# BRANCH DEVELOPMENT IN *PINUS RADIATA*— MODEL OUTLINE AND DATA COLLECTION

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## ABSTRACT

The location of branches attached to the tree stem and the dimensions of the initial part of these branches which become encased within the stem are major determinants of timber quality. The branching characteristics of *Pinus radiata* D. Don were summarised and this information was used to define the structure of a branch model. The data necessary to define the mathematical form of these functions were obtained by destructive sampling of selected trees.

**Keywords**: branches; knots; *Pinus radiata*.

## INTRODUCTION

The location of branches attached to the tree stem, and the dimensions of the initial part of these branches which become encased within the stem, are major determinants of timber quality. The influence of branches on the quality of *Pinus radiata* logs is predicted in the software system, STANDPAK (Whiteside 1990) using branch index and internode index. Branch index is the mean diameter of the four largest branches in a nominated log length, one branch being selected from each quadrant (Inglis & Cleland 1982). Internode index is the sum of the lengths of internodes greater than or equal to 0.6 m divided by the log length (Grace & Carson 1993). However, the need has been perceived for a modelling system which provides more detail about the branching characteristics of *P. radiata*.

In this paper we summarise current knowledge about branch development in *P. radiata*; we describe the development of a modelling system designed to give forest managers considerable detail on the position and size of branches encased within the stem; and we outline the procedure used to collect the data needed to develop the mathematical form of the model functions. The mathematical form of the functions will be discussed in subsequent papers.

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† Since deceased

## BRANCHING CHARACTERISTICS OF *PINUS RADIATA*

### Position and Frequency of Branch Clusters on the Tree Stem

*Pinus radiata* is polycyclic (Sweet & Bollmann 1976). However, the most appropriate method to define the end of one annual shoot and the beginning of the next annual shoot is debatable (Burdon 1994). From a mensurational perspective, the end of an annual shoot is assumed to occur in mid-winter when height increment is at a minimum (Tennent 1986). From a morphological perspective, the end of an annual shoot is marked by a zone of compressed parastichies above a branch cluster. However, this zone of parastichies is considered to be formed in summer, and autumn elongation is essentially a "head start" on the spring flush (Burdon 1994).

From measuring the last five annual shoots on 86 trees (14 years old) at a South Island site (Pigeon Valley, 4 miles west of Wakefield), and using the zone of compressed parastichies to identify annual shoots, Bannister (1962) found that between one and six branch clusters were formed each year. He suggested that six may not be the maximum for *P. radiata*. At the other extreme, Fielding (1960) considered that the long internodes on two trees (open-pollinated progeny of a tree characterised by long internodes) represented at least 2 years of growth.

The number of clusters formed per year appears to be under strong genetic control after the first 5–6 years (Fielding 1960). Jacobs' (1938) suggestion that suppression results in fewer clusters in an annual shoot was supported by Fielding (1960) who measured up to 11 trees from each of eight clones selected for different branching habits and found a positive correlation between the number of branch clusters on the trees and stem diameter at breast height (dbh). Measurement of trees from a single clone planted at two North Island sites indicated that the number of clusters formed each year was greater at the warmer site (Bollmann & Sweet 1976).

Measurements on 220 trees (7 years old) and 86 trees (14 years old) at Pigeon Valley, and 25 trees (10 years old) at Whakarewarewa in the central North Island (Bannister 1962) indicated that the mean number of branch clusters formed per year increased with age. Measurements on 92 trees showed little variation in the mean number of clusters formed per year between 15 and 40 years of age (Bannister 1962). Jacobs (1938) suggested that "old age" tends to force trees toward a uninodal habit.

For the 14-year-old trees at Pigeon Valley, most of the variation was due to differences between trees (Bannister 1962). Small parts of the variation could be explained by tree age, and by annual shoot length.

From comparing his own and Fielding's (1960) results, Bannister (1962) suggested that for a given number of clusters within an annual shoot, their relative position within the annual shoot may be influenced by environmental conditions.

