.5 cm × 9.5 cm. Most cants of this size only produced one piece of timber (either a small board size or a 70 mm × 35 mm or 70 mm × 45 mm structural piece, in finished dimension), but if one cant dimension was 2.5 cm wider (9.5 cm × 12 cm), two pieces were usually obtained. Eight logs, having a mean sedub of 15.3 cm. were squared to the 9.5 × 12 cm size and returned a mean conversion of 24.7% (ranging from 21.6 to 30.3), while the 19 logs squared to 9.5 × 9.5 cm were only slightly smaller in diameter (mean sedub of 15.0 cm) but had much lower mean conversion (12.3%).

Because these 19 logs appeared unrepresentative of the relationship between cant diameter and percentage conversion, and because they only contributed a small amount to the total volume of timber obtained in the study, they were excluded from the regression analysis.

After an analysis was carried out using the reduced data set, two other logs appeared to be outliers. These were also excluded from the final results (Section 7.4.4, p.90).

Figure 7.4 Relation between percentage conversion and nominal cant diagonal length



7.4 The fitted regression models

Regression analysis was used to establish the relationship between percentage conversion (Equation 7.2) and sedub and sweep ratio (Equation 7.5). Log length was also found to have a significant but slight effect on percentage conversion.

7.4.1 Small end diameter under bark

Of the variables tested, sedub had the largest influence on percentage conversion. Alone it explained 24.7% of variation, the relationship being:

$$C = 14.3 + 0.746 \text{ sedub.} \qquad [7.6]$$

N.B. sedub is expressed in centimetres

Figure 7.5 shows C plotted against sedub, and Figure 7.6 shows the residuals against fitted values for this regression.

Figure 7.5 Percentage conversion versus sedub for all saw logs included in the final analysis

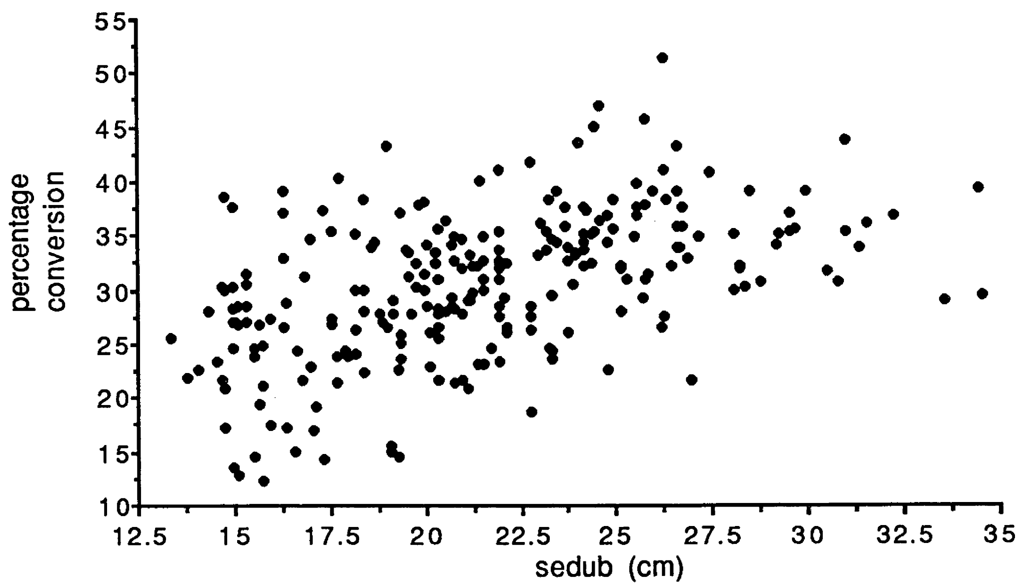


Figure 7.6 Residuals versus fitted values for a linear regression fitted to the scatter plot in Figure 7.5

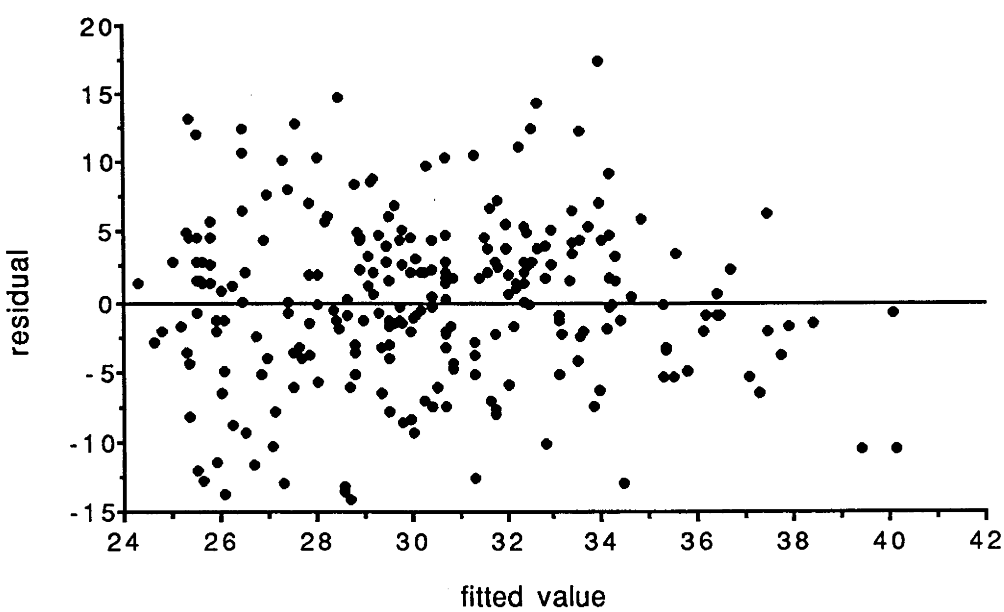
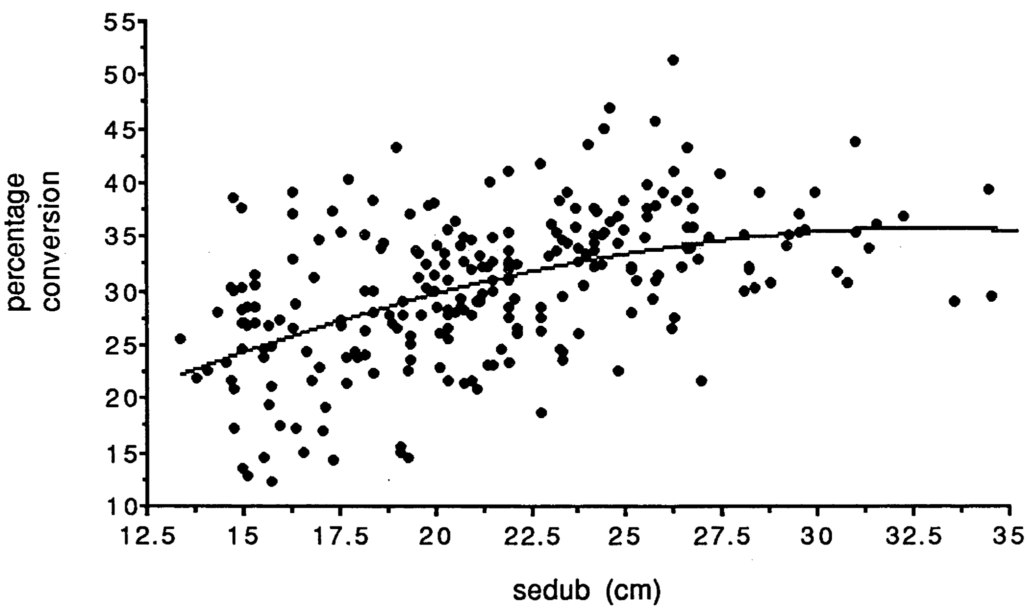


Figure 7.6 indicated that the relationship may be curvilinear. For example, of 22 logs with predicted conversion greater than 35%, 18 had

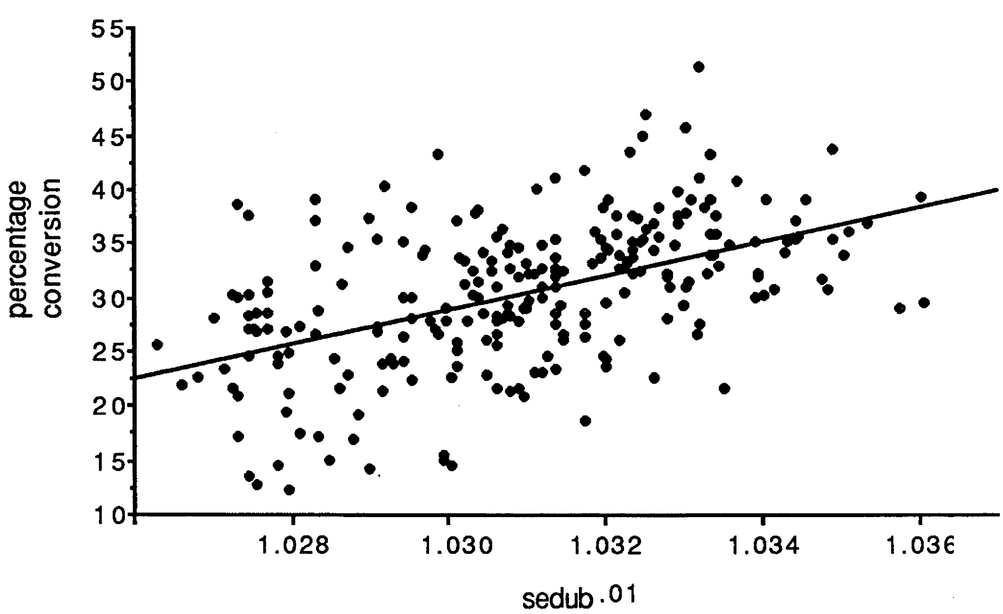
negative residuals associated with them, while only 4 had positive ones. Two nonlinear curves were fitted (Figure 7.7).

Figure 7.7 Curvilinear fits to the scatter plot shown in Figure 7.5

(a) 2nd order polynomial



(b) Power law



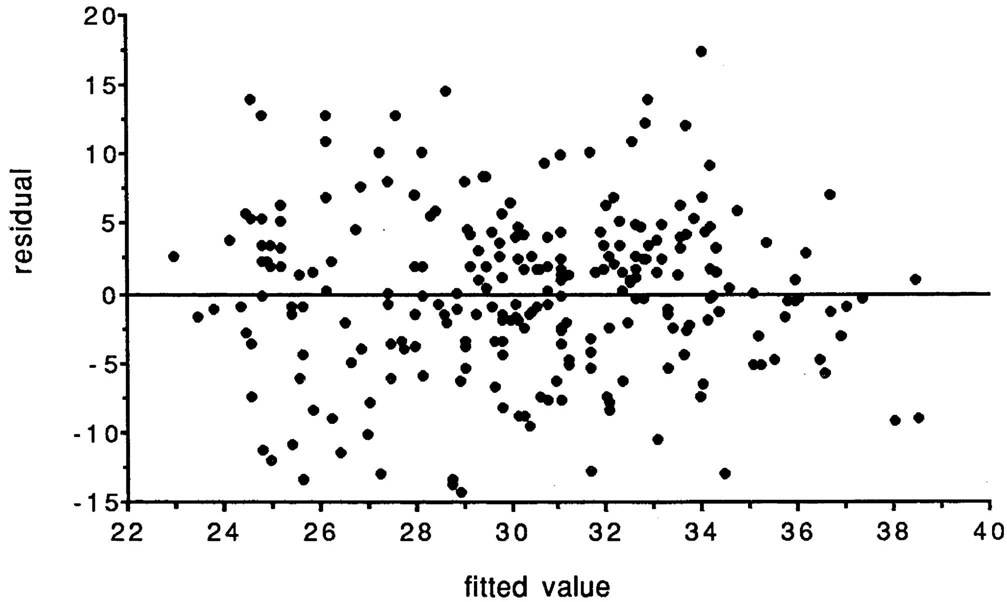
A 2nd order polynomial fitted the data better ($R^2 = 0.263$ compared with $R^2 = 0.247$ for the linear relationship) but for logs with a sedub more than 33 cm the line actually curved downwards (Figure 7.7a) so that for extrapolation to large diameter logs the model probably became unreliable. For example, conversion from a log of 33 cm sedub was predicted to be 35.7%, compared with only 31.2% from one of 45 cm sedub. Because it was necessary to extrapolate to larger logs (Section 7.6, p.92) this model was not used, as it is unlikely percentage conversion decreases with increasing sedub.

A power of sedub, with index 0.01, also fitted the data better than the non-transformed sedub measurements with the best regression being:

$$C = -1607.9 + 1589.13\ \text{sedub}^{.01} \qquad (R^2 = 0.256)$$

Unlike the polynomial, this regression continued to trend upwards as log diameter increased and probably, therefore, gave a better estimate of percentage conversion for large diameter logs (Figure 7.7b). However a plot of residuals against fitted values for this regression indicates percentage conversion from large diameter logs may be overestimated (Figure 7.8). The large saw logs in this particular sample may have returned relatively low percentage conversion as they were generally the most 'swept' of the larger diameter logs. The straighter logs larger than 25 cm sedub were mostly classified as veneer quality, and therefore not sawn for timber.

Figure 7.8 Residuals versus fitted values for the regression relating conversion to sedub$^{.01}$



7.4.2 Sweep ratio

Sweep ratio explained far less variation in percentage conversion than did sedub. The regression of conversion against sweep ratio was:

$$C = 31.86 - 14.63 \times \text{sweep ratio} \quad (R^2 = 0.034),$$

which, although explaining only 3.4 percent of variation, is significant at the 0.01 level because of the large sample size used.

7.4.3 Sedub and sweep ratio

Sedub and sweep ratio together (non-transformed) explained 29.1% of the variation in conversion, the regression being:

$$C = 15.6 + 0.764 \text{ sedub} - 16.85 \text{ sweep ratio}.$$

Thus 4.4% more variation was explained when both variables were included than was explained by sedub alone. With sweep ratio added to the regression the coefficient for sedub changed very little (from 0.746 to 0.764), indicating there was little colinearity between the two variables.

Various transformations of sweep ratio were also tried to investigate the possibility of a curvilinear relationship with percentage conversion. The distribution of sweep ratios was extremely negatively skewed, so a transformation to correct this to a normal distribution was made (power law transformation). A square root transformation did not improve the regression at all. Raising sweep ratio to the power of 1.3 gave the most, but still only slight, improvement. The previous regression became:

$$C = 15.5 + 0.758 \text{ sedub} - 24.811 \text{ sweep ratio}^{1.3} \quad (R^2 = 0.292),$$

and with transformed sedub included it changed to:

$$C = -1625.7 + 1607.7 \text{ sedub}^{.01} - 24.93 \text{ sweep ratio}^{1.3} \quad (R^2 = 0.300).$$

7.4.4 Sweep ratio, sedub and log length

With log length included the regression became:

$$\underset{(171.44)}{C = -1632.16} \underset{(166.27)}{+1610.82} \text{ sedub}^{.01} \underset{(6.198)}{- 23.640} \text{ sweep ratio}^{1.3} \underset{(0.376)}{+ 0.658} \text{ length} \qquad [7.7]$$

The standard errors (in brackets) of the individual b coefficient estimates show that those for $\text{sedub}^{.01}$ and $\text{sweep ratio}^{1.3}$ are significant at the .0001 level using Student's t test, while the coefficient for length is significant at the .05 level.[1] Overall the regression is significant at the .0001 level using an F test.

[1] Initially, Equation 7.6 was fitted using a slightly larger data set. However, two logs appeared to be outliers, with standardised residuals of 3.4 and 3.5 respectively (P<

The coefficient of determination (R^2) was 31%. Analysis of variance (ANOVA) details are given in Appendix 2.

Equation 7.7 indicates that log length was positively but weakly correlated with percentage conversion. Normally log length would have the opposite effect. It could be speculated this unusual result arose from the method used to calculate sweep ratio. Alternatively the effect may have resulted from the chipping method used to square logs at the mill before sawing. However the effect of log length was very small and the inclusion of log length in the regression made very little difference to the coefficients for sweep ratio and dbhob. Length was included in the final analysis because it made a slight improvement to the predictive power of the regression.

7.5 Use of Equation 7.7 to predict the loss of sawn volume caused by sweep

Equation 7.7 allowed the contribution of sweep to losses of sawn volume to be determined for each log. This was done by multiplying log volume by the sweep ratio term in Equation 7.7 :

$$\text{loss of sawn volume due to sweep} = \text{vub} \times 23.64 \text{ sweep ratio}^{1.3}$$

The purpose of defining the model was to estimate the loss of value recovery caused by sweep (lvr_{sw}) in each log (Section 5.3.2, p.57). For each saw log, the estimated loss of sawn volume due to sweep was multiplied by the average market price per cubic metre of timber recovered, to estimate lvr_{sw}. The results of these calculations are detailed in Chapter 8.

0.0002). These have been excluded from the final analysis. When they are included, Equation 7.6 becomes:

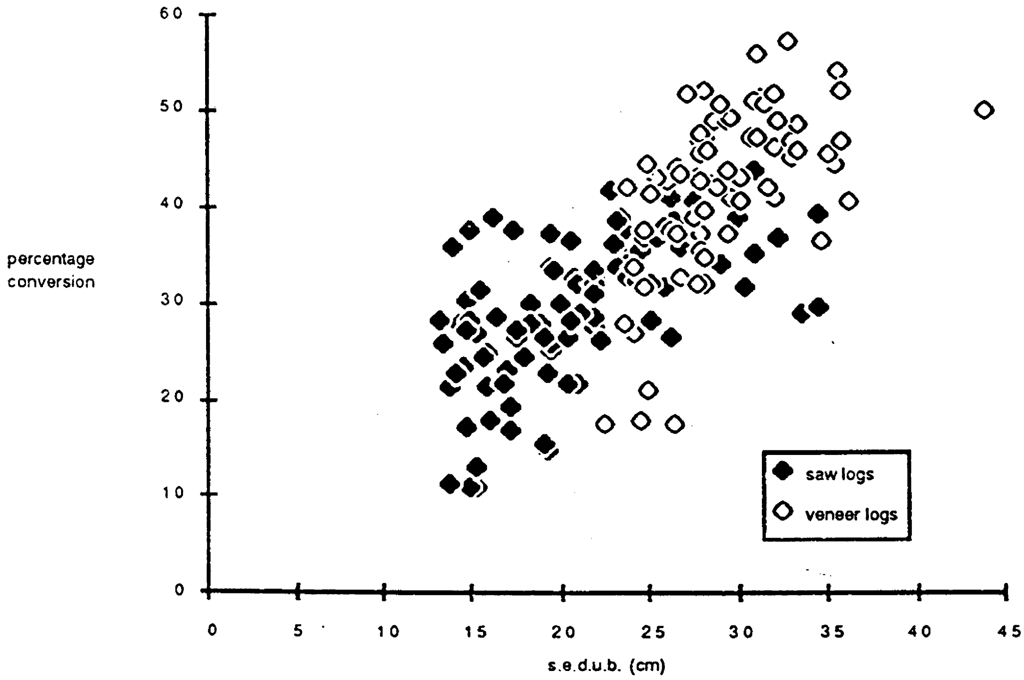
$$C = -1663.9 + 1640.7 \text{ sedub}^{.01} - 22.10 \text{ sweep ratio}^{1.3} + 0.80 \text{ length.}$$

7.6 Use of Equation 7.7 to estimate the loss of conversion caused by bends in veneer logs

The original aim had been to repeat the regression analysis using the veneer recovery data and so find an equation for predicting the effect of sweep on percentage conversion from the veneer logs. The intention was to use the equation to estimate loss of veneer recovery caused by bends in the same way as Equation 7.7 was employed for estimating loss of recovery from saw logs. In the end, it was decided not to use a separate predictive equation for veneer recovery. Instead percentage conversion and subsequently lvr_{sw} from each of the 70 veneer logs in the study was predicted using Equation 7.7 assuming they were not peeled for veneer but sawn for timber. This decision was taken for the following reasons:

(i) Log classification was partly controlled at the stump by the subjective decisions of several different observers acting independently. Therefore, differences in value recovery between trees may have been partly influenced by personal biases rather than real differences in the suitability of logs for conversion to particular products. The two milling studies indicate that logs more than about 28.0 cm sedub, returned a much higher percentage conversion if peeled rather than sawn, as illustrated by Figure 7.9. Thus trees from which one or more logs were processed for veneer generally returned a greater volume of product than similar sized trees from which all logs were sawn. As a consequence, differences in tree value may not always have been caused by differences in stem straightness, branch diameter or stem size.

Figure 7.9 Conversion versus sedub for all logs (saw and veneer) processed during the mill study



(ii) It was difficult to compare value recovery from veneer logs and saw logs. During the veneer recovery study only the quantities and grades of individual veneer sheets were tallied. Normally veneer sheets are not sold singly but glued and pressed together to make plywood. Since the grade of plywood is determined only by the two face sheets, a grade reducing defect in a single sheet does not necessarily mean reduction in plywood value, since the 'defective' sheet can be incorporated into the middle of the plywood. Therefore, it is difficult to value a single veneer sheet in a way comparable to valuing a single piece of sawn timber.

(iii) It was difficult to estimate precisely the influence of sweep on percentage conversion from veneer logs because the sample size was smaller and the range of variation of sweep among the veneer logs was less than among the saw logs. Further, each veneer log was cross cut into two x 2.6 metre bolts with no opportunity to measure sweep in each bolt before peeling.

The resultant bolts effectively contained far less sweep than the original logs so that sweep may have had very little effect.

Regression equations were fitted using the percentage conversion, sedub and sweep ratio data from the 70 veneer logs. The best fitting regression was:

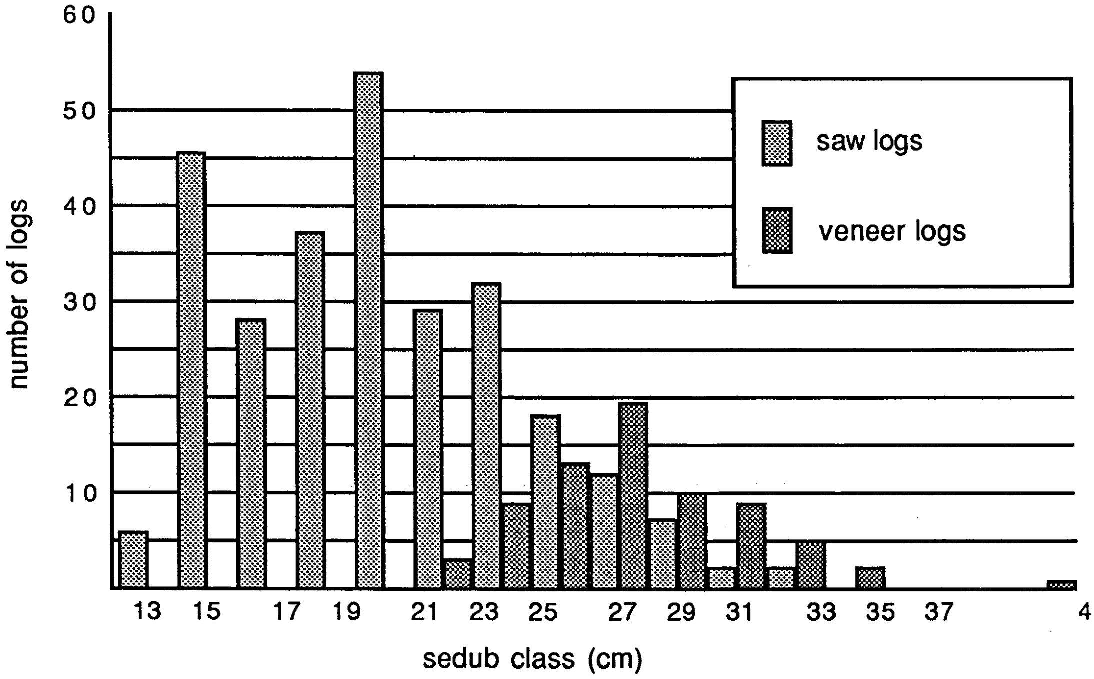
$$C = \underset{(2.09)}{33.54} + \underset{(0.805)}{4.703}\sqrt{\text{sedub}-23.6} - \underset{(8.483)}{9.271}\ \text{sweep ratio} \quad (R^2 = .351). \qquad [7.8]$$

The sweep ratio term in this regression did not differ significantly from zero and only explained 1.2% of variation in percentage conversion.

The method described in Section 7.5 to estimate the loss of conversion caused by bends and subsequently lvr_{sw} has also been used for the 70 veneer logs, assuming they had been sawn for timber instead. The results are detailed in Chapter 8. The sweep ratios of the veneer logs were well within the range of sweep ratios of the saw logs used to derive Equation 7.7. The sweep ratio term in this equation is assumed to be an unbiased predictor of the loss of conversion caused by sweep that would have occurred had the 70 veneer logs been sawn.

The sedub's of the veneer logs were mostly in the range of sedub's covered by the saw log data set (Figure 7.10). However a few were larger than any of the saw logs and therefore the prediction of 'sawn conversion' from the veneer logs required some extrapolation beyond the range of the data used to find Equation 7.7. As noted in Section 7.4.1 (p.88), the regression line probably overestimated percentage conversion from large diameter logs.

Figure 7.10 Saw log and veneer log small end diameters



7.7 Tests of the validity of the model

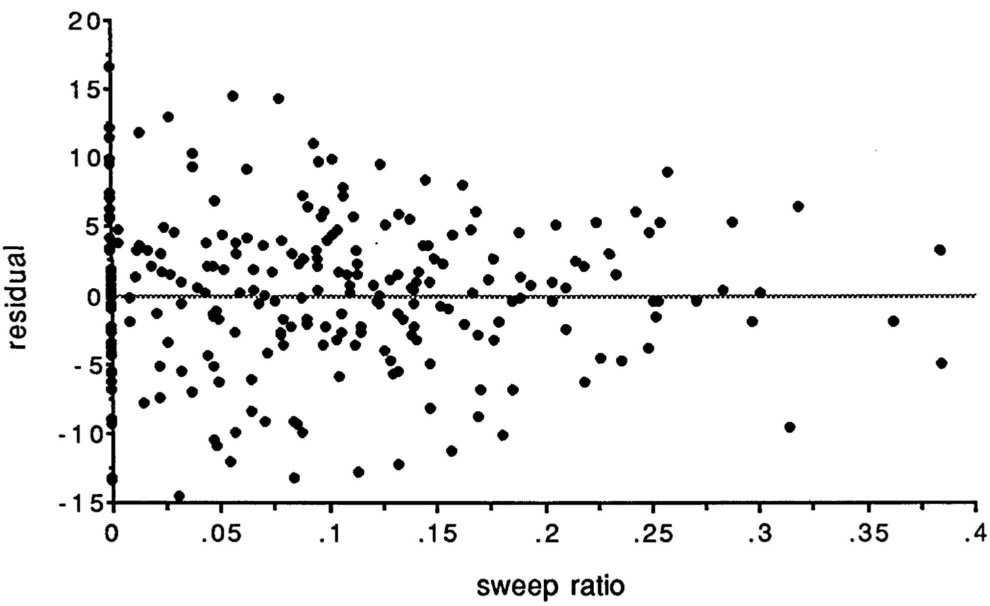
7.7.1 The accuracy of predicted percentage conversion from straight logs and very 'swept' logs

Because the model was used to make predictions about the effect of sweep on conversion from individual logs within the data set, it was important that it gave an unbiased estimate of the effect of sweep. To test the regression, the residuals, after predicting conversion using the model, were calculated for the 47 sawlogs with no sweep and 31 sawlogs with severe sweep (sweep ratio 0.2 or more). For the straight logs the mean residual was -0.1% (25 residuals being negative and 22 positive), while for 'swept' logs the mean residual was 0.5% (14 negative and 17 positive). Thus, predicted percentage conversion appeared to be an unbiased estimate.

7.7.2 Heteroscedasticity in the relationship between percentage conversion and sweep ratio

A plot of the residuals, after evaluation of Equation 7.7, against sweep ratio (Figure 7.11) indicated the possibility of heteroscedacity in the model, that is, variance of the residuals appeared to decrease as sweep ratio increased. It is difficult to explain why this occurred. One reason might lie in the method used by the mill to select sawing pattern. For any log and desired mix of timber sizes there is an optimum sawing pattern, which is determined by log diameter (Whiteside 1982).

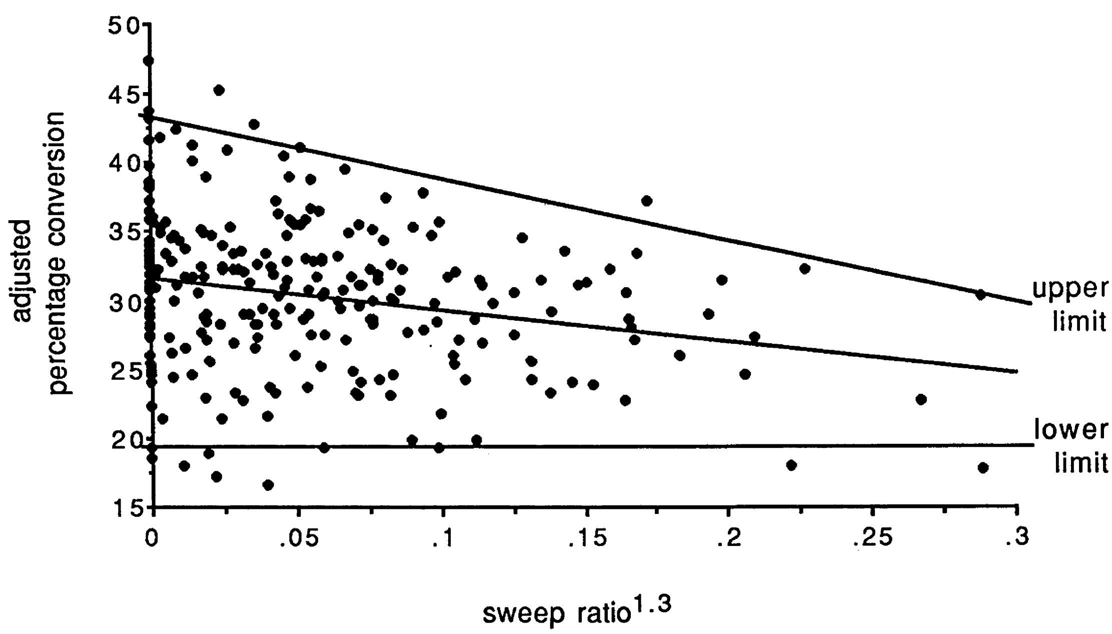
Figure 7.11 A plot of sweep ratio against the residuals from Equation 7.7



If all logs had been sawn to the optimum pattern, average percentage conversion would have been maximised. If, however, logs had not been sawn to the optimum pattern, average percentage conversion would have been reduced.

In technologically advanced mills each log is scanned by a computer, which determines the optimum sawing pattern. Alternatively logs can be sorted into diameter classes and each class sawn separately, using the optimum pattern for that class. At the time the study was conducted the mill involved did not use either method. Logs of all sizes were mixed together and entered the mill in random order. The sawyer had to make an immediate decision as to sawing pattern, and it is possible some logs were not sawn in the optimum way. For some, the pattern may have been far from optimum, resulting in very low conversion.

