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MODELLING BRANCH DEVELOPMENT in RADIATA PINE

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EXECUTIVE SUMMARY

The location of branches attached to the tree stem and dimensions of the initial part of these branches which become encased within the stem are major determinants of timber quality. The branching characteristics of radiata pine (*Pinus radiata*) have been reviewed and a brief summary is presented. This information was used to develop the structure of a branch model which will simulate 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. The basis of the functions within the model are outlined. Graphical outputs from a prototype version, which uses preliminary mathematical functions based on limited data analysis, are shown to illustrate the potential capabilities. While the model is empirical, an attempt has been made to make the functions meaningful in terms of growth processes. This approach should ensure a robust structure, suitable for a wide variety of applications.

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MODELLING BRANCH DEVELOPMENT IN RADIATA PINE

J.C. Grace and D. Pont

INTRODUCTION

In New Zealand, planted production forests cover 1.48 million hectares, approximately 5% of the total land area. Close to 90% of this area is planted with radiata pine (*Pinus radiata* D. Don) which is typically harvested after 25 - 30 years (Ministry of Forestry, 1996). Approximately 40% of the radiata pine is in the Central North Island (Ministry of Forestry, 1996). About 70% of the total area in radiata pine is, or is expected to be, intensively managed with pruning of live branches to a height of at least 4 m to produce clearwood (Ministry of Forestry 1996).

On the unpruned stem section, the location of branches and cones, branch diameter, log diameter, log sweep, internode length (distance between adjacent branch clusters) and wood density all influence the grades of timber produced (Ministry of Forestry, 1988).

While several software packages have been developed which implement models to support the forest industry predict growth and yield (cited in Maclaren, 1993), there are no models for predicting the location and growth of branches attached to tree stems.

In this paper we summarise current knowledge about branch development in radiata pine and discuss the development of a modelling system designed to give the forest manager detailed information on the location and dimension of branches encased within the stem.

BRANCHING CHARACTERISTICS OF RADIATA PINE

Position and frequency of branch clusters on the tree stem

Radiata pine is polycyclic (Sweet and Bollmann, 1976). The most appropriate method for defining the end of an annual shoot is debateable (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 biological perspective, the end of an annual shoot is marked by a zone of compressed parastichies[1] above a branch cluster. 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 (using the zone of compressed parastichies to identify annual shoots) on 86 fourteen-year-old trees at a South Island site (Pigeon Valley, four miles west of Wakefield), Bannister (1962) found that between one and six branch clusters were formed each year. He suggested that six may not be the maximum for radiata pine. At the other extreme, Fielding (1960) considered that the long internodes on two trees

[1] In radiata pine, the scale leaves have decurrent leaf bases.These and the scars of the scale leaves display a pattern of intersecting helices known as parastichies (Bannister , 1962).

(open-pollinated progeny of a tree characterised by long internodes) represented at least two 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 less clusters in an annual shoot was supported by Fielding (1960). Fielding (1960) measured up to 11 trees from each of of 8 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 and Sweet,1976).

Measurements on 220 seven-year-old trees and 86 fourteen-year-old trees at Pigeon Valley and 25 ten-year-old trees at Whakarewarewa, in the Central North Island, Bannister (1962, Fig. 6) indicated that the mean number of branch clusters formed per year increased with age. Measurements on 92 trees aged between from showed little variation in the mean number of clusters formed per year on trees between 15 and 40 years-old (Bannister, 1962). Jacobs (1938) suggested that "old age" tends to force trees toward a uninodal habit.

For the fourteen-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 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. Reproductive maturity 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 contains 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. 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 available (D. McConchie pers. com.).

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 1 to at least 20 with a modal value of between 5 and 8. 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 5 sites in the Australian Capital Territory (ACT) when observations were based on data from the two clusters closest to 1/5 tree height (Fielding, 1960). However the mean number of branches per cluster for clusters was significantly and positively correlated with microsite differences[2] within one compartment in the ACT when observations were based on clusters between 0.2 and 0.7 × tree height on 47 dominant trees (Fielding, 1967). At one site within the ACT , 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 all branches between 20 ft (6.2 m) and 40 ft (12.3 m) above ground level on 19 randomly selected dominant and codominant trees (10 multinodal and 9 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 and Pawsey (1957) found that the ratio of mean branch diameter[2] to mean DBH was 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 Growth and 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 0.5 inch branches, it is approximately 2.5 years. For 2 inch branches, it is approximately 5.5 years (Brown, 1962). The period of rapid growth is followed by a period, generally at least 10 years, where 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, unpublished data). Using measurements of over 1000 branches from trees in a

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[2] Mean branch diameter was defined as the mean diameter of each branch between 8 ft (2.5 m) and 15 ft (4.6 m) above ground level on the northern side of the tree measured 2 inches (5 cm) from the stem surface.

stand spaced at 12 ft (3.7 m) × 12 ft (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, unpublished 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 determines 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 the potential to answer this question. Detailed measurements of crown architecture are used to develop a realistic model of crown development. Simulations can be used to determine the effects 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 just considers 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 to the tree stem, 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.