### Number of Stem Cones and Branches Within a Cluster

The age of reproductive maturity is quite variable; it generally does not occur before 7 years, but can be as late as 26 years (Bannister 1962). Once reproductive maturity is reached, a bud may contain 10–15 long-shoot primordia which, through morphological changes, develop into either branches or cones (Bollmann 1983). Hence, a cluster may contain only branches, branches and cones, or only cones (Bannister 1962). In mixed clusters, cones are usually located below the branches (Bollmann 1983). Cones are rarely present in the last branch cluster of an annual shoot (using the morphological definition). They occasionally occur in the second to last cluster and are generally present in all other clusters (Bannister 1962).

The occurrence of cones is important in terms of timber quality as they leave holes in the wood which have a negative impact on appearance grades and reduce the volume of cutting grades obtainable (D. McConchie pers. comm.).

From data collected at four widely separated sites within New Zealand, Madgwick (1994) showed that the number of branches in a cluster may range from one to at least 20, with a modal value of between five and eight. This range is greater than that observed for long-shoot primordia (Bollmann 1983). Possible reasons include more variation in buds than noted by Bollmann, branches/cones not being visible at the time of measurement, or two very closely spaced clusters being considered as one cluster.

The number of branches in a cluster appears to be genetically controlled (Fielding 1960; Madgwick 1994). No significant difference was observed in the mean number of branches per cluster at five sites in the Australian Capital Territory (A.C.T.) when observations were based on data from the two clusters closest to 0.2 × tree height (Fielding 1960). However, the mean number of branches per cluster was significantly and positively correlated with microsite differences within one compartment in the A.C.T. when observations were based on clusters between 0.2 and 0.7 × tree height on 47 dominant trees (Fielding 1967) (microsite was expressed as the mean height of the sample tree and two nearby dominants). At another site within the A.C.T., cluster height had little effect on the mean number of branches per cluster (Fielding 1960).

## Branch Diameter

Branch diameter is usually measured close to the junction of the branch with the stem. Any obvious swelling is avoided. The maximum diameter of a branch is influenced by the space available for growth (Fielding 1960). However, within an annual shoot, the cluster below the band of compressed parastichies tends to have more large-diameter branches than other clusters (Jacobs 1937).

Within a cluster, branch diameter varies considerably. Madgwick (1994) showed that when branches are ranked in order of decreasing diameter, each successive branch has a mean diameter approximately 12% smaller than the next larger branch. Variation about the means was not determined.

From measurements of all branches between 6.2 and 12.3 m* above ground-level on 19 randomly selected dominant and codominant trees (10 multinodal and nine uninodal type trees), Fielding (1960) concluded that mean branch diameter was negatively correlated with the number of branch clusters in the annual shoot.

From a sample of 162 trees from a spacing experiment at Mt Burr, South Australia, Cromer & Pawsey (1957) found that the ratio of mean branch diameter† to mean dbh was

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* All measurements quoted here have been converted to their metric equivalents.

† Mean branch diameter was defined as the mean diameter of each branch between 2.5 and 4.6 m above ground-level on the northern side of the tree, measured 5 cm from the stem surface.

not significantly correlated with spacing. However, for a given dbh, smaller branches occurred on trees with lower microsite quality as determined by dominant tree height.

### Branch Development

Branch diameter increases rapidly for the first few years. The length of this period depends on the maximum diameter attained by the branch. For 12-mm branches it is approximately 2.5 years. For 25-mm branches it is approximately 5.5 years (Brown 1962). The period of rapid growth is followed by a period, generally at least 10 years, when the diameter remains almost constant although the branch is still alive. The length of this second period does not appear to be related to branch diameter ( Brown 1962).

The angle between the stem and the upper side of a branch is initially small, but increases with age due to increasing branch weight (Jacobs 1938). However, on near-rotation-age trees, this branch angle is more acute for larger branches within a cluster than for smaller branches (J.C.Grace, unpubl. data). Using measurements of over 1000 branches from trees in a stand spaced at 3.7 × 3.7 m, Jacobs (1938) obtained a correlation coefficient of –0.64 for the relationship between branch angle and branch diameter. It is assumed that all the branches were measured at the same time. A positive correlation would be expected if these measurements had been collected over several years. Branch angle is also influenced by genetics and tends to be smaller in uninodal than in multinodal type trees (Fielding 1960).