Figure 7.12 Percentage conversion adjusted to remove the effect of sedub and plotted against sweep ratio$^{1.3}$



Poor choice of sawing pattern may have been equally likely for straight and 'swept' logs. In such cases conversion may not have been limited by sweep ratio but by sawing pattern. Other logs will have been sawn to their optimum pattern, in which case conversion will have been limited by sweep ratio. Figure 7.12 supports this hypothesis. To prepare the figure, conversion was adjusted to remove the effect of variation in sedub, using the slope coefficient from the simplest regression equation (Equation 7.6) of Section 7.4.1 (p.85). For each log the sedub was subtracted from the mean sedub of all the saw logs and the result multiplied by 0.746. Percentage conversion was adjusted by adding this value to the observed percentage conversion. Figure 7.12 shows the adjusted values plotted against sweep $\text{ratio}^{1.3}$. For all sweep ratios the lower limit of the distribution of adjusted percentage conversion was about 18%, as indicated by the lower line in Figure 7.12. The upper limit (perhaps the logs sawn to optimum pattern) was about 45% for logs with no sweep but only 30% for the most 'swept' logs (as indicated by the upper line in the figure). In mills sawing to optimum pattern, the slope of the relationship between conversion and sweep ratio may be closer to that of the upper line.

Brown and Miller (1975) used a sawing pattern aimed at achieving maximum conversion from all logs sawn in their study. They found for logs with sweep ratio larger than about 0.2, sweep ratio had a greater influence on percentage conversion than it did in the present study. For example, for a non-tapered log, Brown and Millers' best regression predicts that sweep causes losses in conversion of 1.0, 3.0 and 6.1% respectively from logs with sweep ratios of 0.10, 0.20 and 0.30. By comparison, Equation 7.7 predicts losses of 1.2, 2.9 and 4.9% from non-tapered logs with these sweep ratios.

7.7.3 Predicted versus actual volume recovery from forty one stems that produced saw logs only

Forty-one trees felled during the study produced only saw logs. For these the volume of sawn timber actually obtained was subtracted from the sawn volume recovery predicted using Equation 7.7. The resulting residuals had a mean of 0.0039 m^3 per stem, or 1.6% of total volume recovered (23 positive residuals and 18 negative). The regression between actual and predicted sawn volume was:

$$\text{actual volume} = -0.0047 + 0.966 \times \text{predicted volume} \quad (R^2 = 0.966).$$

The size and sign of the residuals did not appear to be related to tree size. It appeared the regression model gave an unbiased estimation of the total volume of sawn timber that could be obtained from the stems from which the study logs were derived.

7.8 Further discussion

Although less than one third of the variation in percentage conversion per saw log was explained by the log variables measured in the study, a significant relationship between sweep and sawn conversion was found when the influence of sedub was taken into account. The main reason for quantifying this relationship was to provide a means of estimating lvr_{sw}. To this end, a predictive equation was found that gave an unbiased estimate of the effect of sweep on percentage conversion from the logs sawn in the study.

The model may not be applicable to all sawmills. Many of the variables that influence sawn timber conversion, including mill type, sawing pattern and milling standards (kerf width and overcut allowance), were not measured. It might be expected that for different mills, patterns and standards, the relationship between percentage conversion and sweep would also differ. At the mill used for this study a large amount of variation could have been caused by operator judgement (Section 7.7.2, p.97). This mill is now less reliant on operator judgement than at the time of the study for several reasons, including: the sorting of logs into diameter classes before processing instead of sawing all sizes in random order, and sawing each diameter class according to a largely predetermined sawing pattern. Thus the regression equations fitted to the data may no longer give an unbiased prediction of conversion at the 'new' mill. However, the effect of sweep on conversion probably does not differ greatly among mills. Results from an earlier study by Brown and Miller (1975) differed only slightly from the results in the present study, especially for sweep ratios less than about 0.2. In modern saw mills employing computer scanning, the effect of sweep is probably greater than reported here, since all logs can be sawn in the optimum pattern, and substantial losses of potential recovery resulting from operator's errors in judgment rather than sweep are avoided.

Chapter Eight

CALCULATION OF ECONOMIC WEIGHTS FOR STEM STRAIGHTNESS AND DBHOB

8.1 Introduction

The previous chapter described the estimation of the loss of value recovery caused by sweep (lvr_{sw}) in saw logs. This chapter describes the calculation of lvr_{sw} from stems and details the calculation of economic weights for stem straightness using analyses of the relationships between lvr_{sw} and subjective stem straightness scores. The calculation of economic weights for dbhob, measured at three ages is also detailed. The techniques used for the calculation of economic weights were outlined in Chapter 5.

8.2 Estimation of the loss of value recovery caused by sweep

8.2.1 lvr_{sw} from logs

To calculate the lvr_{sw} from each log (saw logs and veneer logs) the loss of percentage conversion caused by sweep was first estimated by Equation 7.7 (p.90). This estimate was multiplied by the log's vub to calculate the loss of sawn volume recovery caused by sweep.

To convert to value recovery an estimate of the market price of timber sold from the mill, in dollars per cubic metre of timber, was needed. Since it was desirable to avoid variation in value recovery caused by parameters other than sweep, such as branch diameter, the average market price of all the timber recovered in the study was used ($408 per cubic metre) in the calculation. The influence of branches on value recovery was undertaken as a separate analysis (Chapter 10).

To summarise then, lvr_{sw} was calculated as follows:

[1] loss of conversion caused by sweep = $23.64 \times$ sweep ratio$^{1.3}$
(from Equation 7.7, Chapter 7)

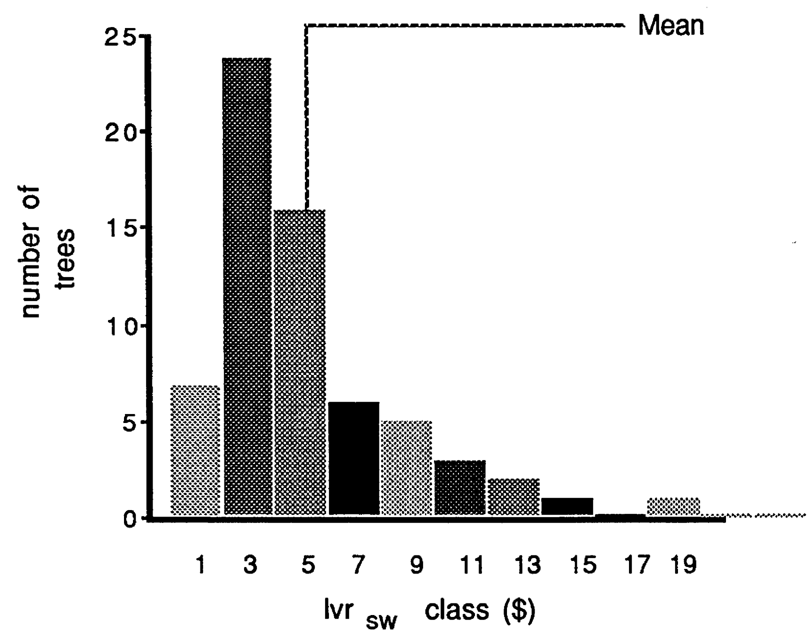
[2] loss of sawn volume caused by sweep = [1] $\times$ vub;

[3] lvr_{sw} = [2] $\times$ \$408 (the average market price of timber in the study, \$ per cubic metre, 1986 prices)

8.2.2 Estimates of lvr_{sw} from the stems felled in PT3

The lvr_{sw} from each tree was calculated by summing the estimates for all logs from that tree. The frequency histogram of lvr_{sw} estimates for the 65 trees felled in PT3 is shown in Figure 8.1. The numbers on the X-axis in the figure are the midpoints of class intervals 2 units (\$) in width. The lvr_{sw} ranged from zero to \$19 per stem. Mostly it was less than \$10 per stem, averaging \$5.17. The lvr_{sw} data from the 20 trees of routine stock felled from the plantation adjacent to PT3 are not shown because these trees were not considered in subsequent analyses as straightness had not been subjectively assessed on them in the past. The lvr_{sw} estimates were in the same range as for PT3 trees (mean \$6.04, range 0 to \$15.85).

Figure 8.1 Frequency distribution of the estimates of lvr_{sw} from the 65 trees felled in PT3



8.3 Relationship between lvr_{sw} and subjective scores for stem straightness

8.3.1 Linear relationships between lvr_{sw} and the stem straightness scores for the five sets of assessments

The lvr_{sw} estimates were used to relate the economic importance of stem straightness to subjective ratings of the trait. As discussed in Chapters 2 and 5, the economic importance of a trait is determined by the change in net worth per stem corresponding to a unit change in the assessed trait score. Chapter 5 outlined a procedure for calculating the relative economic importance of traits. An economic weight for stem straightness is given by β_{1ss}, the slope of a regression line quantifying the relationship between lvr_{sw} and stem straightness score.

The lvr_{sw} was plotted against stem straightness score for each of the five occasions when this trait was assessed on the 65 trees felled in PT3 (Figures 8.2 to 8.6). The mean of the three age 34 scores was calculated for each tree and this value also plotted against lvr_{sw} (Figure 8.7).

The least squares regression lines are drawn on each figure and the statistics detailed in Table 8.1. The slope coefficients in the table estimate the increment in value recovery per stem in dollars, corresponding to a one point increment in straightness score. These coefficients represent crude economic weights for stem straightness. However, these were not accepted as the final weights as it was subsequently found (Section 8.3.2) that stem vub also influenced the relationship.

Figure 8.2 Relationship between stem straightness score at age 16 and lvr_{sw}

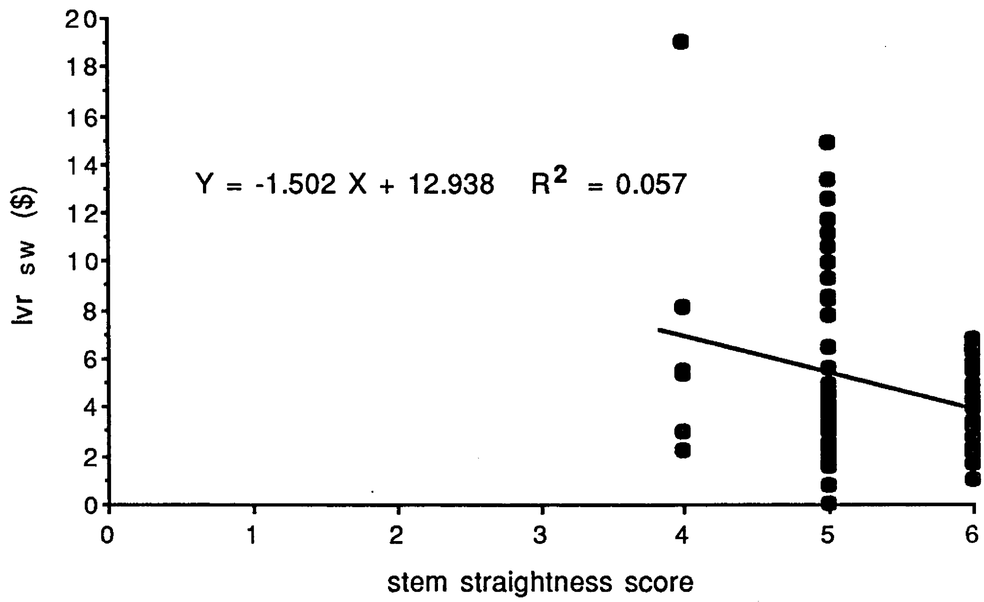


Figure 8.3 Relationship between stem straightness score at age 25 and lvr_{sw}

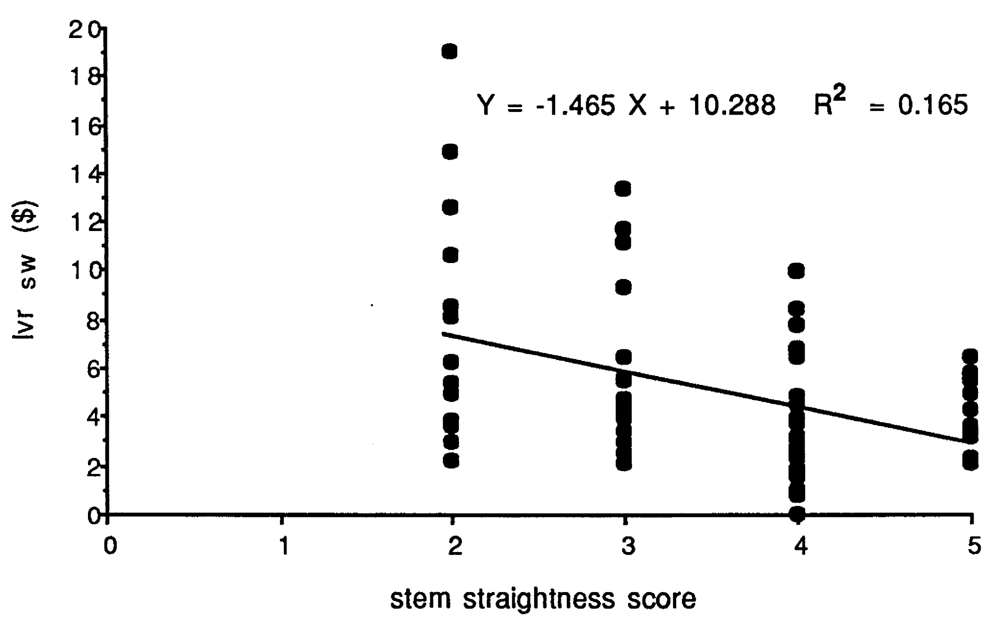


Figure 8.4 Relationship between first stem straightness score at age 34 and lvr_{sw}

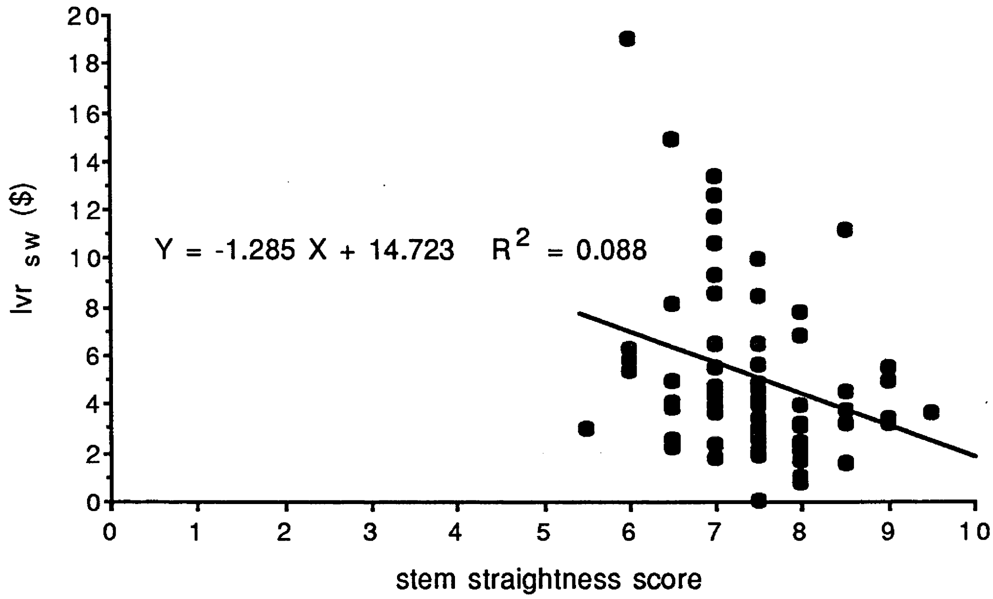


Figure 8.5 Relationship between second stem straightness score at age 34 and lvr_{sw}

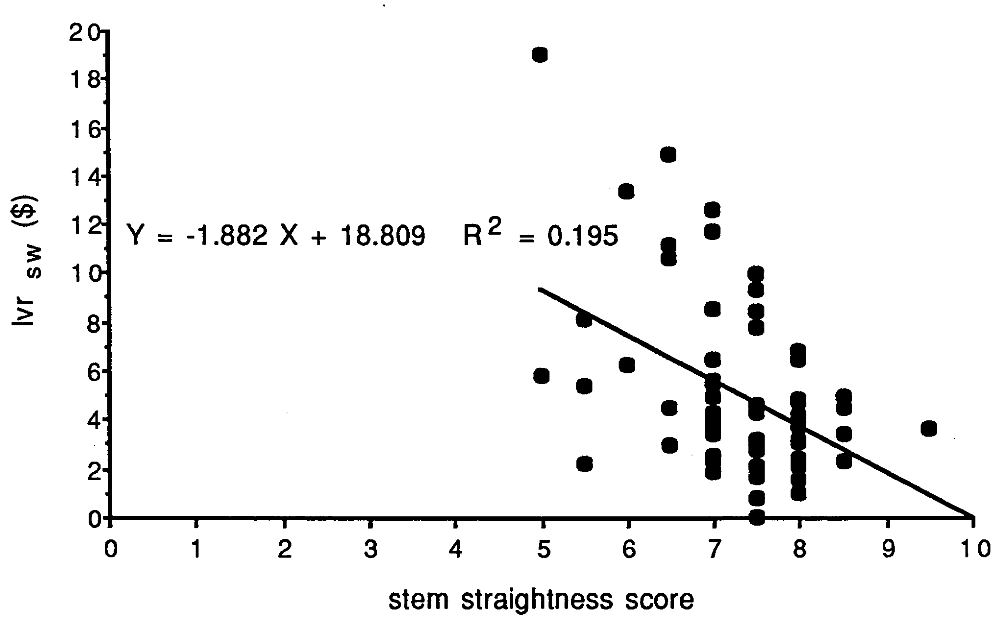


Figure 8.6 Relationship between third stem straightness score at age 34 and lvr_{sw}

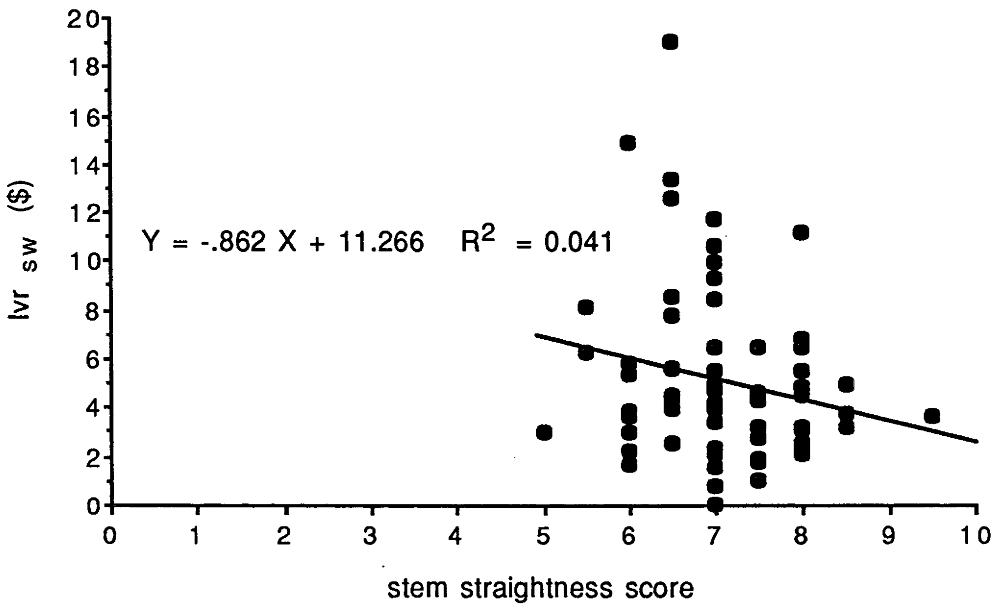


Figure 8.7 Relationship between the mean of the three stem straightness scores at age 34 and lvr_{sw}

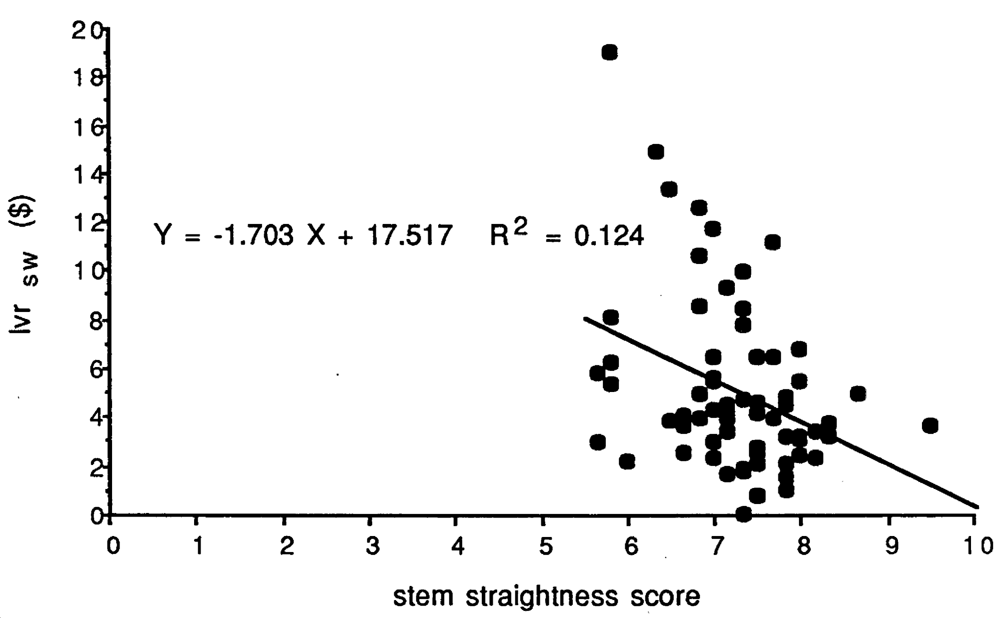


Table 8.1 Least squares regression equations relating lvr_{sw} to each of the 5 straightness scores and to the mean age 34 score, using data from the 65 trees felled within PT3

Assessment	Y-intercept	Slope coefficient (β_{1ss})	(Standard error)	R^2
1. age 16	12.94	-1.50	(0.77)	0.057
2. age 25	10.29	-1.47	(0.42)	0.165**
3. age 34(1st)	14.72	-1.29	(0.52)	0.088*
4. age 34(2nd)	18.81	-1.88	(0.48)	0.195**
5. age 34(3rd)	11.27	-0.86	(0.53)	0.041
6. mean of the age 34 scores	17.52	-1.70	(0.57)	0.124**

* = significant at the 0.05 level
** = significant at the 0.01 level

8.3.2 The effect of stem vub on the relationships

A plot of stem vub against lvr_{sw} indicated a significant correlation. The regression equation for the relationship was:

$$lvr_{sw} = 2.12 + 2.93 \times vub.$$

Although only explaining 9% of the variation in lvr_{sw}, the regression was significant at the 0.05 level.

A multiple regression analysis was carried out to determine whether stem vub at harvest age affected the estimate of economic weights for stem straightness. Regressions using lvr_{sw} as the dependent variable and stem straightness score, stem vub at age 34 and stem straightness score $\times$ stem vub as independent variables, were tried. The best regressions are listed in Table 8.2.

With stem straightness scores and stem vub both included as independent X-variables in the regression equations the amount of variation in lvr_{sw} explained increased significantly (Table 8.2).

Table 8.2 Multiple regression equation relating lvr_{sw} to stem vub and each subjective straightness assessment

Assessment	Y-intercept	Slope coefficient for stem vub	Slope coefficient for vub × score	R^2
age 16	2.43	10.50 (3.66)	-1.51 (0.71)	0.138*
age 25	2.17	8.61 (1.57)	-1.65 (0.35)	0.245**
age 34(1)	1.16	16.33 (3.55)	-1.66 (0.42)	0.237**
age 34(2)	2.07	18.17 (3.00)	-2.09 (0.39)	0.316***
age 34(3)	2.12	9.26 (3.60)	-0.89 (0.49)	0.131*
mean age 34	1.72	18.41 (3.75)	-2.04 (0.48)	0.248**

N.B. Figures in brackets are the standard errors of the estimates
* = significant at the 0.05 level
** = significant at the 0.01 level
*** = significant at the 0.001 level

8.4 The economic weights for stem straightness

In Section 5.3 (p.57) it was shown that the economic weight for stem straightness is approximately equal to $\beta 1_{ss,}$ that is, the economic importance of a one point change in the stem straightness score is measured by the slope coefficient of the regression of lvr_{sw} against straightness score. In the best regressions relating lvr_{sw} to stem straightness score and vub there was a significant interaction between score and vub (Table 8.2). This indicated the economic weight for stem straightness was dependent on the size of the stems when they were felled. In PT3, the average stem size at harvest was 1.04 m^3. If this value is substituted into the regressions in Table 8.2, the resulting equations give the relationships between lvr_{sw} and stem straightness score for stems of average size in PT3. These were:

age 16 $\quad lvr_{SW} = 13.35 - 1.57 \times \text{score}$ [8.1]

age 25 $\quad lvr_{SW} = 11.12 - 1.72 \times \text{score}$ [8.2]

observer 1	age 34[1]	$lvr_{sw} = 18.14 - 1.73 \times score$	[8.3]
observer 1	age 34 [2]	$lvr_{sw} = 20.97 - 2.17 \times score$	[8.4]
observer 2	age 34	$lvr_{sw} = 11.75 - 0.93 \times score$	[8.5]

Note: 1 and 2 indicate first and second observations by Observer 1.

The economic weights for stem straightness were given by the slope coefficients in these equations. The economic weights were thus:

	age 16	$ 1.57 per point
	age 25	$ 1.72 per point
observer 1	age 34[1]	$ 1.73 per point
observer 1	age 34[2]	$ 2.17 per point
observer 2	age 34	$ 0.93 per point

Note: 1 and 2 indicate first and second observation by Observer 1.

8.5 Calculation of economic weights for dbhob

8.5.1 Calculation of value recovery from stems

To estimate the economic weight for dbhob, the relationship between value recovery and dbhob was investigated.

Value recovery was estimated by the following steps (it was not the actual value recovery for each stem because, as noted in Section 7.6 (p.92), total value recovery was not measured for stems from which at least one log was processed into veneer):

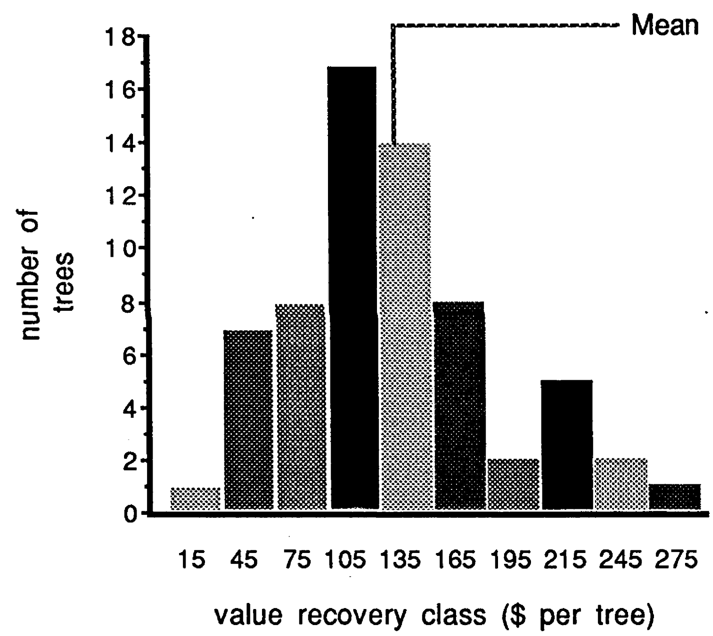
(1) For individual logs (saw logs and veneer logs) Equation 7.7 was used to estimate percentage conversion

(2) This estimate was multiplied by the log's vub to give sawn volume recovery.

(3) Sawn recovery was multiplied by the average market value for timber in the study ($ 408 per cubic metre) to give value recovery. For each tree value recovery was summed for all logs.

Value recovery per stem ranged from $29 to $291, averaging $128. The frequency histogram is shown in Figure 8.8 The values on the X-axis represent the mid points of classes 30 units ($) wide.

Figure 8.8 Frequency distribution of the estimates of value recovery from the 65 trees felled in PT3



8.5.2 The relationship between value recovery at age 34 and dbhob at ages 13, 25 and 34

For each dbhob assessment (at ages 13, 25 and 34) a regression line was fitted relating stem value recovery to dbhob. The regressions are detailed in Table 8.3. Figure 8.9 shows the plot of value recovery against dbhob at age 34 for the trees felled in the study. The slopes of the regression lines represent

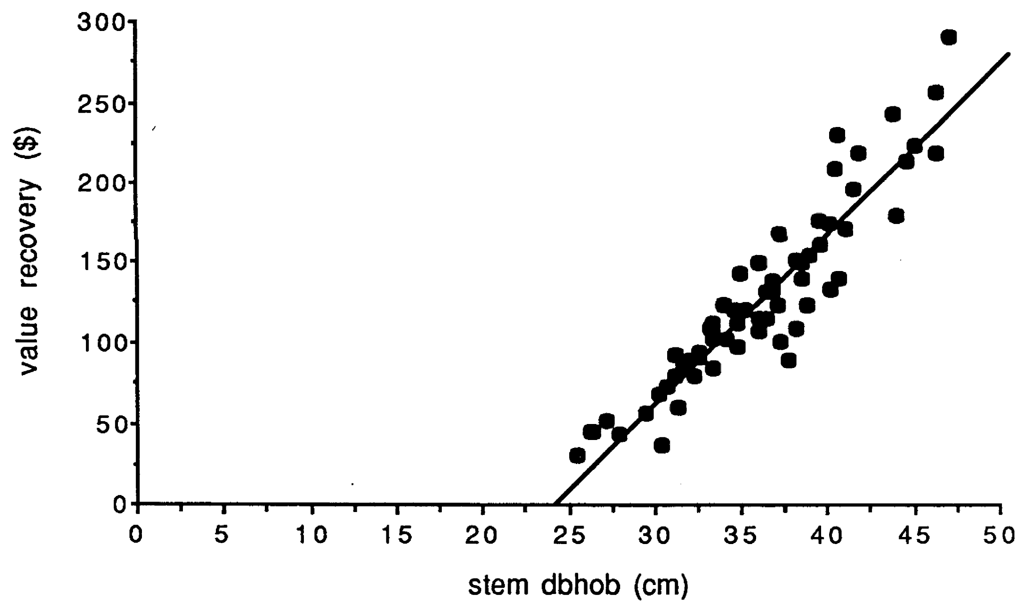
β_1, the increment in value recovery per stem corresponding to a 1 cm increment in dbhob per stem (Section 5.2, p.52).

Table 8.3 Least squares regression equations relating lvr_{sw} to each of the three assessments of dbhob

Assessment	Y-intercept	Slope coefficient (β_{1ss})	(Standard error)	R^2
1. age 16	-150.79	15.71	(1.97)	0.501***
2. age 25	-199.12	11.63	(0.76)	0.787***
3. age 34	-249.89	10.44	(0.68)	0.864***

*** = significant at the 0.0001 level

Figure 8.9 Relationship between value recovery and dbhob at age 34 for the 65 stems felled in PT3



8.5.3 The economic weights for dbhob

In Section 5.2 (p.54) the economic weight for dbhob was estimated to be $0.164 \times \beta_1$. Thus, from the regressions in Table 8.3, the economic weights for dbhob were:

age 13	$2.58 per cm
age 25	$1.91 per cm
age 34	$1.71 per cm

In other words, a 1 cm improvement in the average dbhob at age 34, for example, had a net economic worth of $1.71 per stem. The relative worth of such an improvement in relation to other traits is investigated in Chapter 12.