Many commercial stands of radiata pine in New Zealand are assessed from mid-rotation to shortly before harvesting using the MARVL inventory system (Deadman and 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/ m^3 of each log type. 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 are currently stand level models (Gordon et al, 1995). However individual tree - distance independent models that are compatible with the stand level models are being developed (Gordon and 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 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 output 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 is hoped that by accounting for the mechanisms of growth we can formulate a flexible model, that will realistically represent the variations in branching resulting from genetics, site and silviculture.

The prototype version of the branch model currently contains 13 functions. The mathematical form and coefficients of the functions have been derived from a preliminary analysis of limited data collected during destructive sampling of near-rotation age trees in the Central North Island. We have therefore chosen to describe the functions in words to promote discussion of the concepts rather than the formulae which are likely to be changed as a result of further analyses.

The functions, which can be divided into 5 groups are outlined below.

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 can 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. The diameter of the initial part of each branch that is encased within the stem

As it is relatively easy to observe the branch of largest diameter within a cluster in the field, 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 whether they are 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

BRANCH MODEL - IMPLEMENTATION

An initial implementation of the branch model was made in Object Pascal using the Delphi (Borland International, 1995) visual programming environment. A simple stand growth model is currently used to drive the branch model. A taper function (Gordon, 1983) is used to predict the under-bark stem radius.

A three dimensional geometrical model of the entire stem showing the location of stem cones, and the location and dimensions of the initial part of branches which become encased within the stem is created. This can be viewed at any tree age. Four levels of graphical view are provided, corresponding to obvious levels of tree structure: whole tree, annual shoot, cluster and single branch. Because the graphical model is three dimensional it is able to be rotated interactively. This allows the stem and branches to be viewed from any desired angle, and for spatial patterns to be easily observed.

Diagrams illustrating the range of graphical output are presented in Figs. 1-5. Selected graphical views from the software are presented to illustrate the components of the branch model. These examples show the predicted stem structure of a representative tree from a stand with 600 stems/ha and site index (mean height of the 100 largest diameter trees at age 20 years) 30 m which was grown to age 30 years in annual steps. Two pruning lifts to 3 m and 6 m were simulated at ages 5 yrs and 10 yrs respectively.

In the tree view (Fig. 1), the predicted position of branches is indicated by a sloping line at the appropriate branch angle. Due to the simulated pruning, the branch stubs do not reach to the outer stem surface of the stem near the base of the tree.

The selected shoot view (Fig. 2) shows an annual shoot with 4 clusters. It illustrates how branches are arranged in clusters and the angle of branches with respect to the stem. It also illustrates that there is little variation in internode length when there are more than two clusters. Current branch diameter is modelled by a circle at the end of each branch, adjacent to the surface of the stem. As the image is a flat projection of the three dimensional cluster, the circle appears to be an ellipse, and some branch angles appear steeper than in reality.

The selected cluster view (Fig. 3) shows cones occurring below the branches. The small vertical separation between cone and branch origins is visible on the stem pith. The cluster view also illustrates how the branch diameter increases rapidly for a few years followed by a period of little change.

Fig. 4, a bird's eye view of a cluster, illustrates the azimuthal location of branches and shows that the larger branches are distributed around the stem, rather than just occurring in one sector of the stem.

The branch view (Fig. 5) illustrates branch diameter changes in greater detail. It is also an approximate representation of how the stem and branch wood merge. Branch diameter at each age is modelled by a circle around the branch pith. In this two-dimensional representation they appear to be ellipses. The line through the circles indicates the position of the branch pith.

DISCUSSION

The branch model is empirical in that the coefficients are derived from measured data. However we have aimed to develop a model structure that is robust and suitable for a wide variety of end uses by basing it on our best understanding of the branching process.

For the model to be of practical use to forest managers we need to have a good understanding of the underlying variability of branching characteristics as well as that due to genetics, site and in response to management practices. To date, three sets of data have been collected within the Central North Island to estimate the coefficients in the model functions. The datasets were collected from 12 trees in a spacing experiment, from 13 trees in a timing-of-thinning × stocking trial, and from 16 trees from 8 different families, covering varying levels of polycylcism.

The number of measurements taken on each tree has limited the number of trees sampled. There are two reasons for suggesting that this is not a disadvantage. Firstly, the model is linked with current growth models which enable stem growth to be predicted with acceptable accuracy for all parts of New Zealand. Secondly, a database containing less-detailed information on radiata pine branching from the major areas of plantations in New Zealand is held at the New Zealand Forest Research Institute. The current version of the branch model can therefore be used in conjunction with growth models to simulate the branching characteristics of the trees in the database. These results can be summarised and compared with the actual measurements, thus indicating areas for further intensive data collection. Trees from the families already investigated will be sampled from other sites to increase our understanding of the effects of site on branching characteristics.