### Branch Arrangement

Branches are initiated in a spiral sequence within a cluster. A small vertical separation of about 2–3 mm and a mean azimuthal angle of 137.5° have been observed between successive branches in young clusters. Diameter tended to increase with vertical elevation within the cluster (D. Pont, unpubl. data).

## MODELLING APPROACH

Branches support foliage which, through the interception of solar radiant energy and through photosynthesis, provides the resources for tree growth. However, the location and dimensions of the initial part of branches which become encased within the stem determine the suitability of timber for a particular end-use.

There are likely to be branching patterns which maximise both stem growth and suitability for a particular end-use. Prediction of these patterns will require a process-based modelling approach that utilises detailed information about all aspects of tree crown structure. The AMAP software (de Reffye *et al.* 1995) has potential in this area as detailed measurements of crown architecture are used to develop a realistic model of crown development. Simulations can be used to determine the effects of different branching patterns on tree growth and timber quality.

However, the data requirements mean that the AMAP approach is unlikely to be a practical option for forest managers who wish to predict the quality of timber which will be obtained at the end of a rotation. Since timber quality is determined by the part of the branch that is encased in the stem, a modelling approach which considers just this part of a branch is likely to be more useful to forest managers.

The aim of the present study was to develop a method for predicting the location of branches attached to the tree stem and the size of the initial part of these branches which become encased within the stem, and for projecting their branch diameter forward in time. Two key objectives in developing the system were:

- Suitability for practical applications in decision support systems for forest managers;
- Compatibility with existing models and software available at the New Zealand Forest Research Institute.

Many commercial stands of *P. radiata* in New Zealand are assessed from mid-rotation to shortly before harvesting using the MARVL inventory system (Deadman & Goulding 1979; Gordon *et al.* 1995). The inventory system has two distinct phases—data collection and data analysis. In the forest, trees are described by a set of user-defined quality codes that cover external quality features such as branch diameter, sweep, and form defect. The analysis software is used to determine the potential yield by log type, taking into account stem quality, stem dimensions, and the value of each log type per cubic metre. Within the software there is the ability to project tree growth to harvest age in terms of stem dimensions. However, the projection module does not predict changes in stem quality. The growth models linked with the MARVL system were originally stand-level models (Gordon *et al.* 1995). A prototype individual-tree distance-independent model was linked to MARVL in 1990 (A.D.Gordon unpubl. data). Revised individual-tree distance-independent models that are compatible with the stand-level models are being developed (Gordon & Lawrence 1997) and will be linked with MARVL. It was therefore considered logical to develop an individual-tree distance-independent model that predicts the location of branches attached to the tree stem and the dimensions of the initial part of these branches which become encased within the stem. Efforts were made to provide sufficient detail for practical applications while avoiding the large processing needs of a more complex model.

An added advantage is that it is sufficiently detailed to provide data suitable for a detailed sawing simulator such as AUTOSAW (Todoroki 1991, 1996), which maps knot locations on boards for timber grading.

## BRANCH MODEL—FUNCTIONS

Our knowledge of the mechanisms of tree and branch growth were used in deciding what functions should be within the model. It was hoped that by accounting for the mechanisms of growth we could formulate a flexible model, that would realistically represent the variations in branching resulting from genetics, site, and silviculture.

The prototype version of the branch model currently contains 13 functions which can be divided into five groups. These functions are described below. Data analysis to determine the mathematical form of these functions will be the topic of subsequent papers.

### Group A: Position in the Stem where Branch Clusters were Initiated

Modelling the position of branch clusters within annual shoots represents the growth process and allows us to utilise current height-growth models, based on extensive knowledge of height growth in radiata pine, to predict annual shoot extension.

***Function 1*** predicts the number of branch clusters within the annual shoot.

***Function 2*** predicts the relative position of the branch clusters within the annual shoot, using the output from Function 1.

### Group B: Number of Branches and Stem Cones within each Cluster

Prior to reproductive maturity, a cluster contains only branches. After reproductive maturity, a cluster may contain: only branches; branches and cones; or only cones.