8.6 Discussion

8.6.1 Evaluation of the potential economic gain achievable in PT3 by improving stem straightness

The estimates of the lvr_{sw} per stem were used to gauge the maximum potential percentage improvement in plantation worth achievable through the improvement of stem straightness at the site on which PT3 was planted. Expressed as a percentage of total value recovery, on an individual tree basis, lvr_{sw} ranged up to 22%, but was mostly less than 10%. Expressed on a stand basis, total lvr_{sw} summed for all stems felled in PT3, the overall lvr_{sw} from all trees amounted to an estimated 4.1% of the total value recovery. In other words, had none of the stems felled in PT3 contained bends, it is estimated total value recovery would have been 4.1% greater.

8.6.2 Validity of the economic weights for stem straightness

In calculating the economic weights for stem straightness, a one point change in stem straightness score was assumed to have no effect on costs (Section 5.3.3,p.58). As discussed in Chapter 4, serious bends in stems may increase harvesting costs. However, since the stems felled in PT3 were all reasonably straight, a one point difference in straightness between stems probably had very little influence on harvesting costs, given that most of the stem processing was done by machine. Certainly in relation to the effect of a 1 point increment in straightness on value recovery, the effect on costs was probably negligible.

Further, no detailed analysis of the effects of sweep on product quality was undertaken. As discussed in Section 4.2.2, it is possible sweep is associated with sloping grain and wandering pith in sawn timber. This would lead to down grading of structural timber with consequent reduction in value recovery if a premium were paid for higher grades.

It was also noted in Section 5.3.3 (p.58) that sweep in saw logs may have influenced processing costs. However the overall effect of sweep on the costs of processing was assumed to be negligible.

8.6.3 Reasons why much of the variation in lvr_{sw} was unexplained by the regressions

Much of the estimated lvr_{sw} could not be explained by variation in straightness scores or stem volume. When the effect of stem vub was taken into account, the 'best' linear equation accounted for only 32% of total variation in lvr_{sw}. It was not possible to determine whether this large unexplained variation resulted from poor observer judgement of stem straightness or whether it was caused by uncontrolled influences such as the limited variation in stem straightness within the sample, chance variation in the location of bends within stems or variation in the amount of sweep in butt logs.

8.6.3.a Poor observer judgement of stem straightness

It may have been possible that subjective scores were not a good method for assessing stem straightness. Alternatively the assessment scales themselves may have been suitable but the observers may have applied them incorrectly. It is obvious by comparing the different scatter plots in Figures 8.2 to 8.6 and the regression equations in Table 8.1, that observer judgement of stem straightness varied, so there were at least some differences in observers' ability to judge stems.

8.6.3.b The limited range of variation in stem straightness

The regression relationships in Tables 8.1 and 8.2 were based on a small sample (65 stems). The absolute variation in lvr_{sw} and in the straightness scores was not large. Most of the age 34 scores were in the range $6^1/_2$ to $8^1/_2$ points out of 10. There were fewer data for trees rated subjectively as very straight (a score $8^1/_2$ or more) or very crooked (a score of 6 or less). For this reason it was impossible to determine whether a linear or curvilinear relationship was appropriate over a wider range of scores.

8.6.3.c Location of bends in relation to crosscuts

Some unexplained variation probably arose because of chance location of bends in relation to crosscut positions in each stem. In determining the lengths of logs from each stem a deliberate attempt was made to cut to best advantage. In some stems, the effect of a sharp bend was substantially reduced by placing a crosscut at the apex of the bend. Saw log length varied between 3.65 and 6.10 metres, enabling reduction of sweep and therefore minimisation of the influence of bends on recovery.

Using the definition of sweep as contained in Chapter 4 (p.39) it takes only a slight bend to create a moderate sweep in a long log, while it takes a much sharper bend to cause a similar sweep in a short log. Further, a bend causes more sweep if it is centred towards the middle of a log rather than near one end. The 'straightest' tree in PT3 scored $9^1/_2$ points in all three assessments at age 34, yet estimated lvr_{sw} from it was higher than from 20 other stems. After felling it was found that this tree had one slight bend in the butt, about 2.6 metres up the stem, and another slight bend towards the top of the merchantable stem, with a perfectly straight 20 metre length in between. After crosscutting of the stem, the slight bend in the butt was in the middle of a 5.2 metre log and resulted in gross sweep of 4 cm., and an estimated reduction in sawn value recovery of $1.67. Two straight 6.1 metre logs were cut from the middle of the stem. The top log was also cut to 6.1 metres length. The slight bend in it also caused a gross sweep of 4 cm, which reduced sawn value recovery by an estimated $2.04. Thus, even though the stem was almost perfectly straight, estimated total lvr_{sw} was $3.71, because it contained two slight bends positioned towards the middle of two long logs.

It was concluded that estimates of lvr_{sw} were not always highest from the most crooked looking stems. Chance variation in the position of bends within stems may have caused variation in lvr_{sw}. Several single sharp bends spaced at 4 to 6 metre intervals in the stem probably caused less loss than a greater number of closely spaced, but less severe bends or two or three closely spaced sharp bends.

It was not possible to determine the effectiveness of crosscutting in ameliorating the influence of bends, since sweep was measured after crosscutting and bends eliminated by crosscutting were not measured. Therefore it was not possible to determine to what degree unexplained variation in lvr_{sw} reflected poor observer judgement of stem straightness, compared with the influence of variation in the position of bends in relation to the crosscuts.

8.6.3.d Sweep in the butt logs

Sweep in butt logs consistently caused the greatest lvr_{sw}. Because the minimum log length was 3.65 metres, any sharp bends in the first 3.65 metres of a stem could not be removed by crosscutting.

Furthermore, the butt logs were the largest and, therefore, the most valuable. Thus a given reduction in percentage conversion equated with a much larger lvr_{sw} than a similar loss of percentage conversion from a log high in the stem. The precise location of the centre of a bend had a great influence on value recovery. In this study, sharp bends were eliminated if they occurred above the 3.65 metre point by crosscutting at the bend. Two trees may have had similar looking bends in the butt. If the bend in one tree was at 1.5 metres and that in the other at 3.65 m, a 3.65 metre butt log from the second tree was almost straight, while the same sized log from the first tree contained sweep.

8.7 Summary

The sweep ratio term in Equation 7.7 (Chapter 7, p.90) was used to estimate the loss of value recovery caused by sweep in the 65 stems felled in PT3. The lvr_{sw} estimates were plotted against the subjective stem straightness scores for each of the 65 trees. Stem vub had a small influence on the relationship. With this taken into account by regression, the economic weight for stem straightness at each scoring occasion was equal to the slope coefficient (unsigned) for the straightness score term in the regression. According to the 'best' assessment of stem straightness at age 34, a one point improvement in stem straightness between two stems of average size (for this study) gave an increase in value of $2.15 (using a 10 point stem straightness scale).

Much of the variation in lvr_{sw} could not be explained by the subjective scores or stem size. Sources of unexplained variation may have been poor judgement by the observers, the limited absolute range in stem straightness, or chance location of bends in relation to crosscutting positions.

Chapter Nine

A STUDY OF THE STRAIGHTNESS OF *PINUS TAEDA* STEMS

9.1 Introduction

A supplementary study was undertaken to provide further data relating subjective stem straightness scores to the number and severity of bends measured in felled stems. A high proportion of nearly straight stems was included in the sample to determine whether the presence of one or two slight bends in stems caused significant lvr_{sw}. It is rare to find straight, or even nearly straight *P.radiata* stems in plantations of unimproved stock. *P.taeda* stems, however, are generally straighter. To find an adequate quantity of nearly straight stems in a forest of clear felling age the study was conducted in a 50 year old *P.taeda* plantation at Beerburrum, Queensland.

The procedure was designed to enable measurement of all bends in the felled stems rather than only those remaining after crosscutting, as was done in the *P.radiata* study (Section 6.3, p.66). To determine the influence the positioning of crosscuts had on recovery, bends and log dimensions were measured assuming both fixed and variable log lengths.

9.2 Procedure

As with the *P.radiata* study, stem straightness was scored visually among a group of stems scheduled for felling. Once the stems were felled, but before they were crosscut, detailed measurements of sweep in each stem were made. Equation 7.7 was used as detailed in Section 7.5, p.91, to estimate the loss of percentage conversion caused by sweep in logs, enabling calculation of lvr_{sw} for each stem. As for the *P.radiata* study, regression analysis was used to investigate the relationship between lvr_{sw} and the subjective straightness scores.

9.2.1 Data collected

Eighty trees, meeting the straightness criteria, were chosen in a compartment undergoing clear felling. Trees were deliberately selected having straightness in the range 7 to 9 points out of 10, with a few 6's. The trees were of similar height to those felled in PT3, with a larger average dbhob, due to the absence of suppressed trees removed in previous thinnings (dbhob of the 80 trees ranged from 30.2 to 47.7 cm with a mean of 38.2 cm). The boles were clear of branches up to about 20 metres above ground level, making the visual rating of stem straightness easier than in PT3.

Before felling took place the trees were scored subjectively on a ten point scale similar to that used in PT3. The bend frequency and severity criteria however, were more precise than in the *P.radiata* study (Table 9.1). In reality, the stem straightness ratings in both studies were probably similar.

After felling, each stem was docked at the point where crown break occurred. Unlike *P.radiata* , mature *P.taeda* has a break in the crown towards the top of the stem above which there is little merchantable bole wood. For the trees in this study this point corresponded with an under bark stem diameter of about 20 cm, and a height above ground level of between 15 and 25 metres.

Table 9.1 Subjective scale used to score stem straightness in the *P. taeda* study

Score	Stem description
10	Straight - no bends
9	One or two slight bends
8	Three or four slight bends
7	More than four slight bends. One serious bend also permitted if it was higher then 10 metres up the stem
6	At least one serious bend in the lower 10 metres of stem

A serious bend was one that would cause a sweep of 10 cm or more if it were at the middle of a 5 metre log.

After docking, each stem was snigged in a single length to a flat landing and total merchantable length measured. Each stem was divided theoretically into logs using two different systems:

(1) All logs, except the top log, being 5 metres long;

(2) Log length varying between 3.65 and 6.10 metres and cut to advantage, as in the *P.radiata* study

Sweep ratio for each (notional) log was calculated using Equation 7.5 (Chapter 7, p.83).

Stem diameter over bark was measured at 5 metre intervals along the stem. The measurement points corresponded with the theoretical crosscuts for the 5 metre log length system. Bark thickness was determined at the measurement points from three equispaced points around the stem circumference using a bark gauge. For the varied log length system, the log end diameters were calculated assuming uniform taper between the diameter measurement points. The volume under bark of each theoretical log was calculated by Smalian's Formula (Carron 1968).

9.2.2 Calculation of the loss of value recovery caused by sweep

By treating the logs obtained under both conditions as if they had been sawn in the same milling operation as the *P.radiata* recovery study, the sweep ratio term in Equation 7.7 (Chapter 7, p.90) was used to estimate loss of percentage conversion caused by sweep in each log. This estimate was then multiplied by log volume under bark to give loss of sawn volume caused by sweep. A market price of $408 per cubic metre of theoretical sawn volume recovery (the average for the *P.radiata* study) was assumed, and lvr_{sw} from each log was calculated. The lvr_{sw} for each stem, under each crosscutting condition, was calculated by summing the log by log estimates.

9.2.3 Use of bend measurements in felled stems to 're-score' stem straightness to a precise stem description

Unlike the *P.radiata* study, every bend in the *P.taeda* stems was measured after felling, thus enabling scoring of stem straightness according to the exact number and severity of bends in each stem. Stem straightness was 're-scored', using the bend measurements from the felled stems, according to the description in Table 9.2.

Table 9.2 Scores awarded each stem based on bend measurements in felled stems

Score	Stem description
10	No bends
9	Up to 1 slight bend per 10 metres of merchantable stem
8	Between 1 and 2 slight bends per 10 metres of merchantable stem
7	More than 2 slight bends per 10 metres of merchantable stem. One serious bend more than 10 metres up the stem permitted
6	At least 1 serious bend in the lower 10 metres of stem

A serious bend was one that would cause a sweep of 10 cm or more if it were at the middle of a 5 metre log.

The scoring system was intended to be similar to that used in PT3, with the advantage that the detailed sweep measurements enabled very precise stem descriptions to be used.

In theory, some stems may have looked very similar but scored quite differently. For example, bends causing a 9 cm sweep if located in the middle of a 5.0 metre log look quite serious, but were classed as slight. A stem may have had one such bend in the lower 10 m and if it had no other would have scored 9. If the bend had been slightly worse, that is, causing a sweep of 10 cm, the same tree would have scored only 6. As it turned out, stems that were difficult to classify, did not occur. All stems having one serious bend in the lower 10 metres had several other slight and/or serious bends. Where stems had only one or two bends these were always very slight. The system was not tried for trees that would have scored worse than a '6' judged prior to felling.

9.3 Analysis

9.3.1 Comparison of lvr_{sw} for the fixed and variable log length systems

One of the aims of the analysis was to determine the extent to which varying log length to advantage ameliorated the influence of stem bends on value recovery. Comparison of the mean and range of the lvr_{sw} estimates was made between the fixed and varied log length systems.

9.3.2 The relationship between lvr_{sw} and stem straightness scores

As for the *P.radiata* study, the relationships between lvr_{sw} and the stem straightness scores formed the basis for calculation of economic weights. The relationships were investigated in two stages. First, the simple linear regressions between lvr_{sw} and scores were calculated. Then the effect of adding vub to the regressions was observed. The economic weights were equal to the slope coefficients for stems straightness score in the regression equations. The analysis was conducted for both pre-felling and post-felling assessments using lvr_{sw} calculated for the fixed and the variable log length systems.

9.4 Results

9.4.1 The effect of varying log length on lvr_{sw}

Frequency histograms of lvr_{sw} under the conditions of fixed and variable log lengths are shown in Figures 9.1 and 9.2. With log length fixed, estimated lvr_{sw} ranged from zero to $22.30, the average being $7.40. This compares with a maximum lvr_{sw} of $19.60 and a mean of $5.80 when log length was varied to advantage, indicating that by varying log length to advantage lvr_{sw} was reduced by 22%.

Figure 9.1 Distribution of lvr_{sw} values among the *P.taeda* stems with fixed length cutting

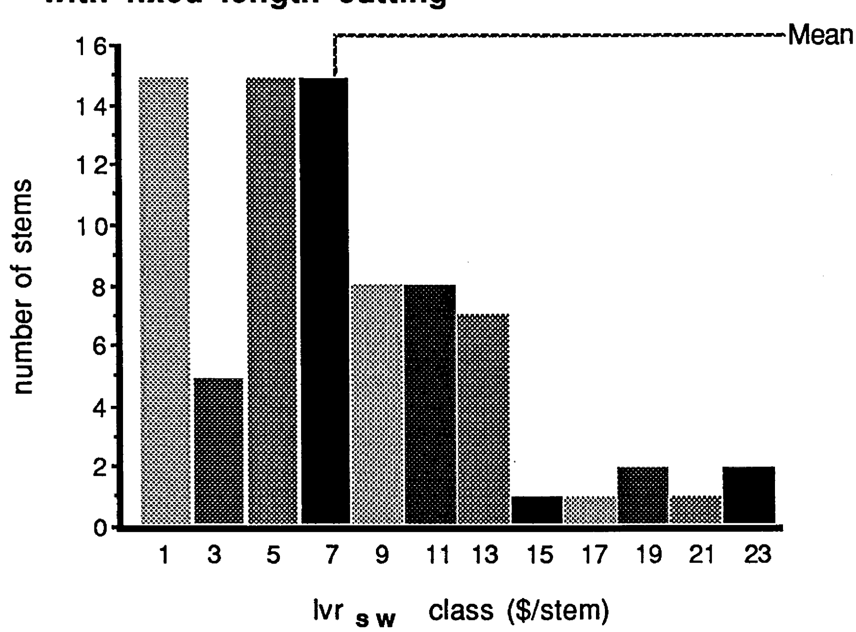
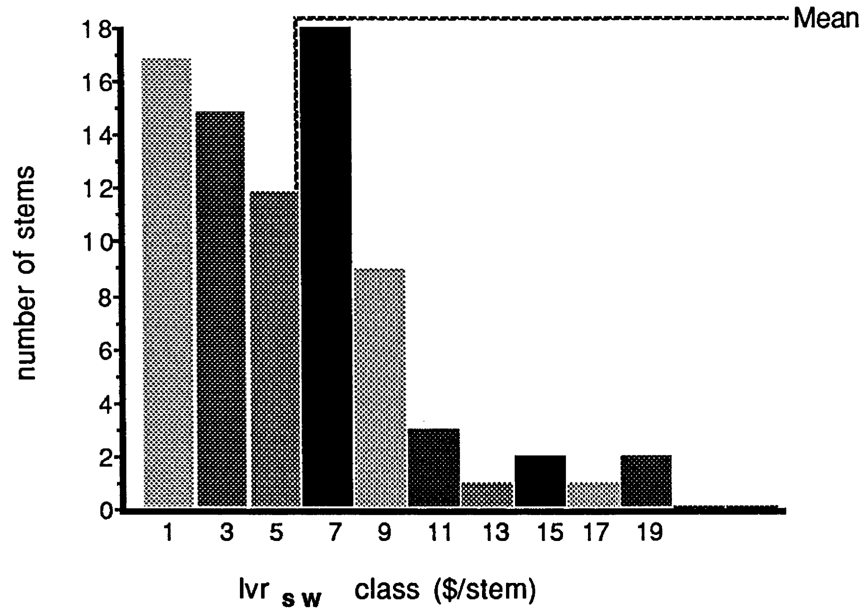


Figure 9.2 Distribution of lvr_{sw} values among the *P.taeda* stems with variable length cutting



9.4.2 The effect of varying log length on the economic weights for stem straightness

Figures 9.3 and 9.4 show lvr_{sw} plotted against the stem straightness score before felling for the conditions of fixed and variable log length, while Figures 9.5 and 9.6 show these plots for straightness scores after felling.

The least-squares regression equations are detailed in Table 9.3. The bracketed numbers are the standard errors of the estimates. The R^2 values indicate the proportion of variation in lvr_{sw} explained by the regressions. The regressions are all significant at the 0.0001 level or better. The slope coefficients predict the change in lvr_{sw} corresponding to a one point change in stem straightness score, and thus represent economic weights for stem straightness (Section 5.3, p.57).

Figure 9.3 Relationship between stem straightness scores before felling and fixed log length lvr_{sw}

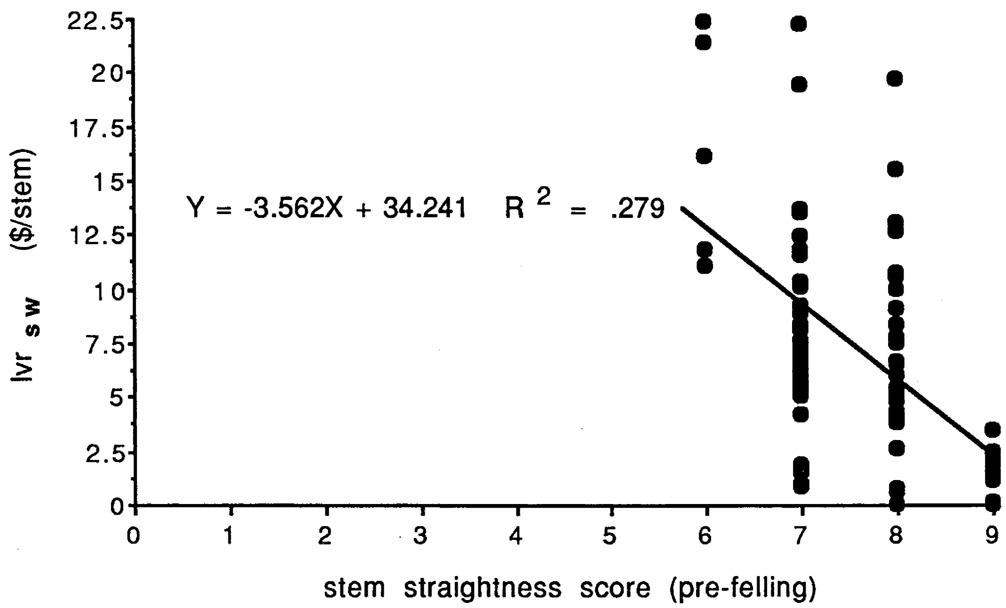


Figure 9.4 Relationship between stem straightness scores before felling and variable log length lvr_{sw}

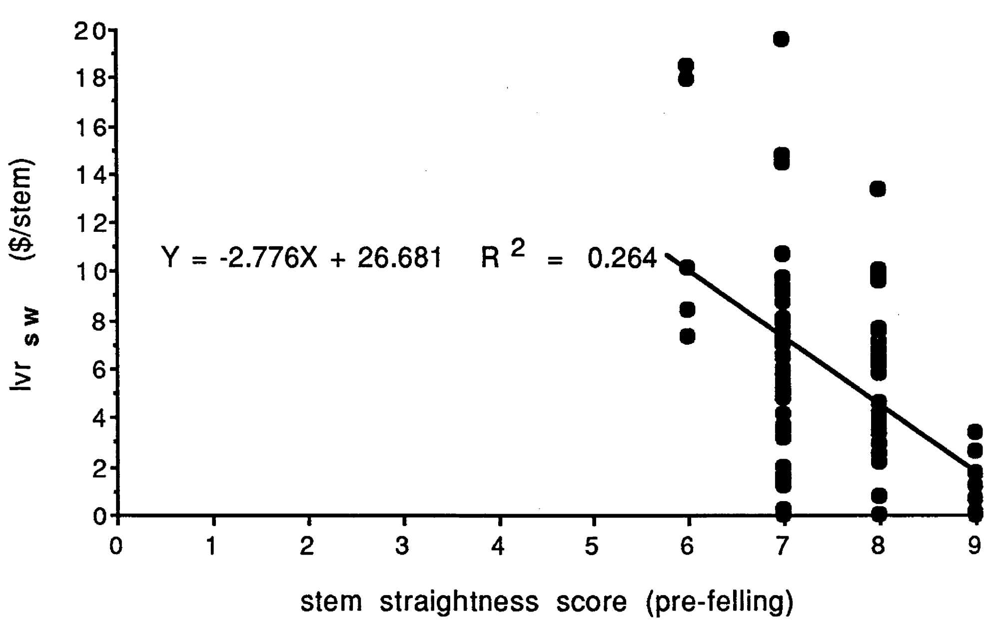


Figure 9.5 Relationship between stem straightness scores after felling and fixed log length lvr_{sw}

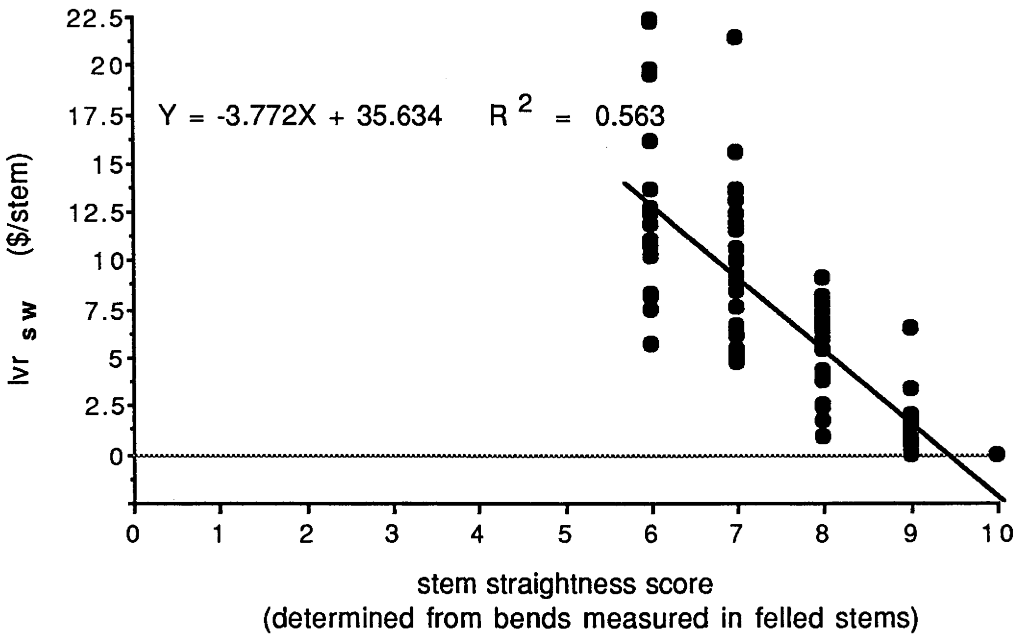


Figure 9.6 Relationship between stem straightness scores after felling and variable log length lvr_{sw}

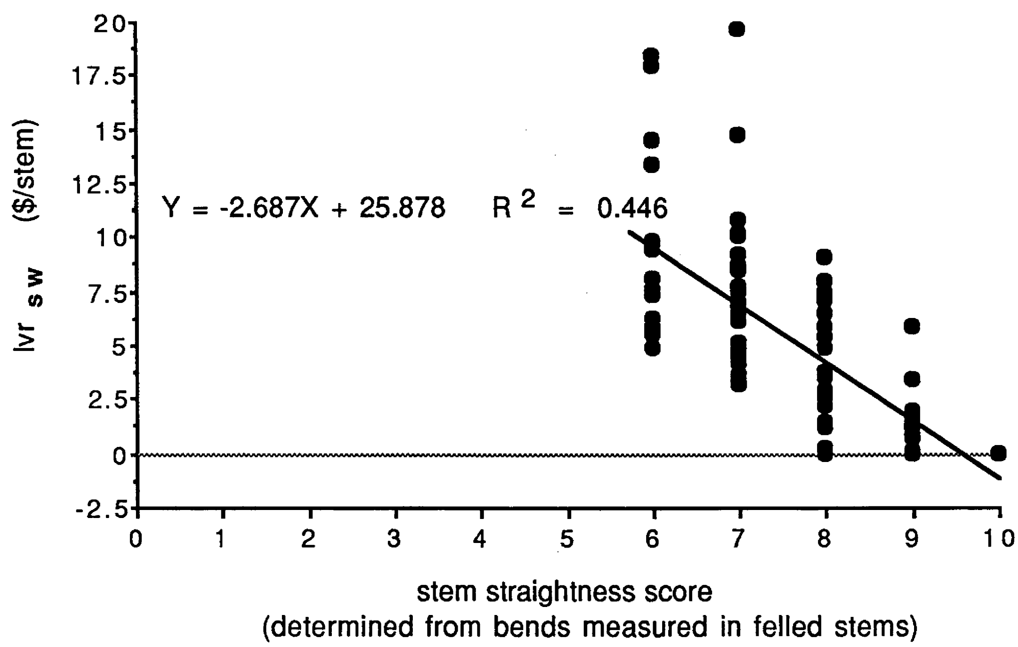


Table 9.3 Least-squares regression equations relating lvr_{sw} to stem straightness scores

Log length	Scoring method	Y-intercept	Slope coefficient	R^2
Fixed, 5.0m	Before felling	34.24	-3.56(0.65)	0.279***
Fixed, 5.0m	After felling	35.63	-3.77(0.38)	0.563***
Varied	Before felling	26.68	-2.78 (0.52)	0.264***
Varied	After felling	25.88	-2.69(0.34)	0.446***

*** = significant at the 0.001 level

As anticipated, sweep had a lesser effect on value recovery when log lengths were varied to advantage. With straightness scores judged before felling, a change in score of one point corresponded to a $3.56 change in recovery when log length was fixed, compared with only a $2.78 change when log length was varied to advantage. For post- felling scores the respective values were $3.77 and $2.69.

9.4.3 The effect of scoring precision on the economic weights

The coefficients for the regressions, and thus the economic weights, based on pre-felling scores differed only slightly from those based on post-felling scores (Table 9.3). However, the post-felling regressions gave a more precise fit to the data and explained more of the variation in lvr_{sw}, emphasising the need for more precise methods of estimating stem straightness in standing trees.

9.4.4 The effect of stem vub on the economic weights

Stem size also weakly correlated with lvr_{sw} as illustrated in Figures 9.7 and 9.8.

Figure 9.7 Relationship between stem vub and fixed log length lvr_{sw}

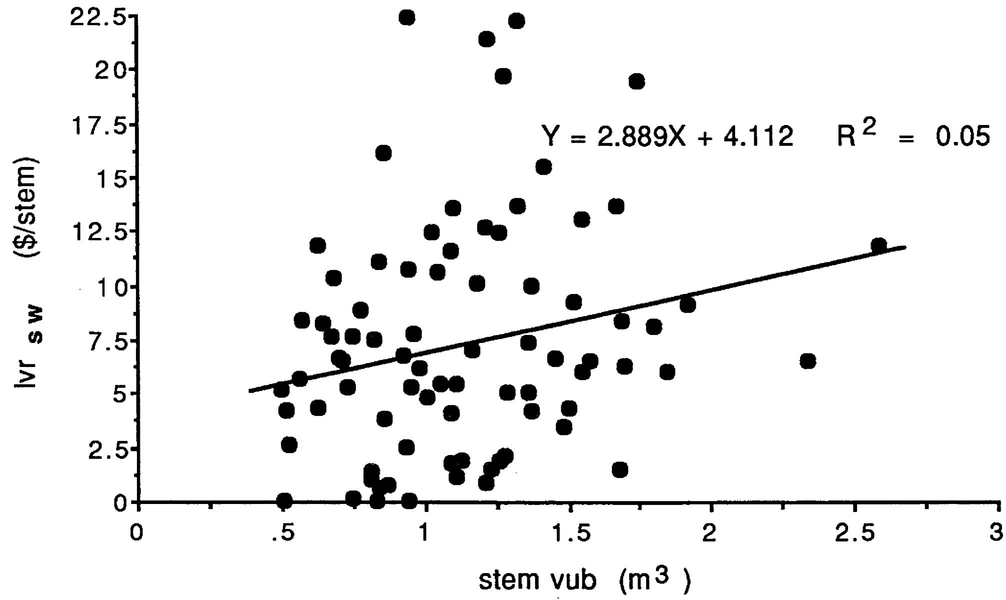
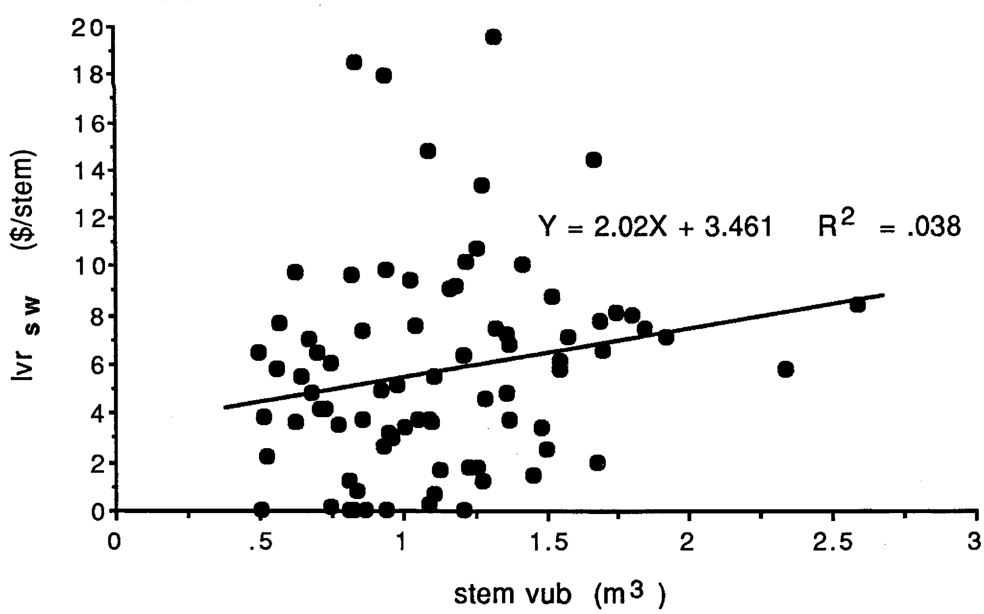


Figure 9.8 Relationship between stem vub and variable log length lvr_{sw}



Details of multiple regression equations relating lvr_{sw} to stem straightness scores and stem vub are given in Table 9.4. Stem vub significantly influenced the relationship only when post-felling scores were involved. Its inclusion in the post-felling regressions explained an additional 7 to 10% of variation in lvr_{sw}. Why it did not correlate significantly with pre-felling scores cannot be explained.

Table 9.4 Best fit regressions relating lvr_{sw} to straightness scores and stem size

Log length	Scoring method	Best regression	R^2
Fixed	Pre-felling	$lvr = \underset{(4.91)}{34.24} - \underset{(0.65)}{3.56}\ ss$	0.279^{***}
	Post-felling	$lvr = \underset{(1.05)}{2.82} - \underset{(0.30)}{3.52}\ ss \times vub + \underset{(2.52)}{30.48}\ vub$	0.656^{***}
Varied	Pre-felling	$lvr = \underset{(3.98)}{26.68} - \underset{(0.52)}{2.78}\ ss$	0.264^{***}
	Post-felling	$lvr = \underset{(2.51)}{23.57} - \underset{(0.32)}{2.79}\ ss + \underset{(0.82)}{2.73}\ vub$	0.515^{***}

*** significant at the 0.001 level

9.5 Discussion

9.5.1 Comparison of the economic weights with those determined for *P.radiata*

In comparison with the *P.radiata* study, there was a stronger relationship between lvr_{sw} and straightness scores in *P.taeda*, although the difference was not statistically significant. For *P.taeda* the relationship based on lvr_{sw}, as calculated for variable length logs and pre-felling stem straightness scores, predicted a \$2.78 improvement in value recovery per stem, for a 1 point improvement in straightness score, with 95% confidence limits of \$1.80 and \$3.80. For comparison, a one point improvement in the second age 34 straightness score in the *P.radiata* study corresponded with a \$1.88 improvement in value recovery per stem (Table 8.1, p.107), with 95% confidence limits of about \$0.92 and \$2.84.

Evidence has been presented that lvr_{sw} was greater from larger sized stems (Section 8.3.2, p.107). The stems in the *P.taeda* study were larger on average than those for *P.radiata* (Section 9.2.1). For *P.radiata* the total vub of each stem was calculated to 7 cm sedub. For *P.taeda*, only volume to about 20 cm top diameter under bark was estimated. Even so, the average total vub for the *P.taeda* was larger than that of the *P.radiata* felled in PT3 (1.13 m^3 compared with 1.04 m^3). The second age 34 regression, including stem vub for *P. radiata* was:

$$lvr_{sw} = 2.07 + 18.17\,vub - 2.09 \times ss \times vub$$

Substituting the average vub of the *P.radiata* stems into the above equation it became:

$$lvr_{sw} = 20.97 - 2.17 \times ss$$

With the additional volume above the 20 cm point included, the *P.taeda* stems might have had average stem vub of about 1.3 to 1.4 m^3. With an average stem vub of 1.35 m^3 substituted into the *P.radiata* second age 34 equation above, it becomes:

$$lvr_{sw} = 26.6 - 2.82 \times ss$$

which is almost identical to the variable log length equation for *P.taeda* based on pre-felling, stem straightness scores, that is:

$$lvr_{sw} = 26.7 - 2.78 \times ss$$

The second age 34 assessment of stem straightness in PT3 and the pre-felling assessment in *P.taeda* were done by the same observer. The relationship between this observer's scores and lvr_{sw} were consistent between the two studies. Once stem vub was accounted for, the relationship between pre-felling stem straightness scores and lvr_{sw} was the same for *P.taeda* and *P.radiata,* indicating the observer's judgement of stem straightness was consistent though not precise.

The same observer also judged the straightness of the stems in PT3 on the first scoring occasion at age 34. For this assessment the best regression was:

$$lvr_{sw} = 1.16 + 16.33\,vub - 1.66\,ss \times vub$$

which differs from his second assessment. With a vub of 1.35 substituted this equation became:

$$lvr_{sw} = 23.21 - 2.24\,ss$$

different again from the *P.taeda* study. This first assessment was done when the observer had little experience in judging stem straightness. The lack of experience is reflected by the somewhat weaker relationship between scores and lvr_{sw}. It appears that having gained some experience the observer's judgement of straightness improved and then remained consistent at two different sites, and for two different species.

9.5.2 The ability of the observer to judge stem straightness correctly

A comparison of the relationship between straightness scores and lvr_{sw} for pre-felling and post-felling assessments, indicated considerable improvement could be made in the observer's judgement of straightness. When log length was varied the pre-felling scores explained 26.4% of variation in lvr_{sw} (Table 9.3). Using the more precise scores determined by post-felling measurements, 44.6% of variation was explained. The difference was even more pronounced for the fixed log length case, 27.9% explained by the pre-felling scores compared with 56.3% by post-felling scores. Thus, while about half the variation in lvr_{sw} was accounted for after felling by a subjective rating of the frequency of bends and their severity, much of the precision was lost in applying it to standing stems. Presumably this resulted from failure by the observer to count the number of bends correctly or judge their severity accurately. However, poor judgement of stem straightness in standing trees did not detract from the economic importance of this trait. Pre-felling and post-felling scores had a similar relationship to lvr_{sw}, that is, the slope of the regression did not differ significantly between pre-felling and post-felling assessments (Table 9.3).

The lower precision of the pre-felling assessment does have consequences for the selection of trees in breeding. While poor judgement by a single observer did not influence the economic importance of stem straightness, it probably did influence other parameters. A Smith-Hazel Index used in the selection of breeding trees incorporates phenotypic and genetic variance information as well as economic weights (Section 2.4.1, p.10). Poor observer judgement may have resulted in error in the calculation of phenotypic and, possibly, genetic parameters. For example, the phenotypic standard deviation of the pre-felling scores was 0.79 compared with 0.99 for post-felling scores. Thus, if the heritability of pre-felling and post-felling scores was the same, the gain in stem worth due to improved straightness by a given intensity of selection would be higher if post-felling scores were used. The observer judging stems prior to felling was reluctant to award low scores (6) or high scores (9 and 10). There were no 10's, ten 9's and five 6's given in the pre-felling assessment. Measurement of bends after felling, revealed that two 10's, thirteen 9's and ten 6's should actually have been recorded. This is an example of the error of central tendency as described by Guilford (1954).

Observer judgement also resulted in different phenotypic correlation between dbhob and straightness scores. For the pre-felling assessment the correlation was -0.257. This compared with +0.010 between post-felling scores and dbhob. It appears that the observer's judgement may have been influenced by the size of the stem being judged, an example of logical error (Guilford 1954). Thus, even though pre-felling and post-felling assessments gave stem straightness the same economic weights, phenotypic parameters differed. Therefore Smith-Hazel selection indices based on them would also be expected to differ.

9.5.3 The lvr_{sw} from nearly straight stems

One of the aims of the *P.taeda* study was to determine whether one or two slight bends in nearly straight stems cause lvr_{sw}. From the results of the study it was apparent that a slight bend did cause a small reduction in value recovery. Bends were expected to cause lvr_{sw} from eight of the ten trees scoring 9 in the pre-felling assessment when log length was fixed, and seven when log length was varied. The mean losses were 1.4% and 1.2%. A similar result was obtained using post-felling scores. Bends were expected to cause lvr_{sw} from all thirteen 9's under a fixed log length system and twelve of them when log length was varied, with mean losses of 1.7% and 1.5%.

A lvr_{sw} of 1.5% equates with a larger percentage loss in the economic value per stem. Stems averaging 1.0m^3 in volume give about $125 worth of timber (gross value, ex-mill, Section 8.5.1, p.110); 1.5% of this is about $1.88. Ignoring any effect the slight bends in stems scoring 9 might have on harvesting costs, the value of a $1.88 improvement in recovery, resulting from elimination of bends, is equal to $1.88 per stem. The value of a 1m^3 stem is approximately 0.164 × $125 (Section 5.2, p.54), or about $20 per stem. Therefore the loss of value caused by bends from stems scoring 9 points out of 10 could be as high as 1.88 / 20, or 9%.

9.6 Conclusions

The *P.taeda* study provided confirmatory evidence that the relationship between stem straightness scores and lvr_{sw} is nearly linear in the range 6 to 10 points on a 10 point subjective, absolute scale. With stem size taken into account the estimated economic importance of stem straightness in the *P.taeda* study was similar to that estimated by the second age 34 stem straightness assessment in *P.radiata* PT3.

Further, complete measurement of bends in felled stems provided evidence that while variation in log length had some effect, low precision in the relationship between straightness score and lvr_{sw} resulted mainly from observer error. As a result the weighting coefficients calculated for a Smith-Hazel Index might be affected.

Finally, varying log length to advantage reduced the influence of bends on value recovery by about 20%. As a result stem straightness was a little less important in determining value recovery when log length was varied to advantage.

Chapter Ten

THE INFLUENCE OF BRANCH DIAMETER ON VALUE RECOVERY FROM SAWLOGS

10.1 Introduction

This chapter concerns the analysis and interpretation of the grade recovery data. The relationship between a single index of branch diameter and the quality of structural framing timber obtained from the logs sawn in the mill study was examined and the results used to quantify the relationship between the index and value recovery from saw logs. The relationship was used to calculate the loss of value recovery caused by large diameter branches (lvr_{bd}) in saw logs, which provided the basis for calculating economic weights.

10.2 Factors influencing the analysis

The analysis was more complex than that used in the study of the effect of log sweep on value recovery. Sweep influenced the quantity of timber obtained from each log, that is, percentage conversion was directly related to sweep ratio. Since sweep ratio and percentage conversion were both continuous variables, the relationship was modelled satisfactorily by linear regression analysis (Chapter 7). Further, since sawn volume recovery from a log is equal to conversion $\times$ vub and volume recovery is closely correlated with value recovery, the relationship between value recovery and sweep was easily quantifiable.

This was not the case with branch diameter, for the following reasons:

(1) Branch diameter influences timber quality, not quantity.

(2) The strength at the weakest point in a piece of timber determines the grade.

(3) The important measure of timber quality used for structural purposes, its strength, is only indirectly related to value recovery. Strength is used to classify timber into a variety of different grades. Value recovery is then dependent on the premium paid for higher grades.

(4) Other variables also influence timber strength.

(5) Branch diameter is difficult to characterise because each log has a unique population of many branches.

10.2.1 The influence of a single branch on timber quality

An important characteristic of any piece of timber used in a situation where it is placed under stress, such as framing timber, is its modulus of rupture (MOR). The MOR in the vicinity of a knot is negatively correlated with knot diameter. Therefore the diameter of a single branch influences timber strength in the vicinity of the branch (Grant, 1980).

10.2.2 The relationship between timber strength and timber grade

The bending strength at the weakest point in a piece of timber is important when grading for structural use and is often the over-riding consideration (Kloot 1973). Furthermore, timber used for structural purposes, *i.e.*, timber for which strength is the most important characteristic, has a minimum useable length. At the mill used in this study the shortest pieces sold for structural purposes were 2.4 metres long. In general, timber strength varies continuously, along a piece; the weakest point generally occurs at, or in the vicinity of, the part of the piece which has the greatest amount of knot wood in the cross section (Standards Association of Australia, 1986). This usually occurs at the largest diameter knot but, may also occur where several small knots are grouped together. Therefore, the largest diameter knot is not always the minimum strength determining defect. Further, the effect of a knot of given diameter on strength depends partly on where in the cross-section the knot occurs.

10.2.3 The relationship between MOR at the weakest point and timber value

The MOR does not directly determine the market value of individual pieces of timber. The MOR can only be measured by breaking the timber and rendering it unusable. Past studies have quantified the relationship between MOR and the bending strength of timber, measured by its modulus of elasticity (MOE) (Huddleston and Anton 1967, Whiteside 1974). The latter variable can be measured without destruction of the timber, using a stress grader (Standards Association of Australia 1978). In the present study the framing timber was classified into one of 5 grades according to the MOE at the weakest point. The 1986 market values for timber sold from the mill are shown in Table 10.1.

The relationship between 1986 market value, minimum MOR (estimated from MOE) and machine stress grade for structural framing is illustrated in Figure 10.1. The estimated MOR shown on the X-axis was determined from timber stiffness, measured in the stress grading machine at the mill. The figure shows a very nonlinear relation between minimum MOR and market value.

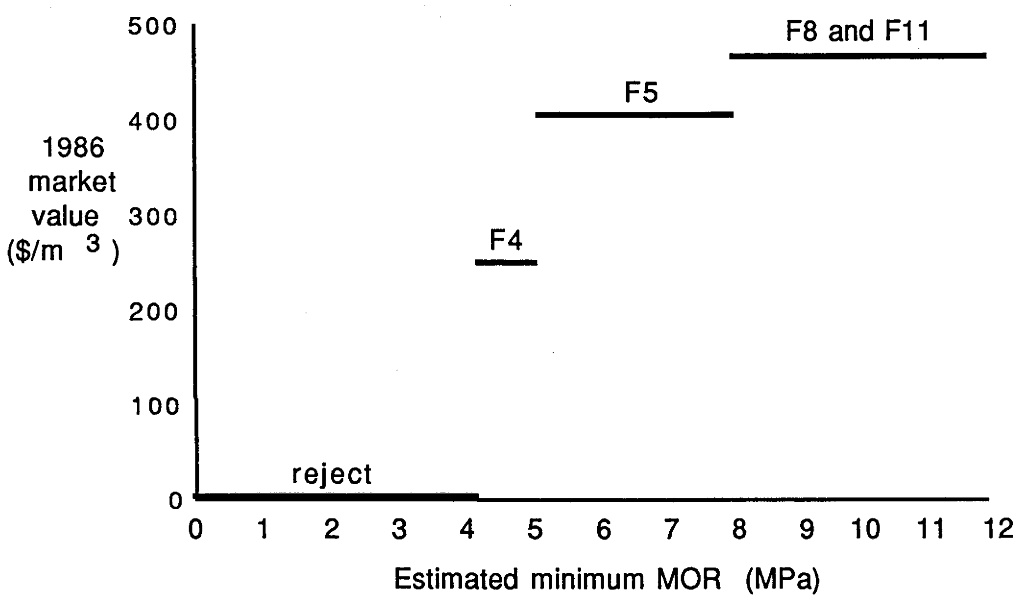
Table 10.1 Timber framing and board values

product type	grade	market value($/m^3)
light structural framing	F11	466
	F8	466
	F5	405
	F4	250
	reject	0
	`heart-in'	-[a]
boards	-	405

(a) In later analysis an average market value of $355 per m^3 is assumed for `heart-in' framing (Section 10.4.2.b).

There is a large price differential between reject, F4 and F5, but a comparatively small difference between F5, F8 and F11. As a consequence, a relatively small variation in estimated minimum MOR among timbers of generally low grade (minimum MOR less than about 5.5 MPa) causes large variation in market value. Above a minimum MOR of 5.5 MPa, variation in MOR has a much smaller influence on market value.

Figure 10.1 Relationship between market value, framing grade and estimated minimum MOR



10.2.4 Other parameters that influence timber strength

Timber strength is also influenced by wood density, grain angle, pith, cone holes and resin pockets (Bamber and Burley 1983). Variation in these parameters within a piece of timber and between timbers may mean the weakest point is not in the vicinity of the largest diameter knot and the relationship between MOR and knot diameter is not constant for all pieces of timber. Further, the effect of knots and these other defects varies according to their position in the timber, sawing patterns and timber dimensions.

10.2.5 The influence of branches on overall log quality

A single log has many branches of varying diameter. The analysis of the influence of branch diameter on the overall timber quality from a log is therefore not confined to the influence of a single branch but to the combined effect of the entire population of branches.

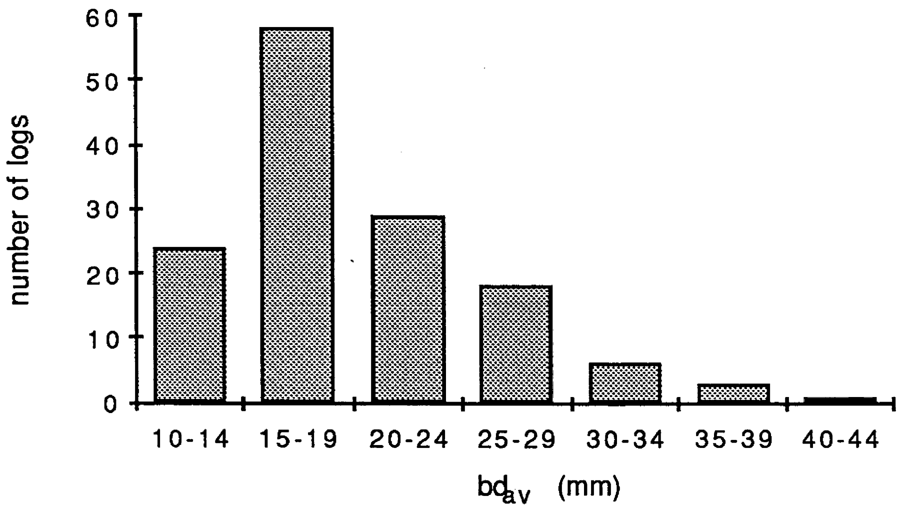
10.3 Initial analysis

Despite the complications outlined above, a simple regression study relating the market value of timber from logs to branch diameter measurements was tried. It was reasoned that there would be a negative correlation between knot diameter and MOR and, therefore, that logs having the largest diameter branches would produce framing timbers of lowest minimum MOR. Since a low minimum MOR equated with a low machine stress grade, and the lower grades had lower market value, it was thought there could be a significant correlation between the average market value of framing timber and the average or maximum branch diameter of individual logs.

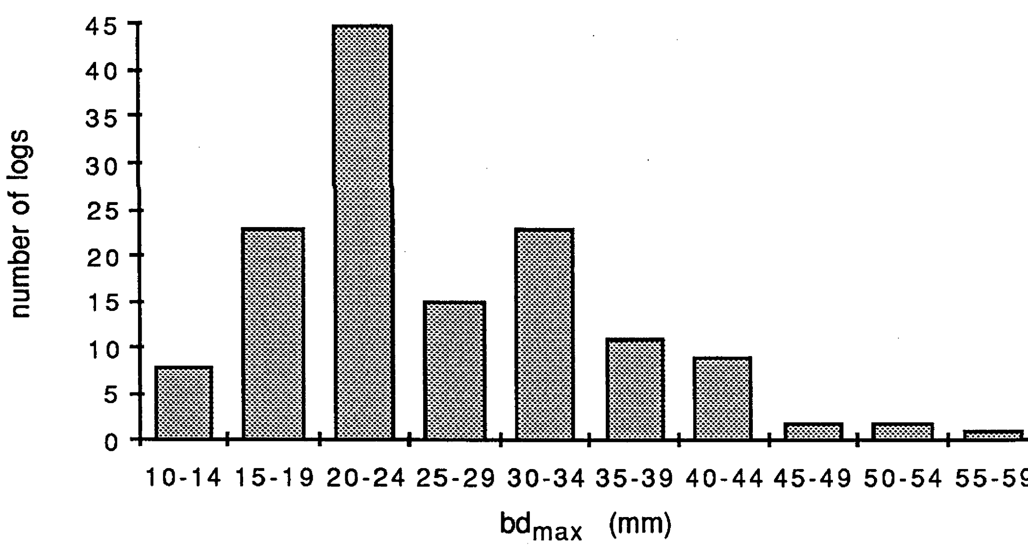
Regression analysis indicated the relationship was statistically significant but very weak, perhaps because of the complications outlined in Sections 10.2.1 to 10.2.5, and because the range in average branch diameters was relatively small. The distribution of average and maximum branch diameter by 5 cm classes is shown in Figure 10.2 for the logs included in the study. In the figure bd_{av} is the mean diameter of all branch measurements on the log and bd_{max} is the average diameter of the four largest branches, of those measured on the log. (N.B. Branch diameters were measured on logs lying on the ground. Only the two uppermost branches of each whorl were measured. On some logs the branches underneath may have been larger.)

Figure 10.2 Range and distribution of branch diameter on individual logs in the study

(a) Average branch diameter index



(b) Maximum branch diameter index



10.4 An alternative method of analysis

An alternative method of analysis was tried in which the pattern of variation in timber grades was compared among logs grouped into 3 classes of branch diameter and 3 classes of log small end diameter under bark (sedub).

10.4.1 Conduct of the analysis in two phases

The analysis was conducted in two phases. In phase one the quantity of all grades in each piece of framing (not merely the worst grade) was considered and the five grades were amalgamated into two groups. The low grade group consisted of the lower three grades (reject, F4 and F5), while the high grade group consisted of F8 and F11. While not reflecting the premiums paid for higher grade timber (the market value of F5 is nearer to F8 and F11 than to reject and F4), this division does reflect similarities in minimum MOR and also gave an even division of framing into the two groups.

In phase two the grades were not grouped, *i.e.* all five grades were considered individually. Further, the analysis was conducted using only the minimum grade in each piece of framing, as opposed to phase one, in which all grades in each piece were considered.

Phase one produced a clear picture of the influence of branch diameter and log diameter on timber grade from logs, while phase two enabled interpretation of the effects in terms of the market value of framing timber.

10.4.2 Data used

10.4.2.a Branch diameter indices tried

The analysis was restricted to logs for which at least one branch was measured per branch whorl (the details of branch measurements were described in Chapter 6, p.67). This restriction reduced the sample size to 138 saw logs. The number of branches measured per log in this group ranged from 6 to 30. Two indices of branch diameter were calculated:

(i) average branch diameter, or bd_{av} (Figure 10.2a)

(ii) mean diameter of the four largest branches, or bd_{max} (Figure 10.2b).

In the analysis it was found bd_{av} was a slightly more reliable indicator of timber grade than was bd_{max}. Therefore, only the results using bd_{av} are presented here.

10.4.2.b Inclusion of the 'heart-in' framing

About ten percent of the framing timber sawn in the study was classified as 'heart-in' and would normally have been rejected (i.e. contained pith and associated low density juvenile wood). At the particular mill used, such rejects were discarded. The Standards Association of Australia's Standard SA2858 allows heart-in to be used as studs. During the study, however, it was observed that many pieces of framing containing pith were not classified as 'heart-in' and were allowed to pass along the green chain. There appeared to be no reason why some pieces containing pith were called 'heart-in' and others not. Because the number of pieces per log designated 'heart-in' varied from zero to three, it was decided to treat all the 'heart-in' material as normal framing. For the phase one analysis it was necessary to determine for each piece whether the 'heart-in' should be placed in the low grade framing group or the high grade group. For phase two of the analysis the minimum stress grades of the 'heart-in' had to be estimated.

A sample of the processed timbers was purchased from the mill for further study. This consisted of 110 pieces 90 mm × 35 mm in cross section. Of these 41 contained pith, that is, were technically 'heart-in'; 28 had minimum machine stress grades of F5, and the remaining thirteen F4.

In phase one of the analysis all 'heart-in' was classed in the low grade group.

It was assumed for phase two that 68% were F5 and 32% F4. This gave an estimated average market value for all 'heart-in' of $355 per cubic metre.

10.4.2.c Grades of the 0.60 metres at either end of each piece of framing

The stress grading machine cannot grade the 0.60 metres at the ends of each piece. These ungraded ends were nominally graded as equivalent to the worst in the piece, unless there was an obviously worse defect present. In many ends, the nominal grade assigned was probably lower than the true grade.

In phase one of the analysis this practice probably caused some bias in the grade recovery estimates. The quantity of low grade was probably overestimated and the quantity of higher grade under estimated.

In phase two of the analysis, only the lowest grade in each piece was important, so these results were not biased.

10.4.2.d Grouping of the 138 logs by bd_{av} and sedub classes

The size class boundaries chosen and number of logs per class are shown in Table 10.2. Delimitation of the groups was arranged so that logs were distributed as uniformly as possible among classes.

Table 10.2 Number of logs per sedub and bd_{av} class

		sedub class(mm)		
		<180	180-219	>219
bd_{av}	≤17	13	23	13
class	17-22	17	15	18
(mm)	>22	13	14	12

10.4.2.e Measurement units used in phase one

In phase one of the analysis the quantities of each grade were not expressed in cubic metres or percentages, but in 'standard' units . Expression on a volume basis added an extra variable, log length and expression, on the basis of percentage of total recovery, did not facilitate easy interpretation of the observed grade distributions. The standard unit (s.u.) was derived to remove the log length effect, and also enabled easy interpretation of the effects of bd_{av} and sedub on grade.

For each piece of framing, the number of s.u.'s of each grade was calculated from the original log length and a standard sawn section size. The most common framing cross section (90 mm x 35 mm) was chosen as the 'standard'. A 'conversion factor' was calculated for each piece of framing:

$$\text{conversion factor} = \frac{\text{actual cross sectional area}}{90 \times 35}$$

The conversion factors for the six framing sizes were:

framing size	conversion factor
70mm × 35mm	0.778
70mm × 45mm	1.000
90mm × 35mm ('standard')	1.000
90mm × 45mm	1.286
120mm × 35mm	1.333
140mm × 35mm	1.556

The quantity in s.u.'s of a particular grade in one piece of timber is equal to the appropriate conversion factor multiplied by the length of framing having that grade, divided by log length. Figure 10.3 illustrates this. The figure shows a piece of framing viewed on the wide face with dye line uppermost. The length of F8 in the piece is 3.3 metres. The total length of the piece is 6.1 metres. If the cross section is 90 mm × 35 mm then the quantity of F8 in the piece, expressed in s.u.'s is 1.000 × 3.3/6.1 = 0.541. Similarly the length of F5, including the 0.6 metres ungraded at each end, is 2.8 metres. This is equivalent to 0.459 s.u. Since this piece has the standard cross section, the total s.u.'s of framing in it is 1.000. Two pieces of framing 90 mm × 35 mm in section, recovered from a log, would give a total recovery of 2 s.u., three pieces of this cross section 3 s.u., and so on.

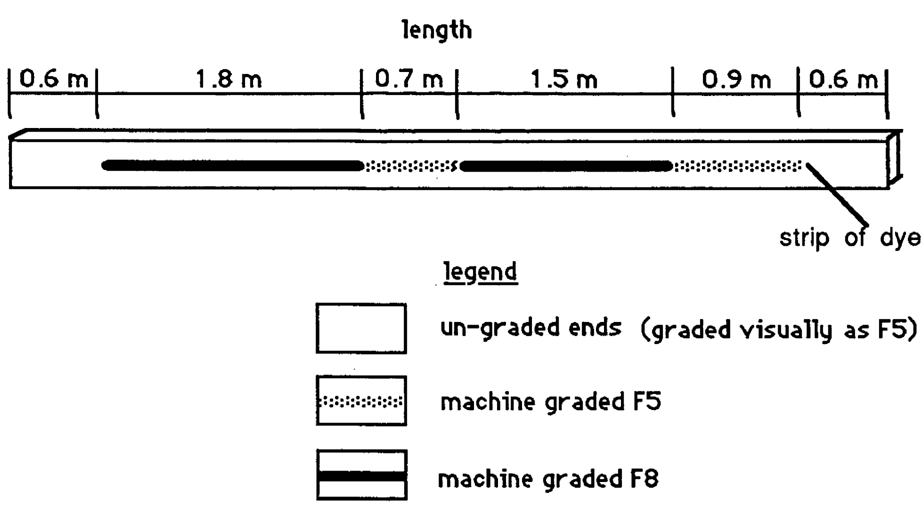
In phase one the numbers of s.u.'s of low grade and high grade framing recovered per log were analysed.

10.4.2.f Measurement units used in phase two

In phase two, only the minimum grade in each piece of framing was of concern. Therefore recovery was expressed simply as the number of pieces of framing of each (minimum) grade.

For framing other than the 'standard' section, *i.e.* other than 90 mm × 35 mm, it was necessary to adjust to the equivalent number of 90 mm × 35 mm pieces, using the conversion factors listed in Section 10.4.2.e. For example, if the piece shown in Figure 10.3 was 90 mm × 45 mm in section it would be equivalent to 1.286 'pieces' of F5 grade, because the lowest grade in it is F5.

Figure 10.3 Stress grades in a typical piece of framing



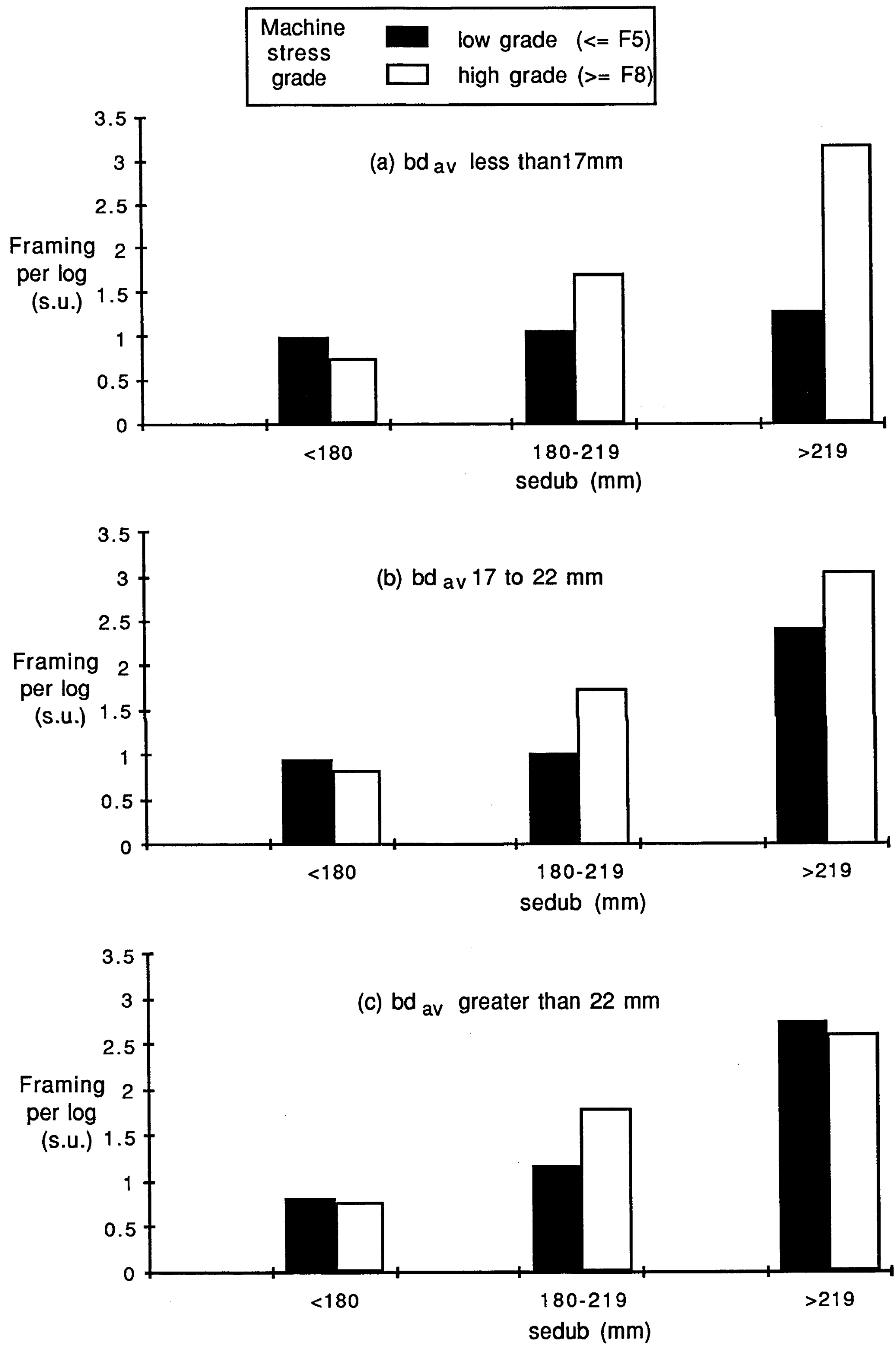
N.B. F5 is the lowest and therefore market price determining grade in this piece.