***Function 3*** predicts the number of branches in each cluster.

***Function 4*** predicts the probability of stem cones occurring in each cluster.

If the cluster is predicted to contain stem cones,

***Function 5*** predicts the number of stem cones in each cluster.

### Group C: Diameter of Initial Part of Each Branch that is Encased within the Stem

As it is relatively easy in the field to observe the branch of largest diameter within a cluster, it was decided to model branch diameter relative to the diameter of the largest branch. This means that if data were being collected to provide starting values for the model, only the largest branch diameter in a cluster would need to be recorded.

***Function 6*** predicts the diameter of the largest branch within the cluster.

***Function 7*** predicts the relative diameter of the other branches from the diameter of the largest branch.

### Group D: Azimuthal Location of Branches

The azimuthal location of branches is important for determining what parts of the log can be used for different products. There are two issues which need to be addressed. Firstly, are azimuthal angles such that there are sectors of the stem without branches. Secondly, do the larger branches occur in the same azimuthal sector of the stem or are they distributed more evenly round the stem.

***Function 8*** predicts the azimuthal angle of branches in each cluster.

***Function 9*** predicts the azimuthal angle between largest branches in adjacent clusters.

### E: Branch Development over Time.

***Function 10*** predicts branch diameter at any age.

***Function 11*** predicts the vertical distance between the point of intersection of the branch pith with the stem pith and the current position of the branch pith.

***Function 12*** predicts the occurrence of bark encasement due to branch mortality.

***Function 13*** predicts the occurrence of bark inclusions above the branch which are not due to mortality.

## DATA COLLECTION PROCEDURE AND ISSUES

### Field Procedure

Destructive sampling of whole trees was chosen in preference to monitoring tree growth through time as the method for obtaining the data required for the branch growth model. The two main advantages of destructive sampling were, firstly, it enabled us to obtain data for determining growth patterns at one initial time, rather than waiting several years to obtain a similar set of data as would be necessary with monitoring. Secondly, it avoided the need to climb trees to obtain data on cluster position and branch diameter. By felling trees close to rotation age, we were able to collect data to understand how branching characteristics varied with tree age.

To date, data have been collected on 49 trees from four sites using the sampling procedure outlined below.

### *Prior to felling*

The north side of the tree was marked so that it was possible to investigate the influence of aspect on branching characteristics. A circular plot, centred on the sample tree, was established. The plot radius was chosen to give 10 trees at the nominal stocking. For each tree within the plot, dbh, and distance and bearing from the sample tree were measured. This provided an estimate of local stocking and allows the influence of neighbouring trees on branching patterns to be investigated (if desired).

### *Felling*

The felling direction was identified to minimise breakage, and ensure that the heads of different sample trees did not overlap. The major vegetation along the felling path was cleared to ensure that as much as possible of the underside of the tree, when it was on the ground, was visible for identifying branches and clusters.

Once the tree had been felled, any hazards created by the felling (for example, suspended broken branches) were made safe, as many measurements were made on the stem. The stem was reassembled above the first break point, and all branches were roughly trimmed to leave clearly identifiable stubs of 10–20 cm. These stubs had to be cut perpendicular to the branch direction so that the branch diameters perpendicular to the branch pith could be measured. The vegetation on both sides of the tree stem was also cleared to provide easy access to and good visibility of the stem.

The northline, or an alternative reference line (whose bearing with respect to north was measured), was then marked along the entire length of the stem to allow the position of branches in consecutive clusters to be compared.

### *Position of branch clusters*

The position of the base and top of each branch cluster was marked by a line drawn across the top surface of the stem, and the cluster was numbered. The base of the cluster is the lowest point where the branches are estimated to join the stem pith. According to D.Barthelemy (pers. comm.), this can be determined from the pattern of bark below the lowest branch in the cluster (Fig .1). The top of the cluster is the highest point at which the branches emerge from the stem. Care needed to be taken to ensure that each cluster was marked as some clusters can be close together, particularly when there is autumn growth (R.Burdon pers. comm.). The height to the base and top of each cluster, with respect to the base of the tree, was then measured using a tape. Stump height was recorded to allow heights above ground level to be established.