10.5 Results

10.5.1 Phase one: the effect of average branch diameter and sedub on all framing grades

The average s.u.'s of low grade and high grade framing yielded per log are shown in Figure 10.4 for each of the bd_{av} and sedub classes.

Figure 10.4 Effect of bd_{av} and sedub on framing per log



10.5.1.a Pattern of grade variation within log diameter classes

(i) Small diameter logs (sedub <180 mm)

Branch diameter had no effect on the quality of material from small logs. Each produced either one or two pieces of framing (average 1.7 s.u.). The percentages of low grade (F5 and lower) in the respective bd_{av} categories were 57, 53 and 52. The quantities of low grade material recovered were 0.99, 0.94 and 0.83 s.u. respectively from logs with small, medium and large bd_{av}.

(ii) Medium diameter logs (sedub 180 - 219 mm)

Branch diameter had no effect on these logs either. The average recovery was 2.7 s.u., with 38% F5 or lower and 62% F8 or F11. Although the percentage of low grade was less than for small diameter logs, the quantities remained much the same, being 1.05, 1.01 and 1.17 s.u. respectively, from logs with small, medium and large bd_{av}.

(iii) Large diameter logs (sedub > 219 mm)

There was a very marked effect of branch diameter on the quality of framing recovered from large diameter logs. The average total recovery of framing was 4.45, 5.46 and 5.37 s.u. from logs with small, medium and large bd_{av}. The quantities of low grade framing were 1.27 s.u. (29%) from logs with small bd_{av}, 2.42 s.u. (44%) from logs with medium bd_{av} and 2.76 s.u. (57%) from logs with large bd_{av}.

These results indicated branch diameter did influence timber quality, but the effect was limited to large diameter logs. As log diameter increased, the effect became more pronounced. There appeared to be a minimum level of low quality material in each log, approximating to 1 s.u. Whether the remainder of the log was high quality depended on branch diameter. When bd_{av} was small (less than about 17 mm) almost all the remainder of the log was high quality. When it was large (larger than about 22 mm) only about 60% of the remainder was high quality.

As noted above, the small branched, large diameter logs in the study gave a lesser total quantity of s.u.'s than either the medium or large branched, large diameter logs. Despite this, the small branched logs produced a greater quantity of high grade framing than those with large branch diameter (3.18 s.u. compared with 2.61). Presumably, if the average sedub of the small branched logs had matched that of the large branched logs the overall difference in timber quality would have been greater.

10.5.1.b Quantifying the relationships by regression

Two regressions were fitted, one relating the quantity of low grade framing obtained per log to sedub and bd_{av}, and the other relating the quantity of high grade framing to these variables.

In both regressions, quantity of framing (either low grade or high grade) was used as the dependent Y variable. Sedub was used as an independent X variable. Dummy variables were assigned to the three different bd_{av} classes. In the regression for low grade framing these were:

dum1 = 1 if a log had medium bd_{av} and 0 otherwise;
dum2 = 1 if a log had large bd_{av} and 0 otherwise.

In the regression for high grade framing they were:

dum3 = 1 if a log had small bd_{av} and 0 otherwise;
dum4 = 1 if a log had medium bd_{av} and 0 otherwise.

The variables dum1 $\times$ sedub^2 and dum2 $\times$ sedub^2 were included in the low grade regression and dum3 $\times$ sedub^2 and dum4 $\times$ sedub^2 in the high grade regression.

The regression equations using the above variables were:

$$\text{low grade (s.u.)} = \underset{(0.104)}{1.097} - \underset{(0.248)}{1.119}\,\text{dum1} - \underset{(0.390)}{1.828}\,\text{dum2} + \underset{(0.0005)}{0.0034}\,\text{dum1} \times \text{sedub}^2 + \underset{(0.0008)}{0.0055}\,\text{dum2} \times \text{sedub}^2$$

$$\text{high grade (s.u.)} = \underset{}{0.010} + \underset{(0.0006)}{0.0039\,\text{sedub}^2} - \underset{(0.875)}{2.411\,\text{dum3}} - \underset{(0.488)}{0.925\,\text{dum4}}$$

$$+ \underset{(0.0020)}{0.0072\,\text{dum3} \times \text{sedub}^2} + \underset{(0.0011)}{0.0025\,\text{dum4} \times \text{sedub}^2}$$

The respective coefficents of determination (R^2) were 0.452 and 0.504. The figures in brackets are the standard errors of the coefficients. Both regressions were significant at the 0.001 level using an F test. The individual coefficients were also significant at levels between 0.05 and 0.001 or better when tested against their respective standard errors using a Student's t test. The relationships are depicted graphically in Figures 10.5 and 10.6. (*N.B.* Figure 10.5 includes the slight, but non-significant trend for small branched logs).

10.5.2 Phase two: the effect of sedub and bd_{av} on the minimum grade per piece

Figure 10.7 shows average grade distributions of framing based on the minimum grade in each piece. The figure shows the number of pieces of framing of each grade, standardised to 90 mm x 35 mm in section, obtained per log in each class. The pattern of variation was similar to that observed when all grades in each piece were considered. Grades from small and medium diameter logs were virtually unaffected by bd_{av}.

Within the large sedub class there was marked variation in grade distribution between the bd_{av} classes. More than half (54%) the total number of pieces from small branched, large logs were F8 and F11. This compares with only 32% for large branched, large logs. As a result of these differences, the average market value of framing differed between bd_{av} classes in the large sedub class.

Figure 10.5 Low grade framing per log plotted against sedub for small, medium and large branched logs

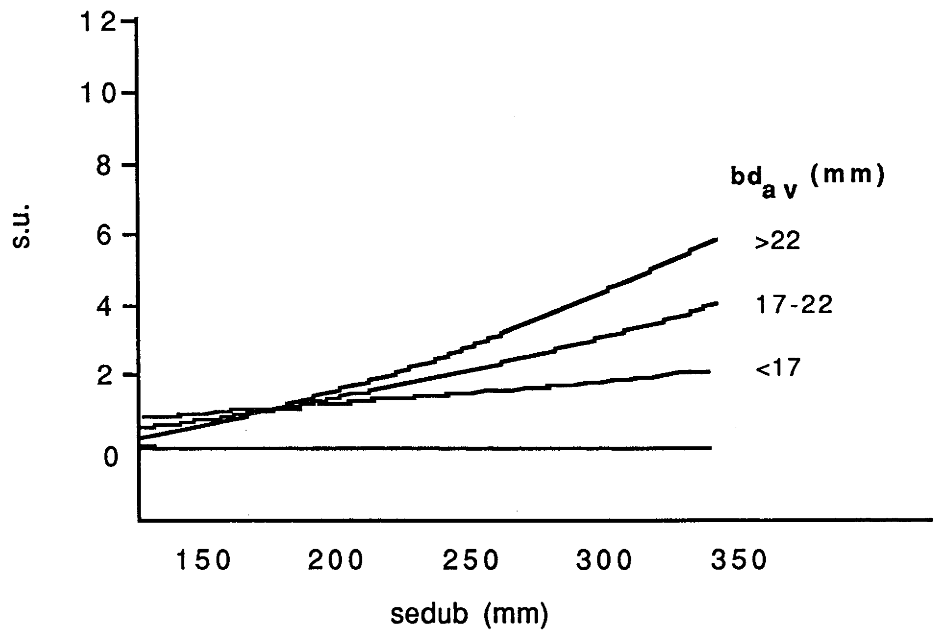


Figure 10.6 High grade framing per log plotted against sedub for small, medium and large branched logs

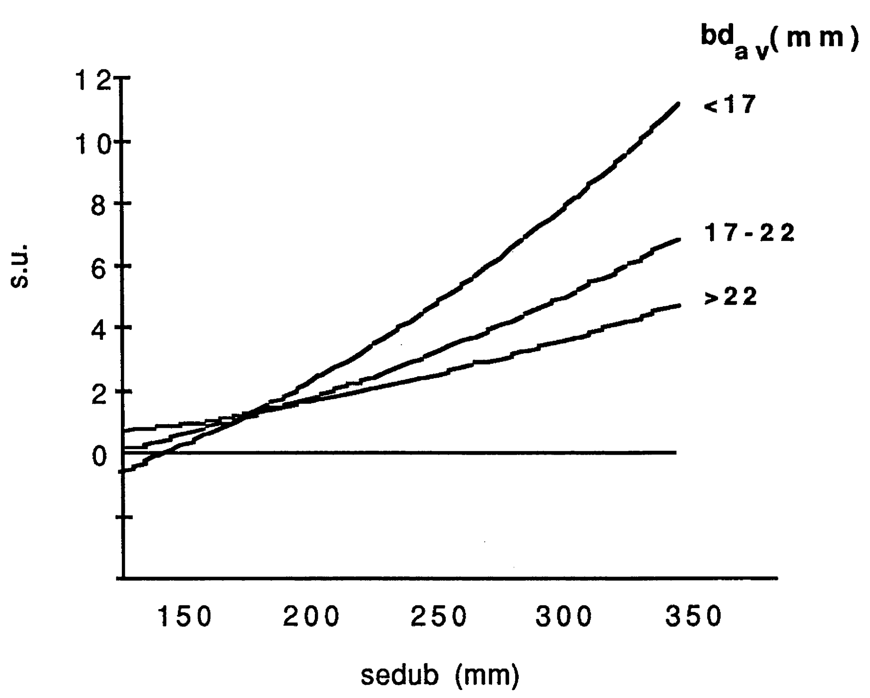
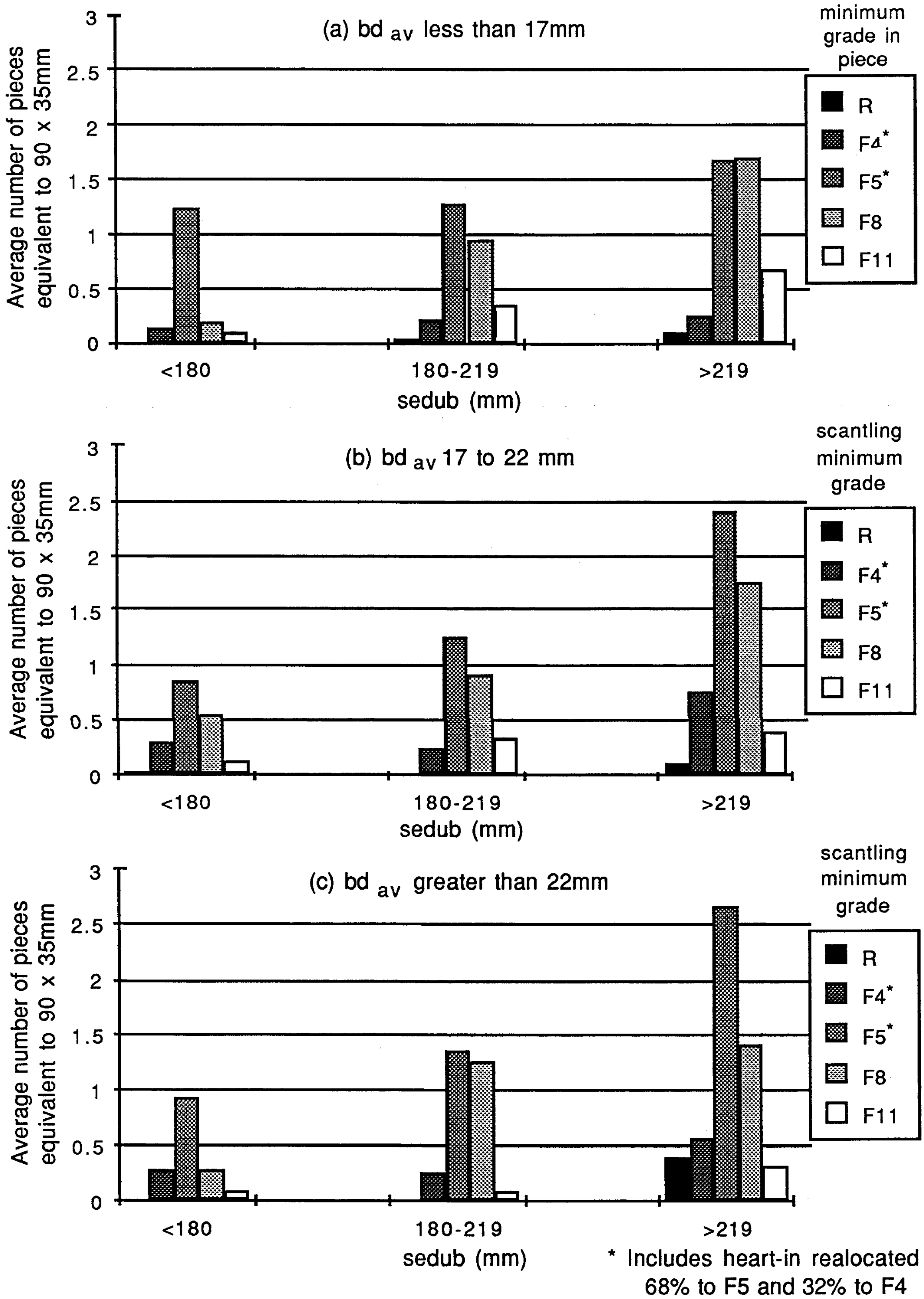


Figure 10.7 Influence of bd_{av} and sedub on stress grades



10.5.3 Average market value of framing in each sedub and bd_{av} class

From the grade distributions in Figure 10.7, an average market value was calculated using the 1986 values in Table 10.1. Within each sedub and bd_{av} class, average market value per cubic metre was calculated by multiplying the average proportion of each grade by the respective market value per cubic metre. For example, from small branched, large diameter logs, the distribution of minimum grades was 2% reject, 7% 'heart-in', 3% F4, 34% F5, 39% F8 and 15% F11. The average market value per cubic metre of framing obtained from these logs was thus:

$$\frac{0 \times 2}{100} + \frac{355 \times 7}{100} + \frac{250 \times 3}{100} + \frac{405 \times 34}{100} + \frac{466 \times (39 + 15)}{100}$$

or $420 per cubic metre.

Similar calculations for other sedub and bd_{av} classes produced the average market values shown in Table 10.3.

An important result in Figure 10.7 is the difference in the quantity of F11 between the small, medium and large bd_{av} classes in the large sedub group. The small branched logs produced more than twice as much F11 as the large branched logs (0.68 pieces per log compared with 0.32). Had a higher premium been paid for F11 material the effect of branch diameter on the market value of framing would have been greater than observed in this study.

Table 10.3 Average market value of timber framing in each sedub and bd_{av} class

		sedub class (mm)		
		<180 (loss)	180-219 (loss)	>219 (loss)
bd_{av} class (mm)	<17	404 (0)	415 (0)	420 (0)
	17-22	402 (0)	419 (0)	400 (20)
	>22	392 (0)	419 (0)	378 (42)
	mean	400	417	not needed

N.B. The figures in brackets represent the estimated loss in market value, per cubic metre of framing, caused by large bd_{av}.

Branch diameter had very little influence on timber grade from logs smaller than 220 mm sedub (Section 10.5.1.a). Therefore, for estimation of the loss of value recovery caused by large diameter branches (lvr_{bd}), market value per cubic metre of framing output was averaged over the three bd_{av} classes within the small and medium sedub classes. The resulting average market values were $400 per cubic metre of output for small diameter logs and $417 per cubic metre for medium diameter logs (Table 10.3).

A one way analysis of variance confirmed that the differences in market value between bd_{av} classes in the large log sedub class, detailed in Table 10.3, were statistically significant ($p < 0.05$).

10.5.4 Calculation of the loss of value recovery caused by large branch diameter

The estimated average market values in each sedub and bd_{av} class were used to calculate the lvr_{bd} for individual logs. Because branch diameter had no effect on the market value of logs smaller than 220 mm sedub, large diameter branches caused no loss of value recovery from these (Table 10.3).

The average market value of framing from large diameter logs with small diameter branches was regarded as representing the maximum market value for framing obtainable from logs of this diameter. For medium and large branched logs in this sedub class, the difference in market value between them and the small branched logs gave an estimate of the loss in market value, per cubic metre of framing. The losses in value respectively from large branched and medium branched, large diameter logs were therefore $42 and $20 per cubic metre of sawn output (Table 10.3). Large diameter logs having large, rather than small, diameter branches resulted in a 10% reduction in the average market value of the framing produced.

Not all the timber recovered in the study was framing. About 17% was ungraded boards, the market value of which was not influenced by branch diameter at the mill involved. The loss in market value caused by large diameter branches was only incurred on the framing timber, not on the boards. To determine the lvr_{bd} from each log (in dollars per log) it was necessary to consider the volume of framing recovered per log. An alternative would have been to grade boards to AS2796 in which knot diameter does influence board grade. If a premium were paid for high grade boards their value would be affected by branches.

Rather than use the actual volume of framing recovered an estimate was obtained using a regression relating framing volume recovery to sedub:

$$\text{framing } (m^3) = 0.0006 \text{ sedub} - 0.076 \quad (R^2 = 0.622)$$

(N.B. sedub is expressed in millimetres)

Use of this regression avoided uncontrolled variation in the relative proportions of framing and board timber recovered per log. It also enabled estimation of framing recovery from the veneer logs. This was necessary because no comparable estimates of the market value of individual veneer sheets was obtained, nor was the effect of branch diameter on veneer grade determined.

The lvr_{bd} per log was equal to:

(loss of market value caused by bd_{av}) $\times$ (estimated framing volume).

10.6 Discussion

10.6.1 An hypothesis explaining the observed framing grade distributions

P.radiata stems have a core of low density wood surrounding the pith for the innermost 12 to 20 annual growth rings (Nicholls and Dadswell 1965). Wood of low density and containing pith has low bending strength and, therefore, is of low stress grade (Grant 1980). Within this central core of wood the branches are probably smaller than their ultimate diameter (Grant and Anton 1984).

Small diameter logs in this study mostly came from the upper part of stems and were therefore composed mainly of juvenile wood. Thus, framing cut from them also consist mainly of low density wood. Because only one or two pieces of timber were obtained from these logs there was a high probability these pieces contained pith. Because of the pith and low density, a large proportion of this timber would be of low grade, irrespective of branch diameter. This could explain the absence of a significant relationship between grade and the observed bd_{av}.

Medium diameter logs were from lower in the stem and, therefore, were composed of a greater number of growth rings. They too contained a core of low density wood similar in absolute diameter to that from smaller diameter logs. However, some of these logs were probably composed of intermediate or high density wood of higher strength. Branch diameter in this zone may still not have been large enough to reduce grade, perhaps explaining why timber grade from medium diameter logs also appeared unaffected by branch diameter. Since the diameter of the juvenile core from these logs was probably similar to that of small diameter logs a similar amount of low grade timber was obtained.

However, timber sawn from the zone of wood away from the core was of higher density and therefore of higher grade.

Large diameter logs were from the lower stem. The core of these was probably wider than in smaller logs from the upper stem, having grown when the trees were younger, prior to canopy closure and before the onset of intense competition. Since juvenile wood is a physiological phenomenon, controlled by cambial age rather than stem width, wider growth rings result in a wider juvenile core (Nicholls and Dadswell, 1965). Thus, there was slightly more low grade framing obtained from large diameter logs compared with small diameter logs, even from logs with small diameter branches. However, most of the additional diameter from such logs was of higher density, outer wood, which produced better grade timber. Large diameter logs with thicker branches probably also produced a greater proportion of high density wood. However, branch diameter in the mature wood zone was such that timber cut from here contained wide knots which lowered the stress grade.

10.6.2 Evidence supporting this hypothesis

Further evidence was obtained supporting the hypothesis that timber grade from small diameter logs was influenced mainly by the presence of low density, juvenile wood in association with the pith.

The mean air dry density of each of the 110 pieces of 90 mm x 35 mm framing held for further study (Section 10.4.2.b) was measured, as was the diameter of the widest knot. Pieces were classed by the lowest machine stress grade within each piece. The mean diameter of the largest knot in each grade class was calculated. The frequency of occurrence of pith was noted for each class.

Table 10.4 shows the number of pieces of each grade, the number of each grade containing pith, the mean air dry density of each grade and the mean maximum knot diameter of each grade.

Table 10.4 Comparison of the characteristics of 90 mm x 35 mm framing of different minimum machine stress grades

	lowest machine stress grade in piece				
	F4	F5	F8	F11	all pieces
number of pieces	14	58	37	1	110
number with pith	13	28	0	0	41
mean air dry density	443 (38)	474 (37)	535 (43)	636 (-)	492
mean max knot diam.	23 (4)	21 (6)	19 (3)	15 (-)	21

Figures in brackets are standard deviations.

Pieces of F4 grade had very low density and almost invariably contained pith (Table 10.4). All had therefore been located near the centre of the tree. The F4's also had the largest mean maximum knot diameter but only slightly larger than F5 grade pieces.

Pieces containing pith were always F4 or F5. Those having very low density and relatively large knots (maximum of about 25 mm) were F4. Those with slightly higher density and smaller knots were F5.

Pieces generally attained a minimum grade of F8 if they had relatively high average air dry density, and maximum knot diameter less than about 25 mm, that is, if they were located in the mature wood zone, away from the centre of the stem, and if knots were not excessively large. There was only one piece of F11 grade so that no valid comments can be made, however, this piece had the highest density and had smaller knots than the average F8.

The results of this study support the hypothesis outlined in 10.6.1. Timber sawn from the centre of each log, as evidenced by the presence of pith, was of low mean density. All pieces containing pith were either F4 or F5 grade.

Pieces without pith and therefore sawn from the outer part of the tree were, with one exception, always graded F5 or higher. Knot diameter appeared to influence the grade of these pieces, the maximum knot diameter averaged 24 mm for F5's without pith, compared with 19 mm for higher grade. Mean density also bore a strong relationship with grade, being 481 kg per m^3 from pith free F5, compared with 535 kg per m^3 in F8 timber. The single piece of F11 in the sample had the highest density (636 kg per m^3).

It should be noted knot diameter was relatively small compared with some other studies. In a study of timber grade recovery, Whiteside (1982) observed the effect of knots ranging up to 80 mm diameter, in logs ranging up to about 700 mm sedub. With such variation the effect of branch diameter on timber grades would probably be more obvious than observed in this study.

10.6.3 The effect on loss of value recovery of varying the price relativities for the various framing grades

At the time the study was conducted the mill involved received no premium for the highest grade framing timber it produced (F11). Timber of minimum useable grade (F4) was priced at \$ 250 m^{-3} . Timber meeting minimum requirements for building grade (F5) attracted an additional \$ 155 m^{-3}. The premium grades (F8 and F11) were valued at an additional \$ 61 m^{-3} . Thus, under the price structure adopted at this mill, the greatest economic gain through tree breeding will be achieved by eliminating trees with very large diameter branches from the breeding population, rather than by increasing the proportion of trees having very small diameter branches.

Increasing the premium on high grade material would change this to a small degree. The effect of doubling the premium on F11 grade(*ie.* from \$66 m^{-3} above the price of F5 to \$ 132 m^{-3} above) was investigated. The average price for framing from small branched, large diameter logs increased from \$420 m^{-3} to \$ 429 m^{-3} . That for medium branched, large diameter logs increased from \$400m^{-3} to \$ 404 m^{-3} and for large branched, large diameter logs the increase was from \$ 378 m^{-3} to \$ 381 m^{-3} . In other words, the loss of value recovery from medium branched, large diameter logs increased from \$20 m^{-3} to \$ 25 m^{-3} and for large branched, large diameter logs from \$42 m^{-3} to \$ 48 m^{-3} .

The effect of adopting the price relativities operating in the New Zealand radiata pine market were also investigated. Prices for grades equivalent to Australian machine stress graded framing, listed in Whiteside (1982) were adjusted so that F5 grade was priced the same as in the present study (\$405 m^{-3}). The prices for the other grades became \$ 348 m^{-3} for F4, \$490 m^{-3} for F8 and \$ 547 m^{-3} for F11 (*ie.* the New Zealand prices were more closely related to timber strength). For Large diameter logs, the mean framing prices under this schedule became : \$447 m^{-3} for logs with small diameter branches; \$427 m^{-3} for logs with medium diameter branches and \$399 m^{-3} for logs with large diameter branches. The loss of value recovery caused by large branch diameter was thus \$20 m^{-3} from medium branched logs and \$48 m^{-3} from large branched logs. Under this schedule, therefore, there was greater loss of value recovery from logs with large diameter branches, while the relativity between small branched and medium branched logs remained unchanged.

The New Zealand price list also includes a 'box grade' framing for timber having a machine stress grade less than F4 (classed as reject in the present study and priced at zero). In relation to the price for F5 of \$405 m^{-3} the box grade in the New Zealand list was priced at \$255 m^{-3} . If the reject grade from the study is classed as box grade and the New Zealand list used, the loss of value recovery for the large branched logs is reduced to \$36 m^{-3} .

The above discussion serves to illustrate the sensitivity of the analysis presented in this chapter to changes in the price relativities for the various framing grades. No matter which of the above price schedules is used, small branched, large diameter logs always had a price advantage over medium and large branched logs. The price difference between small branched and large branched logs only varied from \$36 m^{-3} to \$48 m^{-3} , or 25 per cent. Thus, while the results do vary according to the price schedule used, they are not overly sensitive to price variations that could be expected to occur within the radiata pine market.

10.7 Summary

The relationship between average branch diameter and framing grades from logs classified into three bd_{av} and three sedub classes was investigated. Branch diameter only influenced framing grade in large diameter logs. The results enable estimation of the loss in market value caused by large diameter branches.

Chapter Eleven

CALCULATION OF ECONOMIC WEIGHTS FOR BRANCH DIAMETER

11.1 Introduction

This chapter illustrates the method of calculating an economic weight for branch diameter as described in Chapter 5. An estimate of the loss of value recovery caused by branch diameter (lvr_{bd}) is the basic parameter required for the calculation (Section 5.3, p.57). The economic weight is derived from the slope of a least squares regression equation fitted to the relationship between lvr_{bd} from stems and branch diameter measurements or scores.

The information needed for calculating lvr_{bd} from *P.radiata* stems was obtained from the analysis, presented in the previous chapter, of the relationships between the market value of sawn timber recovered from saw logs and an index of average branch diameter (bd_{av}). In this chapter these results are used to calculate the lvr_{bd} from the stems felled in PT3. The analyses of the regressions between lvr_{bd} and branch diameter measurements or scores at ages 13, 25 and 34 are presented and the economic weight for branch diameter at each of these ages determined.

11.2 Calculation of the loss of value recovery, caused by large diameter branches

11.2.1 The lvr_{bd} from individual logs

Analysis of grade distributions of timber framing recovered from saw logs showed branch diameter only had a significant influence on timber grades and, consequently, market values, when bd_{av} was larger than 16 mm and sedub was greater than 219 mm (Section 10.5.3, p.151). From this result it was concluded branch diameter did not cause any lvr for logs having bd_{av} less than 17 mm and sedub less than 220 mm (Section 10.5.3). For logs of large sedub the price differential between logs having small bd_{av} and logs having medium or large bd_{av} represents the loss in market value of framing timber caused by large branches. Table 11.1 summarises these results. The losses in market value are expressed in dollars per cubic metre of framing timber recovered.

Table 11.1 Estimates of the loss in market price caused by large bd_{av}, derived from Table 10.3 (\$ per m^3 of framing recovered)

	sedub class of the log (mm)	
bd_{av} class of the log (mm)	<219	>219
<17	0	0
17-21	0	20
>21	0	42

The lvr_{bd} for each log was calculated by multiplying the estimated volume recovery of framing timber by the loss in market value according to Table 11.1.

The steps used to calculate lvr_{bd} for each log in the study were thus:

[1] locate the appropriate cell in Table 11.1 according to the log's bd_{av} and sedub, and read the appropriate value;

[2] estimate framing volume recovery according to the equation:

$VR = 0.0006 \times \text{sedub} - 0.076$; (Section 10.5.4,p.150)
N.B. sedub in mm

[3] $lvr_{bd} = [1] \times [2]$.

Step [2] was included for two reasons:

(1) There was no comparable estimate of the loss in market value caused by large bd_{av} in veneer logs. Therefore veneer logs were treated as if they were saw logs; thus creating the necessity to predict volume recovery from the log parameters. For saw logs, sedub showed the strongest correlation with framing volume and the equation gave the best predictive model for recovery.

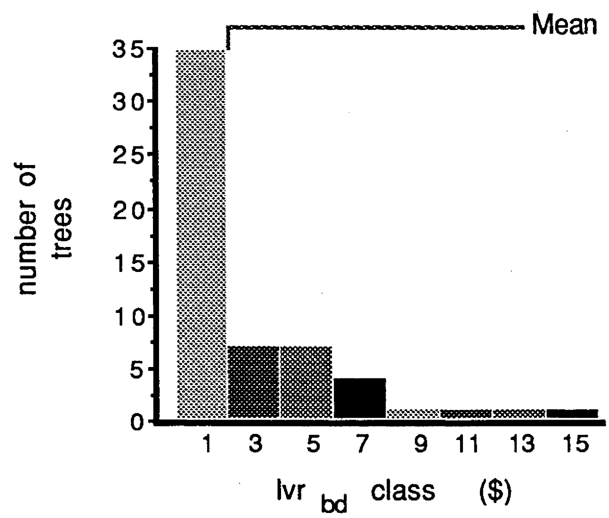
(2) For consistency, framing recovery from saw logs was also estimated by this equation, rather than using the actual volume of framing recovered from each saw log. This avoided the effect of random variation in processing and prevented other log parameters such as sweep from affecting the calculation of lvr_{bd} (Section 10.5.4, p.153).

11.2.2 The lvr_{bd} from whole stems

For each stem, total lvr_{bd} was determined by summing the log by log estimates. For eight of the 65 trees felled in PT3, lvr_{bd} was not estimated due to insufficient branch diameter measurements on some logs. Reasons for the incomplete data set were detailed in Section 6.3 (p.67). The frequency distribution of lvr_{bd} from the remaining 57 trees felled in PT3 is depicted in Figure 11.1. The numbers on the X-axis represent the mid points of \$2 classes.

Only a few stems had lvr_{bd} of more than $8; the average was $2.05. From 31 stems there was no lvr_{bd} (In Figure 11.1 these are included in the 0 to $1.99 class). This was partly the result of small stem size. Trees having dbhob less than about 30 cm did not produce any logs larger than 220 mm sedub and therefore were not effected by bd_{av}. The implications of this are discussed later.

Figure 11.1 Frequency distribution of lvr_{bd} from 57 trees in PT3



11.3 The relationships between lvr_{bd} and branch diameter measured at age 13 and scored subjectively at ages 25 and 34

11.3.1 Simple linear regressions

When the trees in PT3 were 13 years old the diameters of the branches at the base of each stem had been measured. At ages 25 and 34 branch diameter on these stems had been scored subjectively on a 5 point scale (Table 6.3, p.65). For each of the age 13 measurements and the age 25 and age 34 scores, branch diameter was plotted against lvr_{bd} and least squares regression lines drawn (Figures 11.2 to 11.4). In each figure the Y-axis represents the loss of value recovery estimated to have been caused by large average branch diameter, expressed in dollars per stem. The X-axis shows the branch diameter measurements or scores on the standing stems at the time of the assessment.