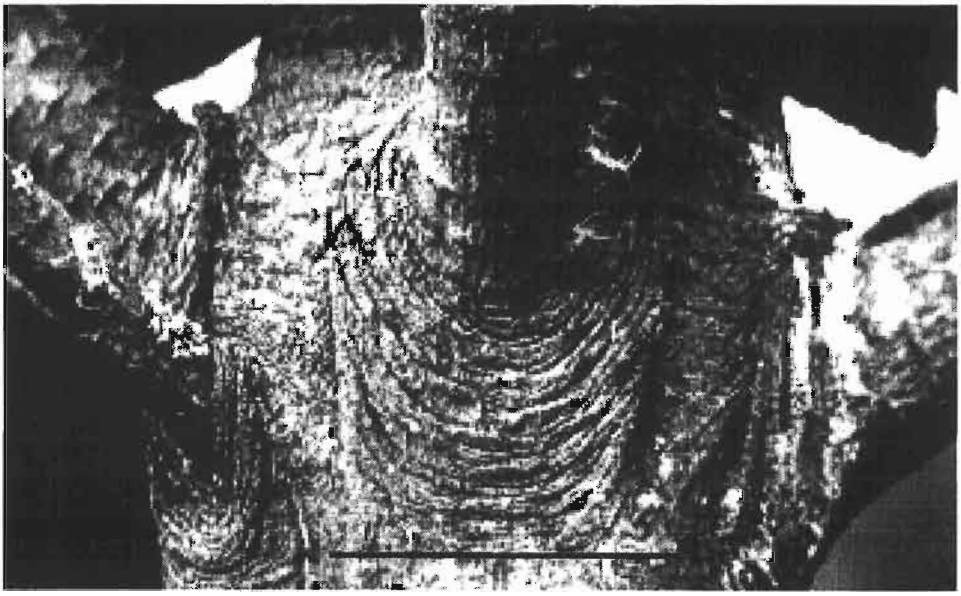

FIG. 1–Pattern of bark below a branch. In an operational procedure it will be sufficient to look for the base of the scarring pattern, marked here by a horizontal line. (It is considered that the actual join is a few millimetres above this point but is more difficult to determine.)

### *Measurement of clusters*

The stem was crosscut into discs, about 10 cm outside the marked cluster boundaries, so that each cluster was contained within a separate disc provided that clusters did not overlap. The tree and cluster number were then recorded on the top surface of the disc. It was important to be consistent in the marking as this provided positive identification of the top of the cluster for future measurements.

The number of stem growth rings on the base and top of each disc was counted. It is preferable to count the rings as soon as possible after the discs have been cut as the rings become less clear as the sample dries. These data, together with the heights of the clusters, were used to determine the number of clusters within an annual shoot and the relative positions of the clusters within the annual shoot (Functions 1 and 2).

For each cluster, the numbers of branches and stem cones were recorded. The horizontal diameter of each branch adjacent to the stem, but avoiding any swelling, was measured to the nearest millimetre using callipers. The azimuthal angle of each branch and cone with respect to the reference line was measured using a circular protractor placed on top of the disc, centred on the pith, with zero aligned with the reference line. There was a degree of judgment in determining the angle of branch emergence from the stem as the point where the branch emerges is generally some distance from the top of the disc. This method only gives the angle of azimuth at the time of felling. At this stage we consider that the changes in angle of azimuth over time are small and that a separate function to model the change in angle of azimuth through time is not necessary. These data enabled us to derive the coefficients for Functions 3–9 inclusive.

Stem diameter above and below the cluster was also recorded.

### *Measurement of branch development*

To determine branch diameter development over time, one branch was selected from a cluster. The sample branch was cut from the cluster as follows. The first cut was approximately parallel with the branch pith, but to one side of the branch. The second cut was parallel to the first cut but on the other side of the branch. The third cut was at right angles to the first two, and gave a section that included the branch (*see* Fig. 2). This section was then numbered with the tree and cluster number. One side of the section was planed, to expose the pith of the branch and the stem. This side needed to be carefully chosen so that the planed surface was convex, not concave as, because of the width of the planer, it was difficult to plane a concave face. The tree and cluster number were written on the opposite side prior to planning.

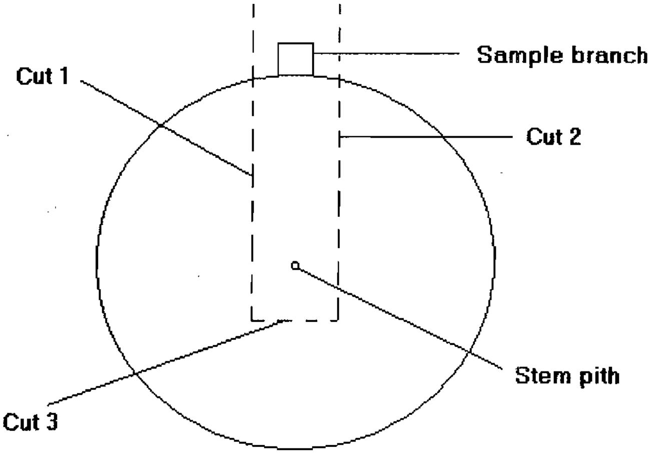

FIG. 2–How a sample branch is cut from a stem disc.

If the sample was satisfactory, a line was drawn from the join of the stem and branch pith at approximately a right angle to the stem pith and the stem growth rings. There was some subjectivity in the position of this line if the stem pith was swept. The stem radius for each year that the stem had grown was marked and then measured along this line. The height of the branch pith above the marked line was measured for each year that the stem had grown. The stem growth rings were used to identify the diameter of the branch for each year that the stem had grown by following the stem growth rings through to the branch (*see* Fig. 3). The branch diameters were then measured. The position of defects and any bark encasement due to mortality were recorded. These data were used to determine the coefficients for Functions 10–13 inclusive.

It was preferable to identify the features to be measured as soon as possible after the sample had been planed as the rings are most visible immediately after planing and become less clear as the sample dries.

## Data Capture

At the first two sites data were recorded on paper, then punched and checked. This was the most appropriate approach as the methodology was still being developed, and we often

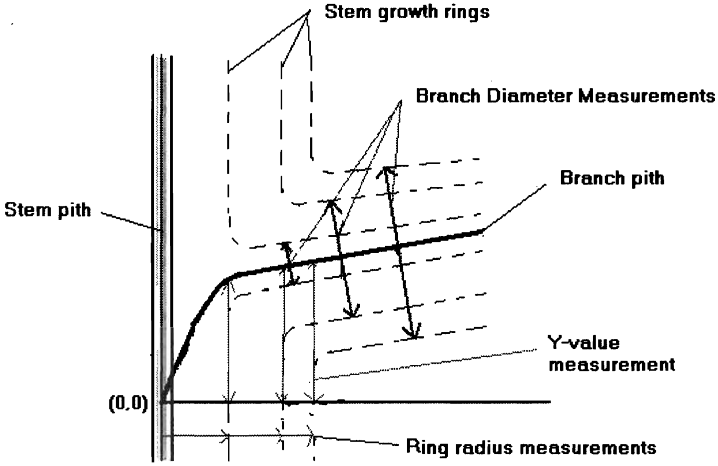

FIG. 3–How the stem growth rings merge with the branch growth rings.

needed to make comments on interesting and unusual features. Even after these two studies, the development of purpose-written data collection software was precluded by time and cost.

Near the beginning of the third study, a general-purpose commercial data-capture package (EASYDC, version 4.0—White 1996) was purchased, and this was used to record most of the field data at the third and fourth sites.

EASYDC allows the user to define a number of data entry forms and use them for recording data. In addition to a basic definition such as the name, type, and size of fields, the user can also set up prompt text, default values, data validation, on-the-spot calculations, and other sophisticated features for each data entry field. In use, several data entry forms can be open at one time, and the user can move between them, entering data.

The program was used on a HUSKY Hunter 16 computer, and the following forms were used in this data collection exercise:

*Comment*

Any observations or notes, recorded against tree number and, where appropriate, cluster number and branch number.

*Cluster header*

Position of base and top of cluster; stem ring counts above and below the cluster; overbark stem diameters above and below the cluster.

*Cluster detail*

Diameter, azimuth, and status of each branch and cone in a cluster.

*Branch header*

Pith and sapwood radii, stem ring counts, bark encasement, branch diameter, and presence of bark inclusion for each planed sample branch.

### *Branch detail*

Stem radius, branch diameter, branch radius below the pith, and distance of branch pith from a horizontal reference line, for each year of stem growth.