Figure 11.2 Relationship between the branch diameter measurement at age 13 and lvr_{bd}

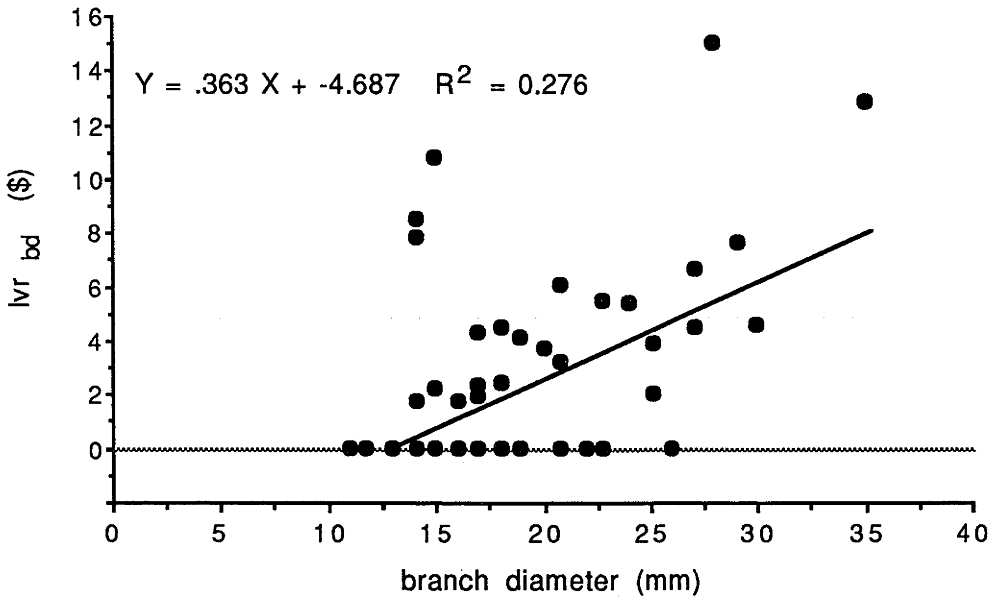


Figure 11.3 Relationship between the branch diameter scores at age 25 and lvr_{bd}

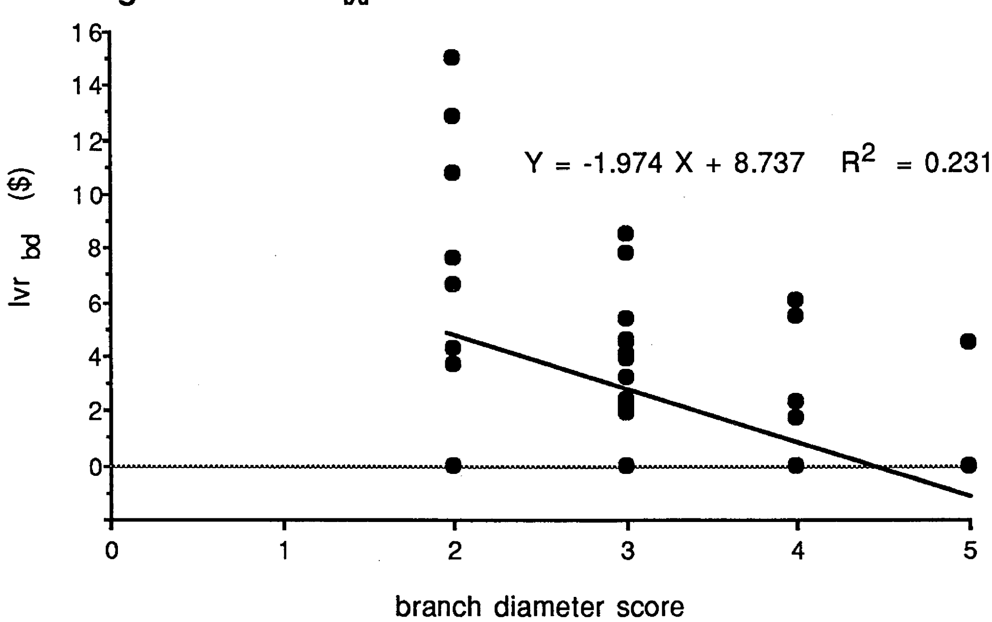
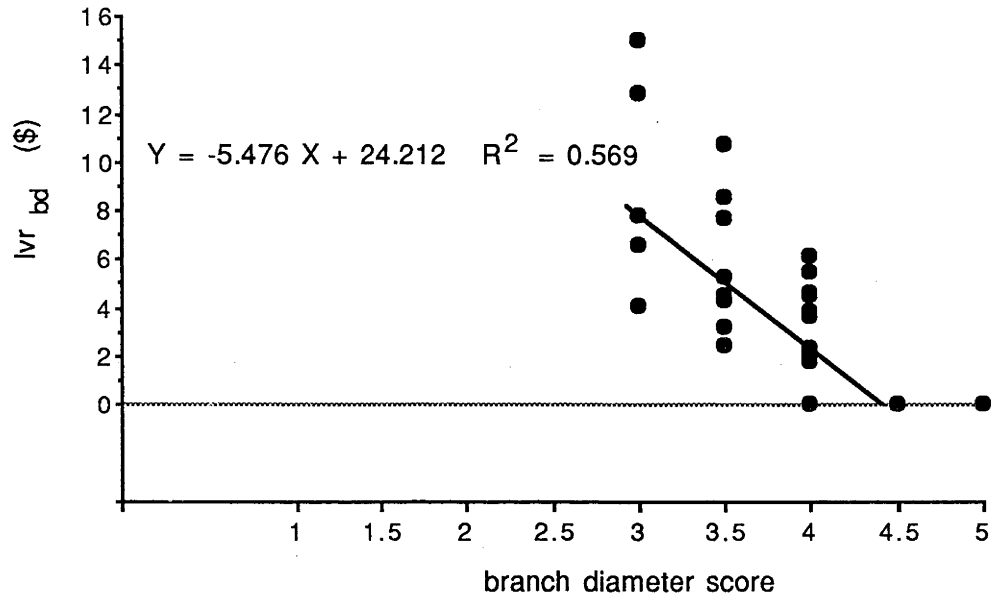


Figure 11.4 Relationship between the branch diameter scores at age 34 and lvr_{bd}



There was a statistically significant correlation between lvr_{bd} and branch diameter ($P< 0.001$ in all cases). As judged by the R^2 shown in Figures 11.2 to 11.4, more than half the variation in lvr_{bd} was explained by the age 34 branch diameter scores and about one quarter by the earlier measures and scores.

The difference in the direction of slope of the regression using age 13 branch diameter compared with regressions using later age branch diameter is due to the assessment scales used. At age 13 branch diameter was measured directly on a few branches at the base of each stem; thus a large measure indicated large diameter branches. In the other two assessments subjective scales were used on which a high score represented small diameter branches (Section 6.2, pp.64 and 66).

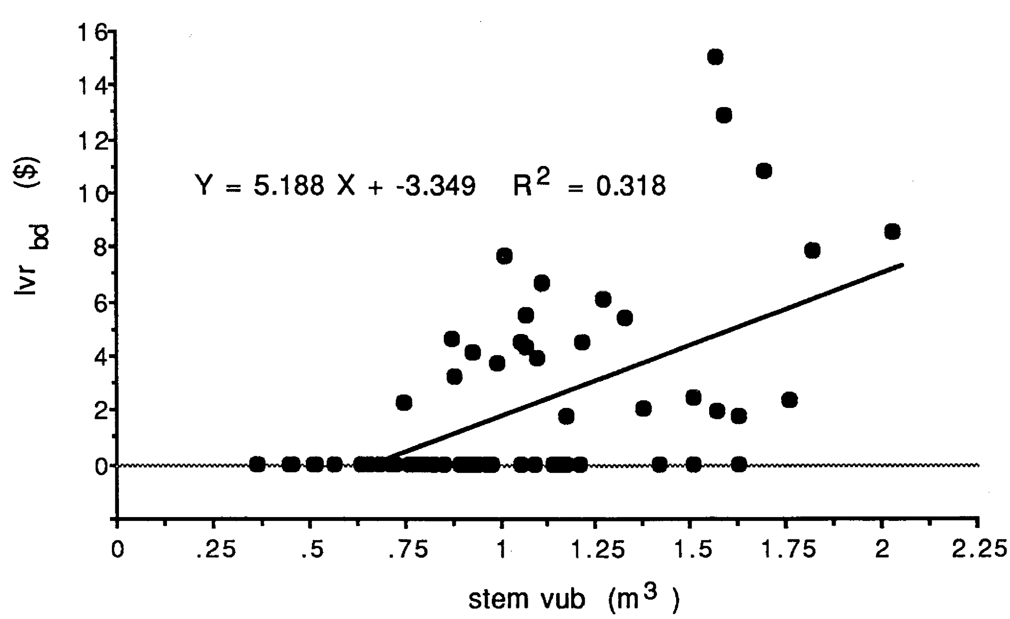
Although the age 25 and age 34 assessments were both on 5 point scales the slopes of the two regressions differed significantly. A 1 point change in the age 25 scores corresponded with a $1.97 change in lvr_{bd}, while a 1 point change in the age 34 scores corresponded with a $5.48 change in lvr_{bd}. This was partly because stem straightness at age 25 was judged relative to the best and worst in the experiment resulting in a spread of scores across 4 points out of the possible 5, while at age 34 stem straightness was judged on an absolute scale, resulting in a narrow spread of scores in this particular case. As a consequence 1 point in branch diameter at age 25 represented a smaller absolute range than 1 point at age 34.

11.3.2 The influence of stem vub at felling age on the relationships

Before calculating economic weights, the relationship between lvr_{bd} and stem size was investigated. The plot of lvr_{bd} against age 34 stem vub indicated a significant positive correlation (Figure 11.5). The least squares regression equation was:

$$lvr_{bd} = -3.35 + \underset{(0.958)}{5.188}\,vub. \qquad R^2 = .318$$

Figure 11.5 Relationship between age 34 stem vub and lvr_{bd}

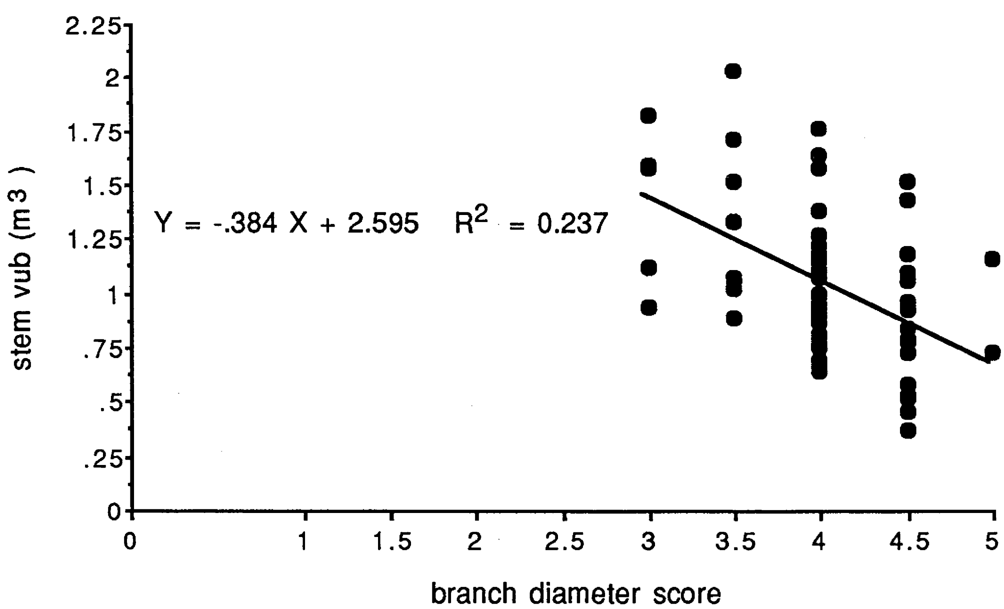


There were two reasons for the existence of this significant correlation. Firstly, branch diameter only influenced value recovery from logs larger than 220 mm sedub (Section 10.5.3, p.151). If no logs were larger than 220 mm sedub, there was zero lvr_{bd}. As stem size increased, an increasing volume of timber came from logs larger than 220 mm sedub. Therefore the volume of timber influenced by branch diameter also increased.

Secondly, there was a significant negative correlation between stem size and branch diameter score. As indicated in Figure 11.6, the largest stems had low branch diameter scores (*i.e.* the largest diameter branches), and therefore the greatest lvr_{bd}.

Multiple regression analysis including age 34 stem vub and branch diameter at ages 13, 25 and 34 as X variables produced the regression equations detailed in Table 11.2.

Figure 11.6 Relationship between age 34 stem vub and age 34 branch diameter score



Seventy one per cent of the variation in lvr_{bd} was explained by the age 34 equation. It indicated that a one point increment in age 34 branch diameter score resulted in an increment in value recovery per stem equal to $4.26 × vub. From a stem of average size (1.04 m^3) this equated with a $4.43 difference. The economic weights for branch diameter were, therefore, dependent on the size of the stems at clear felling age.

Table 11.2 Regression equations relating stem vub at age 34 and branch diameter at age 13, 25 and 34 to lvr_{bd}

Age of branch diameter assessment	Regression equation	R^2
13 (standard errors)	-3.38 + 0.29 bd × vub (0.67) (0.03)	0.562
25 (standard errors)	-2.43 + 9.91 vub - 1.68 bd × vub (0.91) (1.22) (0.33)	0.522
34 (standard errors)	-0.37 + 19.24 vub - 4.26 bd × vub (0.77) (1.67) (0.47)	0.707

If reduction in branch diameter has no effect on the total costs of growing, harvesting and processing (Section 5.3.3, p.58), the increment in value recovery from a stem of average vub at age 34, also represents the increase in net economic worth per stem (ew_{net}) at the same age. This increase can be used as the economic weight. The economic weights for branch diameter were calculated in this manner, *i.e.*, by substituting the average stem vub in PT3 at age 34 into the regressions shown in Table 11.2. The resulting economic weights were:

$ -0.30 per mm for the age 13 branch diameter measurements;

$ 1.75 per point for the age 25 scores and;

$ 4.43 per point for the age 34 scores.

11.4 Discussion

The dependence of the economic weight for branch diameter on another economically important trait, stem size at age of harvesting, has serious implications for tree breeders. It means the stem size of the final crop must be considered during economic weight calculation. Branch diameter is more important when trees are grown on a long rotation at low stocking and using growth enhancing treatments such as weed control and fertilizer application, but less important when trees are harvested young after growing at close spacing with no weed control or fertilizer. In the first case, long rotation, low stocking and growth enhancement would result in large diameter stems and consequently a large volume of mature wood. Also branches would be of large diameter, resulting in large knots. Thus, reduction of branch diameter through breeding would be important. In the second case, stem diameter and branch diameter would be far smaller and consequently there would be little to gain through reduction in branch diameter by breeding.

Chapter Twelve

INDEX SELECTION USING ECONOMIC AND EQUAL EMPHASIS WEIGHTS

12.1 Introduction

The economic weights for stem straightness and dbhob presented in Chapter 8 and for branch diameter presented in Chapter 11 were used, along with estimates of phenotypic and genetic parameters, to calculate Smith-Hazel indices for tree selection in PT3. Alternative indices using equal emphasis weights instead of these economic weights, were also calculated. The two sets of indices were applied to the population of 195 *P.radiata* stems remaining alive in PT3 at age 34. Predicted economic gains were calculated for a 1 in 100 selection among this population. Both sets of indices were evaluated for each tree and the trees ranked in order from best to worst. The aim of the analysis was to show:

(1) whether the relative emphasis placed on the three traits was influenced by the weighting method,

(2) whether use of economic weights produced higher predicted economic gains than use of equal emphasis weights, and

(3) the effect of time of selection on predicted economic gains.

12.2 A comparison of economic with equal emphasis weights

The determination of economic weights using assessments of traits at several ages in PT3 was detailed in Chapters 8 and 11. The weights calculated for the age 13/16 and age 34 assessments are listed in Table 12.1. The weight for stem straightness at age 34 was determined from the mean score of the three assessments. The weights for stem straightness and branch diameter were determined for stems of average vub at age 34 in PT3. As shown in Chapters 8 and 11, the economic importance of these traits was dependent on the average stem vub at the time of clear felling.

The phenotypic standard deviations for each trait are also shown in Table 12.1. The population used in the calculation was the 195 trees alive in PT3 at age 34 (Even though more than 195 trees were present at ages 13 and 16, only the 195 left at age 34 were used in the calculation of standard deviations). As explained in Chapter 2, an equal emphasis weight is the reciprocal of the trait's standard deviation. The equal emphasis weights based on the age 34 and age 13/16 assessments are listed in Table 12.1.

Table 12.1 Economic weights and equal emphasis weights calculated for dbhob, stem straightness and branch diameter in PT3

Age of assessment	Type of weight	dbhob	Stem straightness	Branch diameter
34	Economic	1.71	2.12	4.43
	Equal emphasis	0.13	1.22	2.04
Trait standard deviation in PT3		7.64	0.82	0.49
13/16	Economic	2.58	1.57	-0.30
	Equal emphasis	0.33	1.56	-0.18
Trait standard deviation in PT3		3.05	0.64	5.44

The weights for subjective scores of stem straightness and branch diameter are positive because the scales of assessment were arranged so that a high score indicated a desirable type. The weight for branch diameter at age 13 is negative because this trait was measured objectively. An increase in the measured value corresponded with an increase in the thickness of the branches, which was undesirable and therefore had a negative effect on net economic worth.

A direct comparison of the different weights presented in Table 12.1 does not indicate the comparative importance placed on the three traits by the different weighting methods. The economic weights are easy to understand. They indicate the gains in average net stem worth in dollars at age 34 which would eventuate if each trait were to be improved by an average of one measurement unit. However, the economic weights do not indicate how easy it is to achieve those economic gains. To do this the variability of each trait, that is, the standard deviation, needs to be taken into account.

In contrast, the equal emphasis weights do not indicate the size of economic gains achievable by improving each trait but do indicate the relative ease with which a gain of 1 measurement unit in each trait can be achieved. The lower the equal emphasis weight the easier it is to achieve a gain equal to 1 measurement unit. In PT3 at age 34, for example, the standard deviation for dbhob is much larger numerically than for stem straightness score; 7.64 cm compared with 0.82 of a point. Clearly it would be much easier to obtain a gain of 1 cm in dbhob than a gain of 1 point in stem straightness because the former only requires an average improvement equivalent to 0.13 standard deviations, while the latter requires an improvement equivalent to 1.22 standard deviations. Equal emphasis weights place the emphasis on maximising selection efficiency in terms of the total number of standard deviations of improvement achieved; while economic weights emphasize maximisation of total economic gain.

The economic weights were adjusted to enable direct comparison with the equal emphasis weights. This was done for each assessment by multiplying each trait's economic weight by the phenotypic standard deviation. The resulting values expressed the economic worth of a gain equivalent in magnitude to one phenotypic standard deviation. Based on the age 34 assessment these 'standard deviation economic weights' for dbhob, stem straightness and branch diameter were 13.06, 1.74 and 2.17. Using the same procedure for equal emphasis weights, that is, multiplying weight by standard deviation, the weights are all 1.

Table 12.2 Weights adjusted to show the relative emphasis placed on a one standard deviation improvement in each trait

Age of assessment	Type of weight	Relative emphasis		
		dbhob	Straightness	Branch diameter
34	Economic	7.52	1.00	1.25
	Equal emphasis	1.00	1.00	1.00
13/16	Economic	7.83	1.00	1.62
	Equal emphasis	1.00	1.00	1.00

Direct comparison of the relative emphasis placed on each trait was made by adjusting the 'standard deviation economic weights' to give one trait a weight of 1.00. Since stem straightness had the lowest economic weight, it was adjusted to a weight of 1.00. The full set of adjusted weights showing the relative importance placed on an improvement equivalent to 1 standard deviation in each trait, are listed in Table 12.2. The emphasis placed on each trait by the economic weight compared with the equal emphasis weight can be assessed by dividing the former by the latter.

The results show that when improvement was measured in terms of each trait's standard deviation, the economic importance of the three traits differed. Far from being of equal importance, dbhob was nearly 8 times more important, economically, in PT3 than stem straightness and about 5 or 6 times more important than branch diameter, depending on the age at which the assessment took place. Therefore, in this progeny test, economic gain would not be maximised by selection on an equal emphasis weighted selection index.

The appropriateness of equal emphasis weights depends on the variability of each trait within the population from which selections are made. In a stand of more uniform tree size, but more variable straightness than PT3, as might occur in a *P.radiata* plantation established at a wide spacing, the difference in the relative economic importance of these two traits would be less. PT3 was planted at relatively close spacing (about 1700 stems per ha) and was not thinned for 20 years. Intense competition between trees creates wide variation in dbhob. On the other hand when the space available to each tree is limited, reasonably straight stems with thin branches result. The selective thinning in 1979 may have removed most of the smaller and poorer quality trees, reducing variation in all three traits. Variability within other stands of *P.radiata* will differ from PT3 according to silvicultural treatments and site characteristics. However, it is probably rare that economic weights and equal emphasis weights give the same relative importance to the traits considered during tree selection. Use of equal emphasis weights will virtually always result in lower than maximum economic gain.

12.3 Smith-Hazel indices for tree selection in PT3, calculated using economic and equal emphasis weights

To demonstrate the consequences of using equal emphasis weights instead of economic weights in a Smith-Hazel selection index, four sets of indices were calculated based on phenotypic variance and covariance information from PT3. The experiment was unsuitable for calculation of genetic parameters (Chapter 6, p.62), so the standard heritabilities and genetic correlations for *P.radiata* in Australia, listed by Cotterill *et al* (1988), were used instead. For each of the four sets of weights in Table 12.1 the vector of b coefficients in a Smith-Hazel index was calculated by the formula:

$$[b] = [P]^{-1}[A][w]$$

where: [b] is the vector of coefficients in the Smith-Hazel index

[P] is the phenotypic variance/covariance matrix

[A] is the genetic variance/covariance matrix, and

[w] is the vector of weights from Table 12.1.

Phenotypic and genetic variance and covariance data and the calculations are shown in parts 3.2 to 3.4, Appendix 3. The four Smith-Hazel indices derived are listed in Table 12.3.

Table 12.3 Smith-Hazel selection index coefficients derived using the weights in Table 12.1

Age of assessment	Type of weight	b - coefficients		
		dbhob	Straightness	Branch diameter
34	Economic	0.48	0.03	4.08
	Equal emphasis	0.05	0.32	1.08
13/16	Economic	0.72	1.23	-0.23
	Equal emphasis	0.16	0.53	-0.10

As with the individual weights in Table 12.1, the index coefficients differ between weighting methods partly because different units were used for the economic weights. Thus, when presented in this form, the coefficients do not reveal much about the effect on the index coefficients of varying the relative economic importance of each trait. For a better comparison between indices, each was adjusted to make the b - coefficient for stem straightness equal to one. The results are shown in Table 12.4.

Table 12.4 Smith-Hazel selection index coefficients derived from Table 12.3 adjusted so that stem straightness had a coefficient of 1.00

Age of assessment	Type of weight	Adjusted coefficients		
		dbhob	Straightness	Branch diameter
34	Economic	16.00	1.00	136.00
	Equal emphasis	0.16	1.00	3.38
	(Ratio)	(100)	(1.0)	(40)
13/16	Economic	0.59	1.00	-0.19
	Equal emphasis	0.30	1.00	-0.19
	(Ratio)	(2.0)	(1.0)	(1.0)

In Table 12.4 the ratio between adjusted coefficients for the two types of weighting methods within each age category is important. These ratios show how much more emphasis was given to dbhob and branch diameter in the economic index compared with the corresponding equal emphasis index, if stem straightness had an emphasis of 1.00 in both indices. For the age 34 indices the economic weighted index gave dbhob 100 times more importance than the equal emphasis index, even though the economic weight itself was only 7.52 times the equal emphasis weight (Table 12.2). Similarly, the economic weighted index gave branch diameter 40 times more importance than the equal emphasis index, even though the ratio between economic and equal emphasis weights was only 1.25. This was because in addition to stem straightness having relatively low economic importance at age 34, it also showed moderate positive phenotypic correlation with dbhob. Thus when strong emphasis is given to dbhob in selection, there is direct economic gain through improvement of dbhob, while stem straightness will also be expected to improve due to its correlation with dbhob, so there is little need for direct selection for straightness. While branch diameter was also of low economic importance compared to dbhob at age 34 it was moderately, adversely correlated with dbhob and weakly, adversely correlated with stem straightness. There must necessarily be active selection for branch diameter to offset the deterioration in this trait through its adverse correlation with dbhob.

The difference between the economic weighted index and equal emphasis weighted index using age 13/16 data was relatively minor. From Table 12.2, an economic weight gave dbhob 7.83 times more emphasis than an equal emphasis weight, but the relative difference in the Smith-Hazel index coefficients was only 2 times. A change in the relative weight of branch diameter from 1.62 to 1.00 did not reduce its importance. Clearly the effect on index coefficients of varying the economic importance of traits depended on the other parameters used in the calculation of the index coefficient. In the example presented here these differing effects may have been caused by differences in the phenotypic correlations between traits at the different assessment ages. Table 12.5 lists these correlations. The main difference was in the correlation between dbhob and stem straightness. At age 34 it was moderate (0.476), but at age 13/16 it was weak (0.076).

Table 12.5 Phenotypic correlation between traits, age 34 and age 13/16

Age of assessment		Straightness	Branch diameter
34	dbhob	0.477	-0.552
	Straightness		-0.180
13/16	dbhob	0.076	0.542
	Straightness		0.056

Probably every progeny test has its unique set of parameters, and the results in PT3 cannot be applied generally. In some progeny tests the relative size of individual index coefficients might be very sensitive to changes in the relative economic importance placed on traits. In other progeny tests they might be robust, changing little with a change in relative economic weights. Tree breeders ought to be aware of the degree of sensitivity of selection indices to variation in the relative importance placed on traits. The next section illustrates the effect of the different weighting methods on predicted gains from a 1 in 100 selection in PT3.

12.4 Expected genetic and economic gains using index selection

The genetic gains expected following selections at an intensity of 1 in 100 in PT3 were calculated using each of the four sets of indices listed in Table 12.3. The method used was that described by Cotterill *et al* (1988). The details of the calculations are shown in part 3.5, Appendix 3 and the results presented in Table 12.6.

Table 12.6 Predicted genetic gains resulting from selection at an intensity of 1 in 100 in PT3

Age of assessment	Type of weight	Predicted gains (at assessment age)		
		dbhob (cm)	Straightness(points)	Branch diameter
34	Economic	3.76	0.27	0.11 points
	Equal emphasis	1.50	0.30	0.20 points
13/16	Economic	1.65	0.34	-1.81 mm
	Equal emphasis	1.34	0.45	-3.61 mm

At both ages an economic weighted index gave more gain in dbhob than an equal emphasis weighted index, but less gain in the other two traits.

At age 34, both weighting methods gave a similar expected gain in stem straightness. However, the economic weighted index gave more than twice as much expected gain in dbhob but only half as much in branch diameter score.

For selection at age 13, the economic weighted index gave slightly more gain in dbhob than the equal emphasis index (1.65 cm compared with 1.34 cm) and slightly less gain in stem straightness (0.34 points compared with 0.45 points). The economic weighted indices gave only half as much gain in branch diameter (-1.81 mm compared with - 3.61 mm).

The expected gains in economic worth per stem (ew_{net}) were calculated by multiplying predicted genetic gain for each trait by the corresponding economic weight in Table 12.1 (Part 3.5 of Appendix 3). The results are shown in Table 12.7.

At age 34, an economic weighted index gave 83% more gain in age 34 ew_{net} than an equal emphasis weighted index. In contrast, the difference was small when the age 13/16 index was used (2%).

If tree selection had taken place in PT3 at age 34, the economic gain would have been 83% more if an economic weighted index had been used. For the particular set of parameters in PT3 at age 34 it was therefore extremely important to use the correct economic weights. Equal emphasis weights were certainly inappropriate. If, however, selection had taken place at age 13/16, it would have made very little difference which set of weights was used in the index, despite dbhob being nearly 8 times more important at this age than stem straightness and 5 times more important, economically, than branch diameter. Clearly the importance of using the correct economic weights depends, to some extent, on the other parameters involved in the index calculations.

Table 12.7 Gains in ew_{net} per stem predicted from the genetic gains listed in Table 12.6

Age of assessment	Type of weight	Predicted gain in age 34 ew_{net} ($ per stem)			
		d.b.h.o.b.	Straightness	Branch diameter	Total
34	Economic	6.43	0.57	0.49	7.49
	Equal emphasis	2.56	0.64	0.89	4.09
13/16	Economic	4.26	0.53	0.54	5.33
	Equal emphasis	3.45	0.71	1.08	5.24

It was also determined, using the data in Table 12.7, that gain in ew_{net} at age 34 was 43.5% greater if selection was made on an economic weighted index at age 34 compared with selection on the same basis at age 13/16. However, this extra gain would be achieved after waiting a further 20 years before selection, resulting in an increased generation length from perhaps 17 to 37 years (Cotterill,1986) in which case the gain per decade would be reduced from about $3 per tree to about $2. (Gain per decade was calculated by dividing economic gain in Table 12.7 by generation length and multiplying by

10). Therefore, although the late selection would result in more gain per generation, the early selection would give more gain per decade.

12.5 Comparison of the characteristics of the four sets of ten 'best' trees selected out of the 195 in PT3 using the four selection indices

Each of the four selection indices in Table 12.3 was used to rank the 195 trees standing in PT3 in 1985, and to choose the best 10. Each of the four lists of 10 top-ranked trees was compared with the other three lists. The number of trees (out of 10) common to pairs of selections are shown in Table 12.8.

Only one tree was ranked in the top ten by both the age 13/16 and age 34 indices. Selection at age 13/16, therefore, would not have enabled identification of the 10 most valuable trees at age 34. Further, the trees selected differed between weighting methods. Six trees were ranked in the top ten by both the age 13/16 indices while only five were ranked in the top ten by both the age 34 indices.

Table 12.8 Number of trees common to pairs of selected groups

		Age of assessment		
Age of assessment	Type of weight	34 Equal emphasis	13/16 Economic	13/16 Equal emphasis
34	Economic	5	1	1
	Equal emphasis		1	1
13/16	Economic			6

The characteristics of the four sets of 10 'best' trees according to the different indices are shown in Table 12.9

Table 12.9 Group means for each trait (mean of 10 trees ranked top by each index)

Age of assessment	Type of weight	Age 34			Age 13 or 16		
		dbhob	Straightness	Br. diam.	dbhob	Straightness	Br. diam.
		(cm)	(point)	(point)	(cm)	(point)	(mm)
34	Economic	43.1	7.6	4.2	19.5	5.1	18.4
	Equal emphasis	36.4	7.7	4.6	17.0	5.2	16.3
13/16	Economic	42.0	7.2	3.8	22.4	5.2	16.5
	Equal emphasis	39.4	7.3	3.8	20.6	5.4	13.5
General mean (of 195 trees)		33.1	7.0	4.1	17.5	5.1	18.8

In several instances the means of individual traits for the ten selected trees changed considerably, relative to the general population mean, in the period between assessments. The ten trees selected by the economic weighted index at age 34 had a mean dbhob 1.3 standard deviations above the general mean, but at age 13 the difference was only 0.7 standard deviations (the standard deviations are given in Table 12.1). Similarly, the latter group had a mean straightness score 0.73 standard deviations better than the general mean at age 34 but had no straightness advantage at age 13. The group selected by the equal emphasis weighted index at age 34 had above average dbhob when selected, but slightly below average dbhob at age 13. Both groups selected on the age 13/16 indices had larger dbhob at age 13 than the group selected by the economic weighted index at age 34, but by age 34 had smaller dbhob. The age 13/16 selected groups also had branch diameters well below the general average when selected but their age 34 branch diameter scores indicate they had thicker branches than the general mean by age 34.