Use of direct data capture had the usual benefits: avoidance of problems with lost, damaged, or illegible data sheets; immediate validation of data in the field; removal of the need for data punching, with its associated cost and potential for errors; and immediate availability of data at the end of each day's measurement.

## Issues

### *Sample size*

The detailed level of sampling required for each tree limited the number of trees sampled at a particular site. In the first study, data were collected on 12 trees from a spacing experiment (in the central North Island). In the second study, data were collected on 13 trees from a timing of thinning and spacing trial (in the central North Island). In the third study, data were collected on 16 trees, two from each of eight families with different levels of polycyclism (in the central North Island). In the fourth study (in the South Island), data were collected on eight trees, two from each of four families with different levels of polycyclism.

The low number of trees sampled was not considered a disadvantage in developing a prototype model. Firstly, the sample trees in each study were selected to cover the variability in tree size. Secondly, the model is linked with current growth models which enable stem growth to be predicted with reasonable accuracy for all parts of New Zealand. Thirdly, at the New Zealand Forest Research Institute, there is a database of less-detailed information on branching from all areas of New Zealand. The prototype version of the branch growth model can therefore be used in conjunction with the stand growth model to simulate the branching characteristics of the trees in the database. These can be summarised and compared with the measurements, thus indicating areas for further intensive data collection. To be suitable for planning purposes, the model will need to give reasonably precise and accurate results.

### *Multiple handling of samples*

In the third and fourth data collections we counted stem growth rings as soon as the trees had been cut into discs, and then measured the other data required. Also, we chose to mark sample branches as soon as they had been planed and measure them later. While this approach might seem inefficient, it was probably quicker and more accurate as it was easier to observe, count, and mark the rings while the cut was fresh.

### *Selection of sample branches*

For the first two data sets, the sample branch in a cluster was marked when the cluster was being measured. In the first data set sample branches were selected from successive clusters, on the basis of branch diameter, using the following strategy: large, medium, small, medium, large. This resulted in more small-diameter branches than anticipated because some clusters contain only branches of small diameter. In the second data set, sample branches were selected in the same manner using a different strategy—namely, medium and large. For the third and fourth data sets, sample branches were selected from the branch diameter distribution once all clusters had been measured. This approach was practical using EASYDC. Even though it meant an extra visit to each tree to mark the sample branches, it resulted in a better distribution of sample branch diameters than achieved using the earlier approach.

### *Annual shoots*

An important issue which has arisen during the data collection phase is the question of the most appropriate method for defining an annual shoot. Currently annual shoots are defined based on counts of stem growth rings. This enables the functions developed to be compatible with the current growth models. However, Burdon (1994) has pointed out that *P. radiata* forms a resting bud in summer rather than winter, and for a few years the position of this bud is visible on the stem. But the resting bud may expand during the autumn. Hence, determining annual shoots by the position of the bud may not necessarily coincide with the change in ring counts. Using the resting bud to group clusters appears to offer the possibility of identifying patterns of cluster development related to morphological processes. These patterns do not appear obvious when using ring counts. Further investigation is required to determine the most appropriate methodology.

It was also noticed that the ring closest to the pith is the hardest to discern. It is possible that difficulties occur when there has been extension growth during the autumn. It is planned to microscopically examine some samples to clarify the issues.

## DISCUSSION

Functions required for a model of branch development, and data collection methodology have been formulated. The model will be empirical in that the coefficients are derived from measured data. However, an attempt has been made to develop a framework that is based on our best understanding of the branching process. In this respect we have a model structure that should be robust, and suitable for a wide variety of end-uses. The data from the 49 sample trees are currently being analysed to develop the mathematical form of the functions. The data analysis will be published in subsequent papers.

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## REFERENCES

BANNISTER, H.M. 1962: Some variation in the growth pattern of *Pinus radiata* in New Zealand. *New Zealand Journal of Science 5*: 342–370.

BOLLMANN, M.P. 1983: Morphology of long-shoot development in *Pinus radiata. New Zealand Journal of Forestry Science 13(3)*: 275–290.

BOLLMANN, M.P.; SWEET, G.B. 1976: Bud morphogenesis of *Pinus radiata* in New Zealand: I. The initiation and extension of the leading shoot of one clone at two sites. *New Zealand Journal of Forestry Science 6(3)*: 376–392.

BROWN, G.S. 1962: Stages in branch development and their relation to pruning. *New Zealand Journal of Forestry 8(4)*: 608–622.

BURDON, R.D. 1994: Annual growth stages for height and diameter in *Pinus radiata*. *New Zealand Journal of Forestry Science 24(1)*: 11–17.

CROMER, D.A.N.; PAWSEY, C.K. 1957: Initial spacing and growth of *Pinus radiata*. *Forestry and Timber Bureau, Canberra, Bulletin No. 36.*

DEADMAN, M.W.; GOULDING, C.J. 1979: A method for the assessment of recoverable volume by log types. *New Zealand Journal of Forestry Science 9(2)*: 225–239.

DE REFFYE, P.; HOULLIER, F.; BLAISE, F.; BARTHELEMY, D.; DAUZAT, J.; AUCLAIR, D. 1995: A model simulating above- and below-ground tree architecture with agroforestry applications. *Agroforestry Systems 30*: 175–197.

FIELDING, J.M. 1960: Branching and flowering characteristics of monterey pine. *Forestry and Timber Bureau, Canberra, Bulletin No. 37.*

———1967: Some characteristics of the crown and stem of *Pinus radiata*. *Forestry and Timber Bureau, Canberra, Bulletin No. 43.*

GORDON, A.D.; LAWRENCE, M.E. 1997: Predicting *Pinus radiata* tree diameter increment. Pp.87–98 *in* Ortega, A.; Gezan, S. (Ed.) "Modelling Growth of Fast-grown Tree Species", Proceedings of IUFRO Conference, 5–7 September, Valdivia, Chile.

GORDON, A.D.; LAWRENCE, M.E.; PONT, D. 1995: Assessing potential yield of stands prior to harvesting. *Proceedings of the Institute of Foresters of Australia 16th Biennial Conference*: 193–200.

GRACE, J.C.; CARSON, M.J. 1993: Prediction of internode length in *Pinus radiata* stands. *New Zealand Journal of Forestry Science 23(1)*: 10–26.

INGLIS, C.S; CLELAND, M.R. 1982: Predicting final branch size in thinned radiata pine stands. *New Zealand Forest Service, FRI Bulletin No. 3.*

JACOBS, M.R. 1937: Detection of annual growth in the crown of *Pinus radiata*. *Commonwealth Forestry Bureau, Canberra, Bulletin No. 19.*

———1938: Notes on pruning *Pinus radiata*, Part I. Observations on features which influence pruning. *Commonwealth Forestry Bureau, Canberra, Bulletin No. 23.*

MADGWICK, H.A.I. 1994: "*Pinus radiata*—Biomass, Form and Growth". Madgwick, Rotorua. 428 p.

SWEET, G.B.; BOLLMANN, M.P. 1976: The terminology of pine shoot growth. *New Zealand Journal of Forestry Science 6(3)*: 393–396.

TENNENT, R.B. 1986: Intra-annual growth of young *Pinus radiata* in New Zealand. *New Zealand Journal of Forestry Science 16(2)*: 166–175.

TODOROKI, C.L. 1991: Development of an automated sawing simulator. *New Zealand Journal of Forestry Science 20(3)*: 332–343.

———1996: Developments of the sawing simulation software, AUTOSAW: Linking wood properties, sawing, and lumber end-use. Pp.241–247 *in* Nepveu, G. (Ed.) "Connection between Silviculture and Wood Quality through Modelling Approaches and Simulation Softwares", Proceedings of IUFRO Division WP S5. 01-04 Second Workshop, 26–31 August, Berg-en-Dal, South Africa.

WHITE, R. 1996: "EASYDC Universal Data Collection Program for MS-DOS Handheld Computers. User Guide". R. White, Woods Inc., Victoria, B.C., Canada.

WHITESIDE, I.D. 1990: STANDPAK modelling system for radiata pine. Pp.106–110 *in* James, R.N.; Tarlton, G.L. (Ed.) "New Approaches to Spacing and Thinning in Plantation Forestry". *Ministry of Forestry, FRI Bulletin No. 151.*