12.6 Discussion

12.6.1 The importance of determining economic weights correctly

From the data presented in this chapter stem diameter was a far more important trait for selection in PT3 than either stem straightness or branch diameter. The effect of this on the economic gains expected from tree selection varied markedly with the age at which the selection took place.

If selection had taken place at age 34 in PT3, use of economic weights presented in Chapters 8 and 11 would have led to 83% more economic gain than use of equal emphasis weights. In this case, therefore, the weighting method was extremely important.

If selection had taken place at age 13/16 the economic gain would have been only slightly affected by the weighting method used. Presumably the difference between the age 34 and age 13/16 selections was due to other factors, such as differences in phenotypic parameters or differences in the methods used to assess stem straightness and branch diameter.

While the results are directly applicable only to PT3, they do demonstrate there are circumstances when the expected economic gain from selection is extremely sensitive to the weighting method used. Further studies, encompassing a large number of progeny tests, ought to be undertaken to determine the sensitivity of potential economic gains to the index weighting method used.

Tree breeders should reappraise the use of 'equal emphasis' index weights. When these are employed in tree selection indices the potential economic gains can be substantially below optimum. They can only make such a reappraisal when accurate values for economic weights, such as those presented here, become available.

12.6.2 The use of subjective assessment scales anchored relative to variation within a progeny test

If correct economic weights are to be used in tree selection, subjective scales anchored relative to individual stand variation will not be suitable for tree selection as economic weights will have to be recalculated for every progeny test. Relative scales must be calibrated with a repeatable absolute scale of trait measurement if they are to be used for economic weighting. For example Shelbourne's (1966) photographic method would be useful for standardizing stem straightness scores between progeny tests. In tests scored on a relative scale, a few stems at each extreme and in the middle of the scale could be chosen at random and photographed. Detailed stem straightness measurements could then be made on the photographs and used to derive a repeatable absolute scale of stem straightness measurement against which the relative scale could be calibrated.

12.6.3 The applicability of the economic weights derived in PT3 to other stands

The relative economic weights presented in this chapter will be of greatest benefit to tree breeders if they can be applied to other forest stands. Although they are not directly applicable to other stands, if PT3 is considered typical of first generation seed orchard *P.radiata* stock, on the majority of sites the relative weights of the three traits can be expected to be similar to those reported here.

It has been shown that in PT3 stem size was of paramount importance in determining stem worth. Sweep and large diameter branches resulted in relatively minor reductions in the total value of timber recovered from the stand. The total value recovery from the 65 trees felled was $8 300. The estimated loss of value recovery caused by sweep totaled $336 from the 65 trees, while for the 57 trees for which loss of value recovery caused by large diameter branches could be determined the total loss was $133. Therefore, even if all trees in this group had been free of sweep, total value recovery of sawn timber would only have been four per cent better. Similarly, if all trees had been free of large diameter branches, total value recovery of sawn timber would only have been two per cent better. If the PT3 site is typical of most *P.radiata* sites, there may be little to be gained by attempting to continue to make improvements to stem straightness and branch diameter.

No data were collected that would enable an objective assessment of how typical the PT3 site is. However, as judged subjectively against the appearance of other *P.radiata* plantations of a similar age, it probably is representative of many *P.radiata* sites, being of average to good site quality and free of any peculiar problems such as trace element deficiencies, water logging and shallow soil.

A study by Wright (1967) indicates that final crop trees in *P.radiata* plantations of non improved stock are usually free of major defects. Wright conducted a detailed survey of the variability of a number of traits of *P.radiata* in four of Victoria's six major *P.radiata* regions. In total 620 final crop trees (the best 250 trees per hectare at age 16 years) were examined throughout the four regions. On each tree sweep and kinks to 9 metres height were assessed subjectively. The mean branch diameter in three branch whorls to nine metres height was measured.

Sweep and kinks were not correlated with site index. Most trees had slight butt sweep (in the lower 1.5 metres) and 60 per cent had slight stem sweep and slight kinks. More-severe sweeps and kinks were uncommon. In three regions, branch diameter was shown to be positively correlated with site index. In all regions branch diameter and stem diameter were positively correlated. The average branch diameter in all regions was between two and three centimetres. At a similar age in PT3 the average branch diameter had been about two centimetres.

From Wright's study it appears that even without genetic improvement, the best 250 tree per hectare in *P.radiata* plantations are mostly free of serious stem and branch defects. Given that some improvement in stem straightness and branch diameter has probably been achieved after one generation of tree breeding, it is likely the relative economic weights of stem diameter, stem straightness and branch diameter in PT3 are similar to those that exist at the majority of *P.radiata* sites planted with first generation seed orchard stock.

Chapter Thirteen

AN EVALUATION OF THE ECONOMIC VALUE OF THE TALLAGANDA SEED ORCHARD

13.1 Introduction

An important aim of tree breeding should be to improve the net economic worth of stems. If breeding goals have been achieved, the net economic worth of trees grown from seed orchard seed should be better than that of trees grown from unimproved seed sources. The economic benefits derived from a tree breeding program can be calculated by multiplying the average economic improvement achieved per tree by the number of trees produced by the breeding program, and then subtracting the costs of the breeding program. Since genetic improvement is distributed via seed from seed orchards, the total productivity of a tree breeding program can be determined from the number of trees achieved from improved seeds from an orchard, if the value added to each seed by tree breeding is known.

In the present study it has been possible to evaluate the average economic value of Tallaganda Seed Orchard (TSO) stock by comparing the performance of its progeny with unimproved stock, in conjunction with a record of the number of seeds produced over the orchard's life. The results of this analysis are presented in this chapter.

13.2 History of the Tallaganda Seed Orchard and experimental plantings of orchard seed

In 1957 a *P. radiata* clonal seed orchard was planted at Tallaganda, N.S.W. by the Commonwealth Forestry and Timber Bureau (now the CSIRO Division of Forestry and Forest Products) using 30 selected clones of A.C.T. plus trees. The orchard began producing seed in 1962 and by 1967 was yielding more than one million genetically improved seeds per year. Peak production occurred in 1973, when more than 6 million seeds were harvested. During its productive life from the early 1960's, when the trees were old enough to produce seed, through to the late 1970's, when the trees grew too large for cone collection to be practicable, the orchard yielded over 30 million seeds.

From 1969 onwards, trees grown from TSO seeds were planted in experimental plantations along with trees grown from unimproved seed sources. Because trees from the two seed sources were grown under identical conditions a direct comparison of their growth rates and other traits enabled an evaluation of the improvement effected in individual traits by tree breeding.

A comparison of the traits of TSO stock and an unimproved seed stock in one such experimental planting (Progeny Test Number 52) at Tallaganda State Forest, was made and the average differences between improved and unimproved stock in each trait evaluated in economic terms using the economic weights derived from PT3. The progeny of many control crosses of *P. radiata* select trees were also present in the progeny test. Three of these families, outstanding in at least one trait, were evaluated.

13.3 Comparison of the traits of TSO and an unimproved control

Progeny Test 52 (PT52) was planted in 1971. It is a large progeny test with several hundred controlled crosses of *P. radiata* plus trees, incorporating eight separate experiments, including several North Carolina II mating designs and diallel crosses. The eight experiments are mixed together on a single site. Each experiment is replicated 10 times in randomised blocks, giving a total of 80 experimental blocks. In addition to a complete set of one experimental treatment, each block contains one seedlot from the TSO and one seedlot of an unimproved seed source. The unit plots are 5 trees planted in a single row.

For the purposes of the present study 40 plots of the TSO stock and 40 of the unimproved stock (the controls) were located and marked in the field. In addition, 10 plots of three outstanding *P. radiata* full 'sib' families were marked as well as an additional 10 plots of the reciprocal cross of one of the families. The number of trees assessed for each seed source (excluding dead or missing trees) is shown in Table 13.1.

Assessments of dbhob, stem straightness and branch diameter were made in 1987 when the trees were 16 years old, using the same procedures as in the 1986 assessments of PT3 (Chapter 6, Tables 6.1 and 6.2). One observer (the author) subjectively assessed stem straightness and branch diameter in the TSO and control seedlots twice and in the outstanding families once.

To avoid observer bias the observations were carried out without the observer knowing the identity of plots being tested. Before the assessment began each plot was marked with a yellow ribbon. The positions of the marked plots within the experiment were noted simply as row numbers. When the observer made the subsequent assessments plots were located using the yellow ribbons only, the row number being noted for subsequent cross matching with seedlots. This procedure was adopted so that the observer could not identify individual seed sources during the assessment. However, such was the difference in vigor between TSO and the controls, it was usually easy to guess the seed source of individual plots. The observer may, therefore, have rated TSO stock better than he should, (an example of the error of leniency as described by Guilford, 1954). The difference in stem straightness scores may, have been exaggerated by this error. At the first scoring, the average difference between TSO and the controls was 0.8 points, at the second scoring 1.0 points. The observer may have become familiar with the appearance of the TSO and control seedlots during the first assessment and subconsciously exaggerated the difference on the second occasion. In the analysis of the economic worth of the TSO, the stem straightness scores from the first occasion have been used.

Table 13.1 Number of trees assessed in each seed lot

seed lot	number of trees
control	185
TSO	191
fam. 1	50
fam. 1 recip	48
fam. 2	40
fam. 3	46

The results of the assessments of the TSO and unimproved seedlots are presented in Table 13.2, The TSO had an average dbhob 3 cm larger than the controls and an average stem straightness score almost 1 point higher. The average branch diameter scores were almost identical.

Table 13.2 A comparison of dbhob, stem straightness and branch diameter of the TSO and control seedlots

trait	TSO mean	control mean	differences and their significance	standard errors
dbhob	22.0	18.9	3.1***	0.4
SS (1st)	6.7	5.9	0.8***	0.1
SS (2nd)	6.7	5.8	1.0***	0.1
BD(1st)	3.8	3.8	0.0	0.1
BD(2nd)	3.7	3.7	0.0	0.1

*** significant at the 0.0001 level

During the assessments it was obvious that a relationship existed between the dbhob and branch diameter of individual stems. Large sized stems generally had the largest diameter branches. Given the larger average dbhob of TSO stock it was expected these would have a lower average branch diameter score. However, this was not the case. The mean scores of the TSO and controls were almost identical (Table 13.2). Selection of branch diameter in tree breeding programs may, therefore, have maintained branch diameter at the existing size, rather than effecting an improvement. If there had been no selection for thin branched trees in early *P.radiata* breeding programs, this trait may have deteriorated.

13.4 Economic evaluation of the observed differences between TSO and the controls

The total difference in economic value per stem, between seed orchard and controls was evaluated by summing estimated differences attributable to individual traits. These individual differences were calculated by applying the economic weights detailed in Chapters 8 and 11 to the observed phenotypic differences between TSO and the controls.

The economic weight for age 13 dbhob in PT3 was $2.58, that is, each 1 cm increase in age 13 dbhob in PT3 increased harvest age economic value by an average $2.58. This economic weight was applied to the average difference in dbhob between TSO and the control seedlot in PT52, necessitating an assumption that the trees in PT52 will be harvested when about the same size as those in PT3 at age 34. The predicted difference in harvest age economic value per stem between TSO and unimproved stock, due to the difference in dbhob, was $2.58/cm $\times$ 3.1 cm, or $8.00.

Stem straightness in PT3 was scored out of 7 points at age 16, but in PT52 a 10 point scale was used. The economic weight for age 16 stem straightness calculated for PT3 was not therefore directly applicable to the assessment used in PT52. For the purpose of the analysis, the economic weight for age 34 stem straightness was used because the 10 point assessment scale used in PT52 was the same as that used in PT3 at age 34. The economic weight for stem straightness was therefore $2.12 per point of stem straightness. Again, this assumed the stems would be harvested with an average vub of about 1.04 m^3. The average 0.8 point difference in stem straightness between TSO trees and unimproved trees was multiplied by the economic weight, giving a value of $1.70 per stem.

The total predicted difference in economic value per stem between TSO trees and the controls, taking into account the increases in average dbhob and improvement in stem straightness, was $9.70, *i.e.*, each TSO stem at harvest age will be worth an average $9.70 more than a stems of the control seedlot. Excluding the costs incurred in breeding for the improved seed, the value added to TSO stock by breeding was therefore $9.70 for each tree reaching clearfelling age.

Not all seeds obtained from the TSO will grow on until clearfelled. Some seeds will fail to germinate and some less vigorous seedlings will be culled from the nursery. A further proportion will be harvested as thinnings. Economic weights were not calculated for trees removed during thinning operations. It is possible the relative economic importance of traits varies according to the age at which trees are harvested, so that the weights presented in Chapters 8 and 11 may not apply in thinning operations.

It was assumed only 50% of TSO seeds are actually planted in the forest, and a further 80% of these are removed as thinnings. Thus it was assumed only

10% of the total seed harvest from the TSO carries the \$9.70 economic advantage over unimproved stock. The average increase in value of TSO seed over unimproved seed is, therefore, 0.10 × \$9.70, or \$0.97 per seed obtained.

The \$ 0.97 per TSO seed does not take into account the cost of the breeding program. To produce genetically improved seed it was necessary to find suitable parent trees for the orchard by extensive searching for 'plus' trees. These trees had to be cloned in numbers large enough for establishment of the orchard and cross breeding for progeny testing and further breeding. The orchard had to be prepared, planted and maintained and the seed had to be collected annually. A definitive cost-benefit analysis of the TSO would have required that these costs be taken into account. No suitable data were obtained; however an approximation was gained from data published by Cameron and Appleton (1978) and Danbury (1971). In 1986 figures, it was crudely estimated that TSO cost between one to two hundred thousand dollars.

13.5 Flow of discounted benefits from the TSO

The gross economic value of seed production from the TSO between 1963 and 1976 was evaluated using interest rates of 5% and 8%, representing the approximate range of current inflation free market interest rates. The economic worth of each year's seed production was evaluated by multiplying the number of seeds yielded by \$0.97. Assuming a rotation length of 34 years (the same as in PT3) the economic benefits from each year's seed yield will not be realized for 35 years from the time the seeds were obtained. Each year's economic return was discounted from the year revenue will be received, back to 1957, the year the TSO was established. In 1965 for example, 486 600 seeds were obtained which will have an added worth over that of unimproved seed, of \$472 000 in the year 2000. Using discount rates of 5% and 8% this was discounted to \$57 914 and \$17 245 in 1957. The calculations of the gross discounted worth of all years' seed production for 1963 to 1976 are detailed in Table 13.3.

Table 13.3 Annual flow of discounted benefits from the TSO

year seed was harvested	total seed yield (000's)	year trees will be harvested	incr'd value of improved seed at harvest age ($000's)	discount factor to 1957 at 5%	8%	gross worth ($000's) 5%	8%
1957	0						
:	:						
:	:						
1963	70.6	1998	68.5	7.39	23.46	9.27	2.92
1964	136.7	1999	132.5	7.76	25.34	17.09	5.24
1965	486.6	2000	472.0	8.15	27.37	57.92	17.24
1966	898.0	2001	871.0	8.56	29.56	101.76	24.46
1967	1205.0	2002	1168.9	8.99	31.92	130.02	36.62
1968	2850.0	2003	2764.5	9.43	34.47	293.16	80.20
1969	4071.6	2004	3949.4	9.91	37.23	398.53	106.08
1970	1658.8	2005	1609.0	10.40	40.21	154.72	40.02
1971	1341.7	2006	1301.4	10.92	43.43	119.18	29.96
1972	2889.6	2007	2802.9	11.47	46.90	244.37	59.76
1973	6229.4	2008	6042.5	12.04	50.65	501.87	119.30
1974	3819.9	2009	3705.3	12.64	54.71	293.14	67.72
1975	1252.6	2010	1215.0	13.27	59.08	91.56	20.56
1976	3073.0	2011	2980.8	13.94	63.81	213.83	46.72
total	29 983.5		29 083.7			2626.4	656.80

The analysis was highly sensitive to the interest rate used. At 5% the discounted worth of the orchard at the time it was planted was $2.63 million, at 8% $0.66 million. If crude estimates of the cost of establishing and maintaining the TSO are taken into account, the net worth would be slightly less.

The estimates in Table 13.3 are probably below the correct value. As noted, in calculating the economic worth per TSO seed ($0.97) no account was taken of the value added to stems that would be harvested in thinning operations. It was assumed only those stems removed in the final harvest had an economic advantage over unimproved stock. In reality, economic benefits from breeding could also be obtained from trees removed in thinnings.

13.6 A comparison of TSO stock with the three good families

The measurements from PT52 were used to compare TSO stock with the three good families. The three families were ranked among the best in the progeny test in terms of dbhob, stem straightness or branch diameter in previous assessments. They are therefore representative of the best genetic stock presently available. The comparisons are shown in Table 13.4.

Table 13.4 Comparison of TSO stock with the best families

seedlot	dbhob (cm)	straightness (out of 10)	branch diam. (out of 5)
TSO	22.0	6.7	3.8
family 1	25.2	7.1	3.6
family 1 reciprocal	25.1	7.0	3.6
family 2	23.4	6.2	3.1
family 3	24.0	7.7	3.8

From these results it is clear continued improvements in growth rate and straightness can be made. The dbhob and stem straightness of TSO stock are halfway between that of the control stock and the best families. However, no family combines the best growth rate with the best straightness. Further, no family had good growth rate and small branch diameter. It therefore appears simultaneous improvement of branch diameter and dbhob is not possible. Probably the best that can be achieved is an increase in growth rate and maintenance of branch diameter at present levels.

The economic weights were used to judge the best family in economic terms. Differences between the TSO and each family were evaluated using the age 13 economic weight for dbhob in PT3 and the age 34 weights for stem straightness and branch diameter.

The predicted differences in worth per tree between TSO and each family were:

family	Increase in worth per tree
family 1	$8.22
family 1 reciprocal	$7.75
family 2	- $0.55
family 3	$7.28

Clearly, family 2 is unsatisfactory as it actually has a lower predicted average worth per stem than TSO stock. Family 1 has the highest predicted worth. Additional economic gain similar to that achieved after one generation of breeding would be achieved by using only the best families in future plantations, that is, family 1 and its reciprocal cross and family 3.

13.7 Summary

Tallaganda seed orchard seed provides an additional value per stem at clear felling compared with unimproved stock. However the additional costs associated with establishing a seed orchard would have to be taken into account in any definitive cost/benefit analysis. Using an approximation derived from published cost estimates, the TSO returned positive net economic worth at discount rates of 5% and 8%. Given that the value at by tree breeding to thinnings was not taken into account, the TSO has probably yielded an economic return of at least 10%.

Further gains in net economic worth can be attained by selecting 'superior families'. It will be possible to improve growth rate and stem straightness but not branch diameter.

Chapter 14

THE INFLUENCE OF OBSERVER AND SELECTION AGE ON TREE SELECTION IN PROGENY TEST 3

14.1 Introduction

The most efficient selection method (index selection) uses estimates of the economic importance of different traits and of phenotypic and genotypic variances and covariances. It was shown in Chapters 8 and 11 that the economic weights for particular traits differed according to the age at which assessment was undertaken. The weights for stem straightness at age 34 also differed between the observers. There may also have been differences in the estimates of phenotypic parameters due to differences in assessment methods, change in the appearance of the trees over time and observer judgement. It was important to consider whether variations in measurements or scores between observers and assessments influenced the expected response to selection and the corresponding predicted economic gains. It was also important to consider how the observer and age of assessment influenced the rankings of individual trees as these rankings determine which are selected.

To this end, an analysis was made of the influence of the observer and stand age at assessment on phenotypic parameters, predicted responses to selection and tree rankings based on index values in PT3.

14.2 Data used

The full data set from the 195 trees alive in PT3 in 1985 was used for the analysis. The procedures used to assess each trait at ages 13, 16, 25 and 34 were detailed in Chapter 6.

14.3 Sources of variation in the phenotypic standard deviations and correlations

The phenotypic standard deviations of dbhob, stem straightness and branch diameter, and correlations between them, were calculated for each assessment and observer (Tables 14.1 and 14.2). There were considerable differences between assessments, and to a lesser extent between observers at age 34. The differences between assessment ages were probably due to differences in assessment method, but may also have indicated changes in the appearance of trees over time and variation in observer judgement.

Table 14.1 Phenotypic standard deviations for each trait at each assessment of the 195 trees standing in PT3

Assessment	dbhob	Stem straightness	Branch diameter
age 13	3.05 cm	-	5.44 mm
age 16	-	0.64 points	-
age 25	5.65 cm	0.93 points	0.87 points
age 34, observer 1			
first	7.64 cm	0.94 points	0.49 points
second	-	0.98 points	-
age 34, observer 2	-	0.82 points	-

Table 14.2 Phenotypic correlations between traits at each assessment of the 195 trees standing in PT3

Assessment	Trait	Trait: dbhob	Trait: stem straightness	Trait: branch diameter
age 13/16	dbhob	-	0.076	0.542
	stem straightness		-	0.056
	branch diameter			-
age 25	dbhob	-	0.218	-0.038
	stem straightness		-	0.330
	branch diameter			-
age 34	dbhob	-		-0.552
	stem straightness			
	observer 1 (1st)	0.492	-	-0.204
	observer 1 (2nd)	0.432		-0.135
	observer 2	0.319		-0.115

14.3.1 Phenotypic standard deviations

From Table 14.1 the variability of dbhob increased with forest age. This was probably caused by the effects of both genetic variation and competition between trees. It is likely trees commenced growing at similar rates but that some had a competitive advantage either due to their genotype or to chance variation in local environmental conditions, or to both. When crown closure occurred these became dominant, enabling them to maintain a rapid growth rate. Smaller trees probably became suppressed and therefore grew more slowly so that, as the plantation aged, the variation in dbhob increased.

Stem straightness also showed marked differences in variability between assessment ages; the main reason being the different scales of judgement or measurement used on each occasion.

As noted in Section 6.2 (p.65), the age 16 stem straightness scale used in this study combined separate scores for butt sweep and straightness of the stem above the butt section. On the 4 point subjective scales used at age 16 most trees scored either 2 or 3 points for each trait. When the scales were combined into one, the range of variation was only 3 points out of a possible 7.

At age 25, stem straightness was scored on a 5 point relative scale. The worst stems, scoring 1 point, were all harvested in the 1979 thinning, (unpublished data, CSIRO Division of Forestry and Forest Products) so the scores for the remaining trees were spread between 2 and 5 points.

At age 34 the scores ranged from 4 to 9 $^1/_2$, with the majority of stems scoring between 6 and 8. At this age, three assessments were carried out; one observer made two and a second observer a third. The first observer's stem straightness scores (assessments 1 and 2) showed a wider range in variation than the second observer's. As a result the phenotypic standard deviations differed between observers (0.94 and 0.98 for observer 1 and 0.82 for observer 2).

In addition to the overall variability of scores between the observers, their scores for many individual stems were also different. For each tree, the three stem straightness scores at age 34 were compared. The scores given to individual trees differed by as much as $2^1/_2$ points between the two observers. In the comparison between observer one's second assessment and observer two's assessment, for example, one tree was $2^1/_2$ points better according to observer one's score (8 $^1/_2$ compared with 6), and another tree 2 points worse (5 compared with 7). Only 53 of the 195 trees were given an identical score by both observers. For 57 trees the difference was at least one point, however, one observer was not consistently higher or lower than the other.

Differences in branch diameter assessments were probably due to the different assessment methods used. At age 13, branch diameter was measured with a caliper on the lower few whorls. Consequently its standard deviation was very different from the later assessments.

The age 25 and age 34 branch diameter assessments were both on 5 point subjective scales. However the score distributions differed markedly since the age 25 scale was relative, while the age 34 scale was based on absolute limits.

14.3.2 Phenotypic correlations

The phenotypic correlations between traits also differed according to the age of assessment. The greatest difference among ages was in the correlation between dbhob and branch diameter (Table 14.2). The age 34 correlation was significant, ($r = -0.546$), indicating small stems had thin branches, while at age 25 it was nearly zero ($r = -0.038$). In the latter assessment, the observer may have judged branch diameter relative to stem size, rather than independently, an example of logical error or the error of proximity (Guilford 1954). The correlations were negative because high scoring stems had thin branches, on the scales used. Since the smaller stems tended to have the thinnest branches, smaller stems also had the highest scores for branch diameter at age 34. At age 13, the correlation was almost the same as at age 34 ($r = 0.543$), again indicating small stems had small diameter branches.

There were also differences in the phenotypic correlations between stem straightness and dbhob. At age 13/16 the correlation was very weak (0.076); slightly stronger at age 25 (0.218) and moderate at age 34 (mean of 0.405). There were differences between observers at age 34. The correlation between dbhob and the first observer' 1st. assessment of stem straightness was 0.492. For the second observer it was only 0.319.

14.4 The influence of assessment age and observer on predicted economic gains from index selection in Progeny Test 3

Given the variation in phenotypic parameters detailed in Section 14.3 and the differences in economic weights for the different assessments (Chapters 8 and 11), it was expected the Smith-Hazel indices calculated for the different assessments would also differ. An analysis of the effects of observer and age of assessment on predicted economic gains from a 1 in 100 selection in PT3 was conducted.

Smith-Hazel indices were calculated for all the assessments using the economic weights presented in Chapters 8 and 11. The resulting Smith-Hazel index coefficients, the predicted genetic gains and the corresponding gains in economic worth per stem are listed in Table 14.3. The percentage advantage, in economic terms, of the economic weighted index over the equal emphasis weighted index for each assessment is also shown.

Table 14.3 Smith-Hazel index coefficients, and genetic and economic gains expected following a 1 in 100 selection among the 195 trees assessed in PT3

Age		Equal emphasis weights			Economic weights			Total $ gain expected per tree		%advantage of economic weights
		dbh	ss	bd	dbh	ss	bd	equal emphasis	economic	
13/16	index	0.16	0.53	-0.10	0.72	1.23	-0.23			
	gains	1.34	0.45	-3.61	1.65	0.34	-1.81	5.21	5.31	1.9
	$gain	3.45	0.71	1.05	4.26	0.53	0.52			
25	index	0.03	0.27	0.23	0.35	0.87	0.36			
	gains	1.43	0.45	0.33	3.09	0.30	0.13	4.08	6.65	63.0
	$gain	2.73	0.77	0.58	5.90	0.52	0.23			
34 observer 1										
	index	0.05	0.29	1.08	0.48	0.01	3.94			
1st	gains	1.50	0.36	0.20	3.73	0.30	0.11	4.07	7.39	81.6
	$gain	2.56	0.62	0.89	6.38	0.52	0.49			
	index	0.05	0.26	1.06	0.48	0.19	4.02			
2nd	gains	1.65	0.38	0.21	3.63	0.33	0.11	4.57	7.42	62.4
	$gain	2.82	0.82	0.93	6.21	0.72	0.49			
observer 2										
	index	0.05	0.34	1.08	0.44	0.43	3.58			
	gains	1.58	0.30	0.18	3.56	0.28	0.11	3.78	6.84	81.0
	$gain	2.70	0.28	0.80	6.09	0.26	0.49			

14.4.1 The influence of weighting method on predicted gains

The results in Table 14.3 reinforce the conclusion expounded in Chapter 12, that equal emphasis weights are inappropriate. For all assessments and observers greater economic gain was predicted when selection was on an economic weighted index rather than an equal emphasis weighted index. Predicted economic gains resulting from a 1 in 100 selection among the 195 trees in PT3 at age 34, were 62% to 80% higher when economic weights were used. The difference was 63% at age 25 but only 2% at age 13/16.

In Table 12.2 (p.173), it was shown that at both age 13/16 and at age 34, dbhob had a much higher economic importance than stem straightness and branch diameter (dbhob was nearly 8 times more important than stem straightness and 5 or 6 times more important than branch diameter). It is therefore difficult to explain why the economic and equal emphasis weighting methods gave almost identical gain expectations at age 13/16 but very different gains at ages 25 and 34. The difference can only have been due to differences in the phenotypic parameters . Clearly the importance of using the correct economic weights is dependent on other parameters within the progeny test. If the wider consequences of not using the correct economic weights in tree selection are to be determined it will probably be necessary to investigate the sensitivity of selections to variation in the relative economic importance of traits in a large number of progeny tests. It will also be desirable to use repeatable and precise assessments of traits to remove the effects of variation in assessment methods and observer judgement on calculation of economic weights, phenotypic parameters and gain expectations.

14.4.2 The influence of the observer on predicted economic gains

The results for the three age 34 assessments of stem straightness showed the influence of differences between observers. There was almost no difference in predicted economic gains using either of the first observer's stem straightness assessments when a Smith-Hazel index, calculated with economic weights, was used. Predicted gains were slightly higher (8%) if the first observer's scores were used in preference to those of the second observer.

The differences among observers were more marked when the indices were weighted by equal emphasis. There was an 11% difference in expected economic gain if the first observer's second assessment was used instead of his first. The difference between observer two and observer one on the second assessment was 20.5%. Thus, when stem straightness was given equal importance to other traits (using equal emphasis weighting), variation in scores between observers caused important variation in the economic gains expected from selection. Observer variation was less important when stem straightness was of low relative economic importance, that is, when the economic weights were used.

14.5 The influence of observer variation in subjective scores on the ranks of individual trees

Theoretical calculations of expected genetic gains do not fully demonstrate the influence of varying scores on the ranks of individual trees. In reality, a few trees in a particular progeny test may be so outstanding in several traits they always rank among the best trees, irrespective of selection method.

From the Smith-Hazel index coefficients shown in Table 14.3, calculated using economic weights, observer one's first assessment of stem straightness at age 34 had a very slight influence on tree selection, the coefficient for straightness being 0.01 compared with 0.48 for dbhob. The Smith-Hazel index based on the second observer's assessment gave a stem straightness coefficient of 0.43 compared with 0.44 for dbhob. Despite this difference between observers' indices at age 34, the same two trees were ranked as best and second best by all three economic weighted indices at age 34. The best ranked tree had a dbhob of 48.0 cm, a stem straightness score of $8^1/_2$ on all three occasions and a branch diameter score of 4. The second best ranked tree had a dbhob of 46.1 cm, straightness scores of 8, $7^1/_2$ and 7 and a branch diameter score of 4.

14.6 Summary

This chapter presented the results of an analysis of the effect of observer and age of assessment on phenotypic parameters, selection index coefficients, predicted economic gains and index rankings of individual trees. The main results were as follows:

(1) Phenotypic parameters changed with time and differed between observers.

(2) The importance of the weighting method used in index selection varied between assessments, probably due to differences in phenotypic parameters. At one assessment the economic weighted index gave only slightly more economic gain than the equal emphasis weighted index, despite large differences in the relative economic importance of traits. At other assessments, use of economic weights gave 62% to 80% higher expected economic gain.

(3) The effect of the observer on index coefficients and predicted gains depended on the weighting method. When equal emphasis weights were used, differences in the judgement of stem straightness between the observers resulted in 20% variation in expected economic gains. When economic weights were used, giving stem

straightness relatively low importance, the difference between observers in their judgement of stem straightness, caused expected economic gain to vary by only 8%.

(4) A few trees were outstanding in all traits and therefore when tree selection was based on an economic weighted index, the same trees were selected by all observers.

Chapter Fifteen

SUMMARY AND RECOMMENDATIONS

15.1 Summary of main findings and recommendations

The aims of this thesis were as follows:

(1) To develop a method for determining economic weights for stem straightness, branch diameter and stem diameter to be used in selection indices for *P.radiata* breeding.

(2) To calculate economic weights in index selection.

(3) To determine whether subjective scores for some traits can be used satisfactorily for tree assessment and selections in breeding programs.

(4) To estimate the economic worth of gains already achieved through *P.radiata* breeding.

15.1.1 Development of a method for calculating economic weights and comparison of economic and equal emphasis weights in index selection

After developing a method for estimating economic weights (Chapter 5), they were calculated in one *P.radiata* progeny test using tree assessment and saw mill recovery data (Chapters 7,8,10 and 11). Additional stem straightness data enabling confirmation and clarification of the relationship between subjective assessments of stem straightness and net economic worth of stems, were collected from a selected sample of *P.taeda* stems exhibiting good stem straightness (Chapter 9).

A comparison of selection indices derived from economic and equal emphasis weights in one *P.radiata* progeny test (PT3) demonstrated the importance of accurate weighting in tree selection. Stem dbhob, stem straightness and branch diameter were not of equal economic importance; dbhob was nearly 8 times more important than stem straightness and 5 or 6 times more important than branch diameter. Selection at an intensity of 1 in 100, using economic weights, resulted in 83% more economic gain than selection using equal emphasis weights when selection was at age 34, and 63% more gain when selection was at age 25. However, the difference was only 2% when selection was made using data collected at ages 13 and 16 (Chapters 12 and 14).

Index selection should be employed in advanced breeding programs of *P.radiata* to ensure efficient and effective use of tree breeding resources (Cotterill 1988). The use of accurate economic weights in selection indices maximises the efficiency of this technique. This was demonstrated by the analyses presented in Chapters 12 and 14. While the figures presented are not directly applicable to other progeny tests (Chapter 12) they demonstrate equal emphasis weights were inappropriate in at least one progeny test, indeed their use might seriously reduce the economic benefits derived from tree breeding. Tree breeders could obtain the data necessary for estimating widely applicable economic weights by adopting the following procedure:

(1) Firstly, the sensitivity of selections to variation in the relative economic importance of traits would need to be determined by calculating several selection indices for a large number of progeny tests, each time varying the relative emphasis placed on traits. Trees within each progeny test would then be ranked using each index. Marked differences between indices in the trees selected would serve as an indication that use of incorrect weights in index selection will seriously reduce the economic gains achievable by breeding. The availability of computer data bases and appropriate software packages means these sensitivity tests can be done cheaply.

(2) If selection is found to be sensitive to variation in the relative importance placed on traits, steps should be taken to calculate the correct economic weights. This will entail using a method similar to that outlined in Chapter 5, but with a wider range of data.

15.1.2 The suitability of subjective assessments for tree selection

The analyses in Chapters 8, 9 and 11 showed there were significant correlations between estimated loss of value recovery caused by sweep and large branch diameter and subjective scores for stem straightness and branch diameter. Observers were able to subjectively score these traits, well enough for the scores to provide an indication of economic importance. However, a large proportion of the variation in the estimated lvr_{sw} and lvr_{bd} could not be explained by variation in the subjective scores.

The analysis indicated that observers were able to judge branch diameter better than stem straightness. It was shown in Chapter 9, using data from the *P.taeda* study, that this was partly because the effects of stem bends on stem worth can be reduced by 20% simply by varying the lengths of saw logs to advantage. Consequently, the worst looking stems did not always suffer the greatest lvr_{sw}.

The observer in the *P.taeda* study was not always able to apply the stem straightness scale correctly. A subjective scale of stem straightness applied to standing trees, only explained about half as much variation in lvr_{sw}, as did the same scale reapplied more precisely using measurements of bends in the same stems after felling. However, the inaccuracy in the observer's application of the subjective score to standing stems did not change the economic weight compared with the more accurate assessment.

In the case of branch diameter, there was no evidence that measuring a sample of branches at the base of the stem at age 13 would produce a greater estimate of economic gain than than would a subjective assessment of this trait at ages 25 and 34.

There was an important difference between the age 25 and age 34 branch diameter scores. At age 25, branch diameter was scored relative to the best and worst stems within PT3; it was also judged in relation to stem diameter. At age 34 it was scored on an absolute scale, independently of stem diameter. Consequently the branch diameter scores were more variable at age 25 than at age 34 and the correlation between branch diameter and dbhob differed significantly between the two assessments (Chapter 12). This raises the question as to whether relative or absolute scales should be used to assess traits in progeny tests.

It has been argued that subjective scales of trait assessment ought to be anchored relative to the best and worst stems within the stand being assessed (Australian Forestry Council 1974, Dean *et al* 1986, Cotterill *et al* 1988). Such scales give the best estimates of genetic parameters and, if the distribution of scores has the shape of a normal curve with a standard deviation of 1 point (as it should do if applied correctly), they are convenient for estimating equal emphasis weights. However, use of relative scales makes calculation of widely applicable economic weights difficult. Absolute variation in a trait may differ between stands and age classes. The use of a relative scale will always give the trait a phenotypic standard deviation of 1 point. Thus, the absolute variation and economic weight of 1 point on the relative scale will change from progeny test to progeny test and, between ages within a single progeny test. Therefore, economic weights must be recalculated for each progeny test and assessment if a relative scale is used.

The following is a procedure recommended to overcome this problem, enabling standardisation of both relative and absolute scales between progeny tests :

(1) For each trait a repeatable measurement should be adopted which can be applied to a sample of trees in all progeny tests, irrespective of the variability within the test. In the case of stem straightness Shelbourne's (1966) photographic technique might be suitable. For any stem, two photographs taken at 90 degrees to one another, using a wide angle lens, provide a permanent record of the appearance of the stem, from which accurate measurements of stem bends can be made. For each assessment in a progeny test, a random sample of stems, chosen at the extremes and the centre of the range of stem straightness scores, would be photographed. It may only be necessary to photograph 30 stems in each assessment. The photographs would provide an accurate record of the absolute variation in stem straightness within the progeny test and would enable comparisons to be made between progeny tests.

In the case of branch diameter, detailed measurements of a sample of branches along a representative section of each of a few stems, again covering the range of variation present within the progeny test, could be collected. As with stem straightness, these accurate measurements would enable standardisation of subjective scores between progeny tests.

(2) The accurate assessments made from the photographs in the case of stem straightness, or from the detailed branch measurements in the case of branch diameter, could be used to calculate economic weights. It would be necessary to fell the photographed or accurately measured stems at some later stage (when they were of harvestable size) to determine the relationships between stem worth and the earlier accurate measurements of each trait.

The current practice in breeding faster growing trees requires selections to be made at about age 8 to 10 years. The accurate measurements would therefore, also be made at this time. It would then be at least 20 years before the stems were of harvestable age for clear-felling and economic weight determination. Estimates of economic weights applicable to thinnings could be obtained sooner.

Steps could be taken to obtain useful information earlier. To do this, it would be necessary to collect detailed stem straightness and branch diameter measurements from stems covering a wide range of age classes from about age 10 to clear felling age. Each tree could be reassessed by the same method at 5 year intervals. The data could be used to estimate juvenile - mature tree correlations over the entire range of age classes, from which economic weights could be calculated.

15.1.3 Implications of the results of this thesis for future *P.radiata* breeding program

Although the economic weights calculated using the data from PT3 are not strictly applicable to other sites, it is likely the relative economic importance of the three traits studied will be similar on the majority of *P.radiata* sites (Chapter 12).

It was shown in Chapter 12 that stem diameter was far more important economically, than either stem straightness or branch diameter. At the site on which PT3 was grown there was little scope for improvement in the latter two traits. It was estimated that sweep had reduced the potential value of sawn recovery from the trees felled in PT3 by only four per cent, while large diameter branches had caused a two per cent reduction in potential value recovery. Severe bends and large diameter branches will generally occur infrequently in *P.radiata* grown on average to good sites, especially among the final crop trees in plantations derived from first generation clonal seed orchards. There is probably little to be gained by further improving stem straightness and branch diameter in generations beyond the second generation of genetically improved *P.radiata*.

Instead, tree breeders should examine the economic importance of other traits, such as wood density and, with the increasing incidence of disease and pests in some *P.radiata* plantations, consideration should also be given to the economic importance of disease and pest resistance in future breeding generations.

This is not to say that stem straightness and branch diameter should be dropped as selection criteria. To do so may lead to deterioration of these traits, especially branch diameter, which is adversely genetically and phenotypically correlated with growth rate. Instead, selection indices should be used in which these two traits are given low economic weights relative to the weights given to other, more economically important traits.

15.1.4 Evaluation of the economic worth of the Tallaganda Seed Orchard

A comparison of dbhob, stem straightness and branch diameter was made between Tallaganda Seed Orchard (TSO) and an unimproved control (Chapter 13). The differences between the two seed sources were evaluated using the economic weights presented in Chapters 8 and 11. Assuming 10% of TSO seeds are ultimately clear felled, it was estimated each seed collected from the TSO was worth $0.97 more than a seed of the control. Published records of seed yield from the TSO were used to calculate the additional economic worth of seed production from the orchard. The additional worth of all TSO seed, discounted to the year 1957 was $2.62 million at an interest rate of 5% and $ 0.66 million at 8%. Estimates by Cameron and Appleton (1978) and Danbury (1971), indicated the TSO would have cost less than $ 200 000 in management costs. Therefore the TSO has yielded a substantial net economic return.

Further evaluation of the economic worth of genetically improved stock should be undertaken. If tree breeding programs are to continue it is necessary to demonstrate the success of earlier breeding work. Comparative plantings of improved and unimproved stock should continue on a wide range of forest sites. The economic benefits of tree breeding cannot be fully proved until the genetically superior stock reaches harvestable age. Mill recovery studies can be used to demonstrate conclusively the worth of tree breeding for saw log production.

15.2 Final conclusions

Tree breeding has already added substantially to the economic worth of *P.radiata* plantations in Australia. However, as breeding moves into the more advanced generations it is important that the most efficient and effective use of the resources available for tree breeding be made. To this end tree breeding organisations ought to employ index selection in which the estimates of phenotypic and genetic parameters that have been determined for *P.radiata* over several decades, are put to best use. To do this, however, estimates of economic weights for traits will be needed.

This thesis has demonstrated the importance of using the correct economic weights in index selection. Accurate economic weights, applicable to a wide range of progeny tests can be determined. However, this will require the development of more precise methods for measuring stem straightness and branch diameter. Given the relatively small economic gains that will be possible by further improvement of these traits and the amount of time and effort that will be required to determine widely applicable weights for them, tree breeders may be content to adopt the low relative weights for stem straightness and branch diameter determined in this study, as they are unlikely to be substantially different on other *P.radiata* sites.

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APPENDIX ONE

A *P.radiata* plus tree evaluation sheet typical of those used in the 1960's

P. RADIATA PLUS TREE EVALUATION SHEET.

Plantation .... Comp. .... Tree No. ....

Age .... Girth B.H. .... Height .... Super dominant
Dominant
Co-dominant

Candidate trees should be good in all characteristics and possibly outstanding in one or two traits. Trees inferior in an important character should not be selected in the first place.

*** *** ***

VIGOUR (30 + points possible). Candidate tree to be compared with other trees within a radius of $\frac{1}{2}$ chain. i.e. up to 80 trees.

Diameter. D.B.H.O.B. (10 representative final crop trees to be measured).

Points 0-4	smaller than average	
5	average (of final crop trees)	
6-14	intermediate	
15	equal to largest other tree on plot.	
15-20	Larger than other trees on plot.	....

Girth of 10 representative final crop trees on plot

....	....	
....	....	
....	....	Average ....
....	....	
....	....	

Height. Height of candidate tree to be measured. Ocular comparison to be made with other trees.

Points 0-1	shorter than average	
2	average (of final crop trees)	
3-7	intermediate	
8	equal to tallest other tree	
9-10	taller than other talles on plot.	....

Bonus An extra 1-5 points awarded if the candidate tree is larger (D.B.H.O.B. or height) than any other tree on comparable sites over an area of 1 acre. ________

____

TRUNK FORM (30 points possible)

Trunk perfectly straight 30	....
Basal sweep - deduct 1-5 (may be non-genetic)	....
Trunk bends, spiral bole - deduct 1-20	....
Trunk curves - deduct 1-15	....
Lean - deduct 1 point per degree	....
Cross section - deduct 1-3 if not circular	....
Nodal swellings - deduct 1-5 for detectable swellings.	....

____

____

BRANCHING 30 points possible. Both uninodal and multinodal trees accepted. Describe characteristics of candidate tree.

....

....

....

Branch Thickness (15) To be related to tree vigour.

Points	11-15	remarkably thin for vigour of tree
	7-10	intermediate
	5	average thickness
	0-4	thicker than average ....

Branch Angle (15) To be measured at two positions on trunk - at (10'-20') and at 30', then sum the points

	(10' - 20')	30'
$80^{\circ} - 90^{\circ}$	10	5
$70^{\circ} - 80^{\circ}$	8	4
$60^{\circ} - 70^{\circ}$	6	2
$50^{\circ} - 60^{\circ}$	3	0
$40^{\circ} - 50^{\circ}$	0	-1
40°	-3	-2

....

Branch length Deduct 1-5 for excessive length ....

Ramicorns Deduct 1-10 for evidence of ramicorns ....

PERSISTENT TRUNK CONES. 10 points possible

10 - trunk cones cast shortly after maturity

5 - scattered persistent trunk cones

0 - numerous persistent cones ....

HEALTH. Candidate trees are expected to be healthy and resistant to disease or insect attack. Points should be deducted for evidence of past dead-top, needle cast, etc.

Grand Total

Further Notes:

APPENDIX TWO

Output from the multiple linear regression program in the Statview package, used in the analysis of the influence of log sweep on sawn recovery

In the following tables :

- %r' is percentage conversion (the dependent variable)

- LL is log length (in metres)

- SW^1.3 is sweep ratio raised to the power of 1.3

- sed^.01 is log small end diameter underbark (in centimetres), raised to the power of 0.01.

Multiple - Y : %r'   Three X variables

DF:	R-squared:	Std. Err.:	Coef. Var.:
250	.308	5.62	18.467

Analysis of Variance Table

Source	DF:	Sum Squares:	Mean Square:	F-test:
REGRESSION	3	3476.367	1158.789	36.689
RESIDUAL	247	7801.244	31.584	$p \leq .0001$
TOTAL	250	11277.612		

Beta Coefficient Table

Parameter:	Value:	Std. Err.:	T-Value:	Partial F:
INTERCEPT	-1632.158	171.438	-9.52	
LL	.658	.376	1.751	3.068
SW^1.3	-23.64	6.198	-3.814	14.549
sed^.01	1610.818	166.267	9.688	93.86

APPENDIX THREE

Calculations of Smith-Hazel Indices and expected genetic gains for Chapter 12.

3.1 Phenotypic parameters

Table 1 Phenotypic standard deviations

age	dbhob	straightness	branch diameter
34	7.64(cm)	0.82(point)	0.49(point)
16		0.64(point)	
13	3.05(cm)		5.44(mm)

Table 2 Phenotypic correlations

age 34

	dbhob	straightness	branch diameter
dbhob	-	0.477	-0.552
straightness		-	-0.180
branch diameter			-

age 13/16

	dbhob	straightness	branch diameter
dbhob	-	0.076	0.542
straightness		-	0.056
branch diameter			-

3.2 Phenotypic variance/covariance matrix

This is calculated using methods described by Cotterill *et al* (1988)

age 34

$P_{11} = s^2_{dbh34} = 58.369;\ P_{22} = s^2_{ST34} = 0.672;\ P_{33} = s^2_{BD34} = 0.240$

$P_{12} = P_{21} = r_{P(12)}\, s_{P(11)}\, s_{P(22)} = 0.477 \times 7.64 \times 0.82 = 2.988$

$P_{13} = P_{31} = r_{P(13)}\, s_{P(11)}\, s_{P(33)} = -0.552 \times 7.64 \times 0.49 = -2.066$

$P_{23} = P_{32} = r_{P(23)}\, s_{P(22)}\, s_{P(33)} = -0.180 \times 0.82 \times 0.49 = -0.072$

$$[P]_{34} = \begin{bmatrix} 58.369 & 2.988 & -2.066 \\ 2.988 & 0.672 & -0.072 \\ -2.066 & -0.072 & 0.240 \end{bmatrix} \qquad [P]^{-1}_{34} = \begin{bmatrix} .0310 & -0.110 & 0.235 \\ -0.110 & 1.950 & -0.390 \\ 0.235 & -0.390 & 6.069 \end{bmatrix}$$

age 13/16

$P_{11} = s^2_{dbh13} = 9.302;\ P_{22} = s^2_{ST16} = 0.410;\ P_{33} = s^2_{BD13} = 29.594$

$P_{12} = P_{21} = r_{P(12)}\, s_{P(11)}\, s_{P(22)} = 0.076 \times 3.05 \times 0.64 = 0.148$

$P_{13} = P_{31} = r_{P(13)}\, s_{P(11)}\, s_{P(33)} = 0.542 \times 3.05 \times 5.44 = 8.993$

$P_{23} = P_{32} = r_{P(23)}\, s_{P(22)}\, s_{P(33)} = 0.056 \times 0.64 \times 5.44 = 0.195$

$$[P]_{13/16} = \begin{bmatrix} 9.302 & 0.148 & 8.993 \\ 0.148 & 0.410 & 0.195 \\ 8.993 & 0.195 & 29.594 \end{bmatrix} \qquad [P]^{-1}_{13/16} = \begin{bmatrix} 0.153 & -0.033 & -0.046 \\ -0.033 & 2.456 & -0.006 \\ -0.046 & -0.006 & 0.048 \end{bmatrix}$$

3.3 Genotypic variance/covariance matrix

This is calculated using standard genetic parameters and methods from Cotterill *et al* (1988).

age 34

$A_{11} = s^2_{Adbh34} = 0.20 \times 7.64^2 = 11.674$

$A_{22} = s^2_{AST34} = 0.20 \times 0.82^2 = 0.134$

$A_{33} = s^2_{ABD34} = 0.25 \times 0.49^2 = 0.060$

$A_{12} = A_{21} = r_{Adbh34,ST34} \times \sqrt{A_{11}} \times \sqrt{A_{22}} = 0.35 \times 3.417 \times 0.366 = 0.439$

$A_{13} = A_{31} = r_{Adbh34,BD34} \times \sqrt{A_{11}} \times \sqrt{A_{33}} = -0.25 \times 3.417 \times 0.245 = -0.209$

$A_{23} = A_{32} = r_{AST34BD34} \times \sqrt{A_{22}} \times \sqrt{A_{33}} = 0.35 \times 0.366 \times 0.245 = 0.031$

$$[A]_{34} = \begin{bmatrix} 11.674 & 0.439 & -0.209 \\ 0.439 & 0.134 & 0.031 \\ -0.209 & 0.031 & 0.060 \end{bmatrix}$$

age 13/16

$A_{11} = s^2_{Adbh13} = 0.20 \times 3.05^2 = 1.860$

$A_{22} = s^2_{AST16} = 0.20 \times 0.64^2 = 0.082$

$A_{33} = s^2_{ABD13} = 0.25 \times 5.44^2 = 7.398$

$A_{12} = A_{21} = r_{Adbh13,ST16} \times \sqrt{A_{11}} \times \sqrt{A_{22}} = 0.35 \times 1.364 \times 0.286 = 0.137$

$A_{13} = A_{31} = r_{Adbh13,BD13} \times \sqrt{A_{11}} \times \sqrt{A_{33}} = 0.25 \times 1.364 \times 2.720 = 0.928$

$A_{23} = A_{32} = r_{AST316,BD13} \times \sqrt{A_{22}} \times \sqrt{A_{33}} = -0.35 \times 0.286 \times 2.720 = -0.272$

$$[A]_{13/16} = \begin{bmatrix} 1.860 & 0.137 & 0.928 \\ 0.137 & 0.082 & -0.272 \\ 0.928 & -0.272 & 7.398 \end{bmatrix}$$

3.4 Calculation of Smith-Hazel Indices

The Smith-Hazel Index coefficients are given by $[b] = [P]^{-1}[A][w]$ (Cotterill *et al* 1988).

age 34

$$[b]_{34} = [P]_{34}^{-1}[A]_{34}[w]_{34}$$

using economic weights

$$[b]_{34} = \begin{bmatrix} 0.031 & -0.110 & 0.235 \\ -0.110 & 1.950 & -0.390 \\ 0.235 & -0.390 & 6.069 \end{bmatrix} \times \begin{bmatrix} 11.674 & 0.439 & -0.209 \\ 0.439 & 0.134 & 0.031 \\ -0.209 & 0.031 & 0.060 \end{bmatrix} \times \begin{bmatrix} 1.71 \\ 2.12 \\ 4.43 \end{bmatrix}$$

$$= \begin{bmatrix} 0.485 \\ 0.030 \\ 4.076 \end{bmatrix}$$

$$I = 0.485\ dbh_{34} + 0.030\ ST_{34} + 4076\ BD_{34}$$

using equal emphasis weights

$$[b]_{34} = \begin{bmatrix} 0.031 & -0.110 & 0.235 \\ -0.110 & 1.950 & -0.390 \\ 0.235 & -0.390 & 6.069 \end{bmatrix} \times \begin{bmatrix} 11.674 & 0.439 & -0.209 \\ 0.439 & 0.134 & 0.031 \\ -0.209 & 0.031 & 0.060 \end{bmatrix} \times \begin{bmatrix} 0.13 \\ 1.22 \\ 2.04 \end{bmatrix}$$

$$= \begin{bmatrix} 0.050 \\ 0.319 \\ 1.081 \end{bmatrix}$$

$$I = 0.050\ dbh_{34} + 0.319\ ST_{34} + 1.081\ BD_{34}$$

age 13/16

$$[b]_{13/16} = [P]_{13/16}^{-1}[A]_{13/16}[w]_{13/16}$$

using economic weights

$$[b]_{13/16} = \begin{bmatrix} 0.153 & -0.033 & -0.046 \\ -0.033 & 2.456 & -0.006 \\ -0.046 & -0.006 & 0.048 \end{bmatrix} \times \begin{bmatrix} 1.860 & 0.137 & 0.928 \\ 0.137 & 0.082 & -0.272 \\ 0.928 & -0.272 & 7.398 \end{bmatrix} \times \begin{bmatrix} 2.58 \\ 1.57 \\ -30 \end{bmatrix}$$

$$= \begin{bmatrix} 0.716 \\ 1.226 \\ -0.234 \end{bmatrix}$$

$$I = 0.716\ dbh_{13} + 1.226\ ST_{16} - 0.234\ BD_{13}$$

using equal emphasis weights

$$[b]_{13/16} = \begin{bmatrix} 0.153 & -0.033 & -0.046 \\ -0.033 & 2.456 & -0.006 \\ -0.046 & -0.006 & 0.048 \end{bmatrix} \times \begin{bmatrix} 1.860 & 0.137 & 0.928 \\ 0.137 & 0.082 & -0.272 \\ 0.928 & -0.272 & 7.398 \end{bmatrix} \times \begin{bmatrix} 0.33 \\ 1.56 \\ -0.18 \end{bmatrix}$$

$$= \begin{bmatrix} 0.160 \\ 0.532 \\ -0.101 \end{bmatrix}$$

$$I = 0.160\ dbh_{13} + 0.532\ ST_{16} - 0.101\ BD_{13}$$

3.5 Calculation of expected genetic gain

From Cotterill *et al* (1988), expected genetic gain in trait j is

$$\Delta G_j = cov(A_jI)i/s_I$$

where $cov(A_jI) = S_j\, b_j A_{jk}$

i = selection intensity on I,

and s_I = standard deviation of the index values in the population being selected from.

age 34

using economic weights

$cov(A_1I) = 0.485 \times 11.674 + 0.030 \times 0.439 - 4.076 \times 0.209$
$= 4.823$

$cov(A_2I) = 0.485 \times 0.439 + 0.030 \times 0.134 + 4.076 \times 0.031$
$= 0.345$

$cov(A_3I) = -0.485 \times 0.209 + 0.030 \times 0.031 + 4.076 \times 0.060$
$= 0.144$

Assuming 1 in 100 selection (i = 2.67):

$\Delta G_{dbh34} = 4.823 \times 2.67/3.425$
$= 3.76$ cm

$\Delta G_{ST34} = 0.345 \times 2.67/3.425$
$= 0.27$ point

$\Delta G_{BD34} = 0.144 \times 2.67/3.425$
$= 0.11$ point

using equal emphasis weights

$cov(A_1I) = 0.050 \times 11.674 + 0.319 \times 0.439 - 1.081 \times 0.209$
$= 0.495$

$cov(A_2I) = 0.050 \times 0.439 + 0.319 \times 0.134 + 1.081 \times 0.031$
$= 0.099$

$cov(A_3I) = -0.050 \times 0.209 + 0.319 \times 0.031 + 1.081 \times 0.060$
$= 0.065$

$\Delta G_{dbh34} = 0.495 \times 2.67/0.883$
$= 1.50$ cm

$\Delta G_{ST34} = 0.099 \times 2.67/0.883$
$= 0.30$ point

$\Delta G_{BD34} = 0.065 \times 2.67/0.883$
$= 0.20$ point

age 13/16

using economic weights

$$\begin{aligned}
cov(A_1I) &= 0.716 \times 1.860 + 1.226 \times 0.137 - 0.234 \times 0.928 \\
&= 1.283 \\
cov(A_2I) &= 0.716 \times 0.137 + 1.226 \times 0.082 + 0.234 \times 0.272 \\
&= 0.262 \\
cov(A_3I) &= 0.716 \times 0.928 - 1.226 \times 0.272 - 0.234 \times 7.398 \\
&= -1.400
\end{aligned}$$

$i = 2.67 \quad s_I = 2.072$

$$\begin{aligned}
\Delta G_{dbh13} &= 1.283 \times 2.67/2.07 \\
&= 1.65 \text{ cm} \\
\Delta G_{ST16} &= 0.262 \times 2.67/2.07 \\
&= 0.34 \text{ point} \\
\Delta G_{BD13} &= -1.40 \times 2.67/2.07 \\
&= -1.81 \text{ mm}
\end{aligned}$$

using equal emphasis weights

$$\begin{aligned}
cov(A_1I) &= 0.160 \times 1.860 + 0.532 \times 0.137 - 0.101 \times 0.928 \\
&= 0.277 \\
cov(A_2I) &= 0.160 \times 0.137 + 0.532 \times 0.082 + 0.101 \times 0.272 \\
&= 0.093 \\
cov(A_3I) &= 0.160 \times 0.209 - 0.532 \times 0.272 - 0.101 \times 7.398 \\
&= -0.750
\end{aligned}$$

$i = 2.67 \quad s_I = 0.551$

$$\begin{aligned}
\Delta G_{dbh13} &= 0.277 \times 2.67/0.55 \\
&= 1.34 \text{ cm} \\
\Delta G_{ST16} &= 0.093 \times 2.67/0.55 \\
&= 0.45 \text{ point} \\
\Delta G_{BD13} &= -0.750 \times 2.67/0.55 \\
&= -3.61 \text{ mm}
\end{aligned}$$

Calculation of expected gain in average net stem worth

Expected gain in net stem worth = $w_1\Delta G_1 + w_2\Delta G_2 + w_3\Delta G_3$

(Expected gain in age 34 stem worth if selection on index in PT3 is at a 1 in 100 intensity.)

age 34

Selection on an economic weighted index:

Gain in stem worth = $1.71 \times 3.76 + 2.12 \times 0.27 + 4.43 \times 0.11$
= \$7.49 per stem

Selection on equal emphasis index:

Gain in stem worth = $1.71 \times 1.50 + 2.12 \times 0.30 + 4.43 \times 0.20$
= \$4.08 per stem

age 13/16

Selection on an economic weighted index:

Gain in stem worth = $2.58 \times 1.65 + 1.57 \times 0.34 + 0.30 \times 1.81$
= \$5.33 per stem at age 34

Selection on equal emphasis index:

Gain in stem worth = $2.58 \times 1.34 + 1.57 \times 0.45 + 0.30 \times 3.61$
= \$5.25 per stem at age 34

APPENDIX FOUR

Appendix Four

RECOMMENDED IMPROVEMENTS FOR THE CALCULATION OF WIDELY APPLICABLE ECONOMIC WEIGHTS IN FUTURE STUDIES

A4.1 Introduction

This section details some limitations of the present study and outlines improvements that will be necessary if widely applicable economic weights are to be calculated in the future. There are two main areas of improvement. The first relates to the methods used to determine the net economic worth of stems. The second is concerned with the number and variability of stems used in the calculation of the economic weights presented in Chapters 8 and 11 and the economic worth of the Tallaganda Seed Orchard in Chapter 13.

A4.2 Testing of some of the assumptions made in the determination of the net economic worth of stems

A4.2.1 Inclusion of cost data

In this study, no cost data were obtained, either for determining the net economic worth of individual stems, or for evaluating the net economic worth of the Tallaganda Seed Orchard. In the former case, untested assumptions were made concerning the influence of different traits on the costs of growing, harvesting and processing individual stems (Chapter 5). Incorrect cost assumptions may have resulted in incorrect estimates of the relative economic thinning schedules, treatments with fertilisers and weedicides and site quality.

A4.2.3 Determining the influence of tree breeding on the economic worth of thinnings

In determining the economic weights and in the analysis of the worth of the Tallaganda seed orchard, no account was taken of the effect of tree breeding on the economic worth of thinnings. Since the average size of stems removed in thinnings is less than that of stems removed at the final harvest, the effect of tree breeding on stem size is likely to be of greatest importance. Harvesting costs are very sensitive to average tree size.

A4.3 Expanding the range of progeny test data used to calculate economic weights and evaluate the worth of the Tallaganda Seed Orchard

A4.3.1 Calculation of economic weights

The economic weights determined in this study were calculated using a limited sample of stems (65) in PT3. The variation in stem straightness, branch diameter and stem size within PT3 was limited. On the 10 point stem straightness scale used at age 34 most stems scored in the range 6 to 8 points, while on the branch diameter scale of 5, most stems scored between 3 and 5. Further data for reasonably straight stems were obtained from *P.taeda* but no extremely crooked or heavily branched stems were included in the recovery study. It is possible that on some sites, or under other silvicultural treatments the same genetic stock may have exhibited poorer average stem straightness or branch diameter, or wider variation. In such cases these traits may have been more important, economically than was measured in PT3. However in forests growing on reasonable site quality, the range in stem straightness and branch diameter is probably similar to that observed in this study.

A4.3.2 The comparison of TSO and unimproved stock in PT52

The layout of the 5-tree row plots in PT52 may have exaggerated the difference in growth rate between the TSO and the unimproved stock. The dbhob of stems is influenced by competition between trees. In PT52 all the TSO and non-improved stocks were planted in randomised layouts with trees of controlled crosses between plus trees. Therefore the TSO and non-improved stocks will have been in direct competition with genetically superior stock. The growth rate of the non-improved stock, in particular, may have been less than if these trees had been competing only with trees of similar genetic stock.