The next step is to comprehensively analyse the above datasets and update the model functions. We intend to add functions to predict the incidence of, and consequences of a change in leader. Field observations indicate that clusters incorporating a change in leader tend to have steeper branches than other clusters. We have added published wood density and spiral grain functions to the model so that we can show the interactions of branching and wood properties. There is interest in using the model to generate trees to be used with the sawing simulator AUTOSAW, and interest in using parts of the model to recreate the internal branching pattern in scanned logs.

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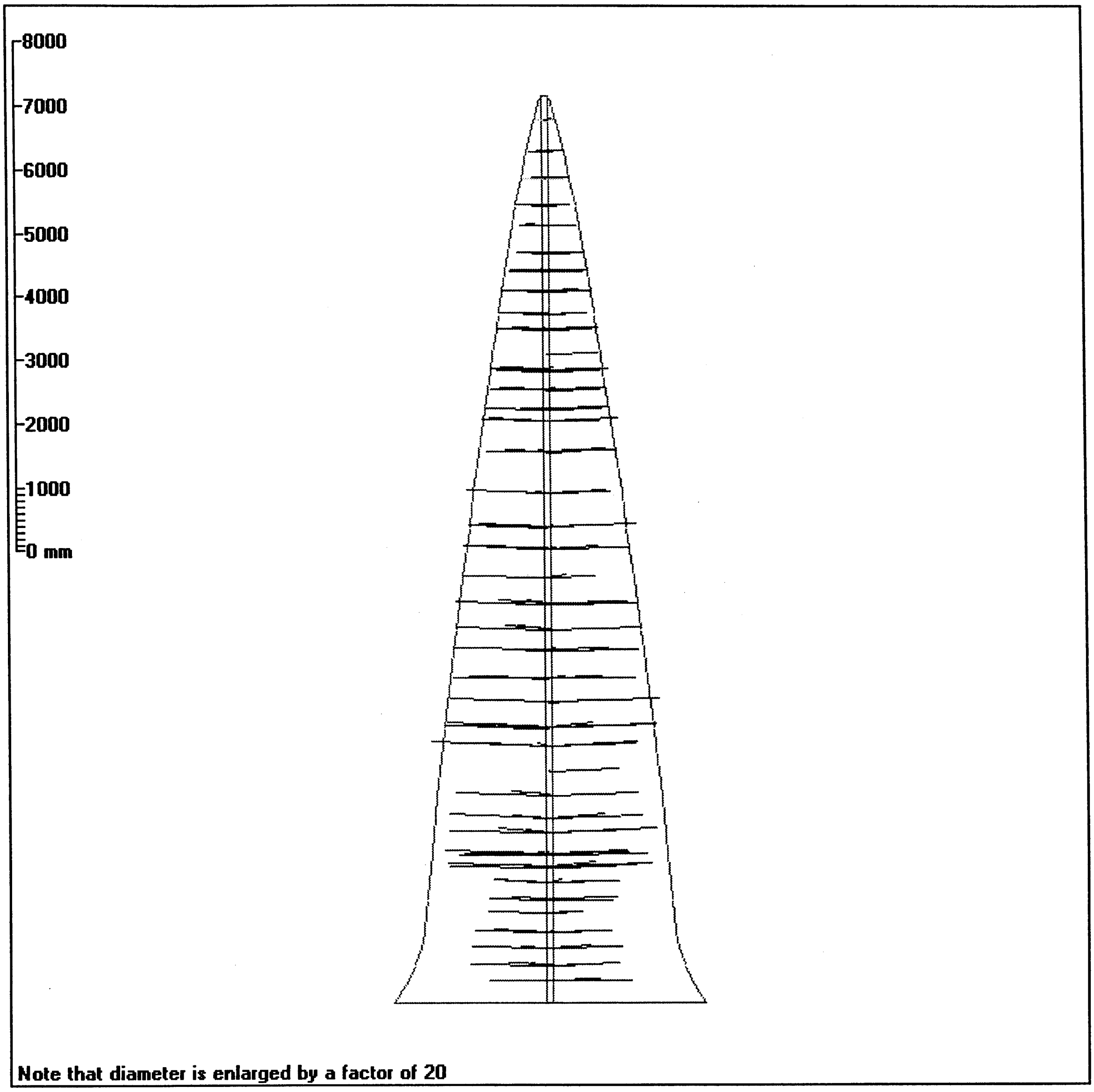

Figure 1. Whole stem at age 10.

Branches are represented by a line from the stem pith to the end point of the branch pith. Pruning has been simulated leaving a knotty core surrounded by clearwood at the base of the tree.

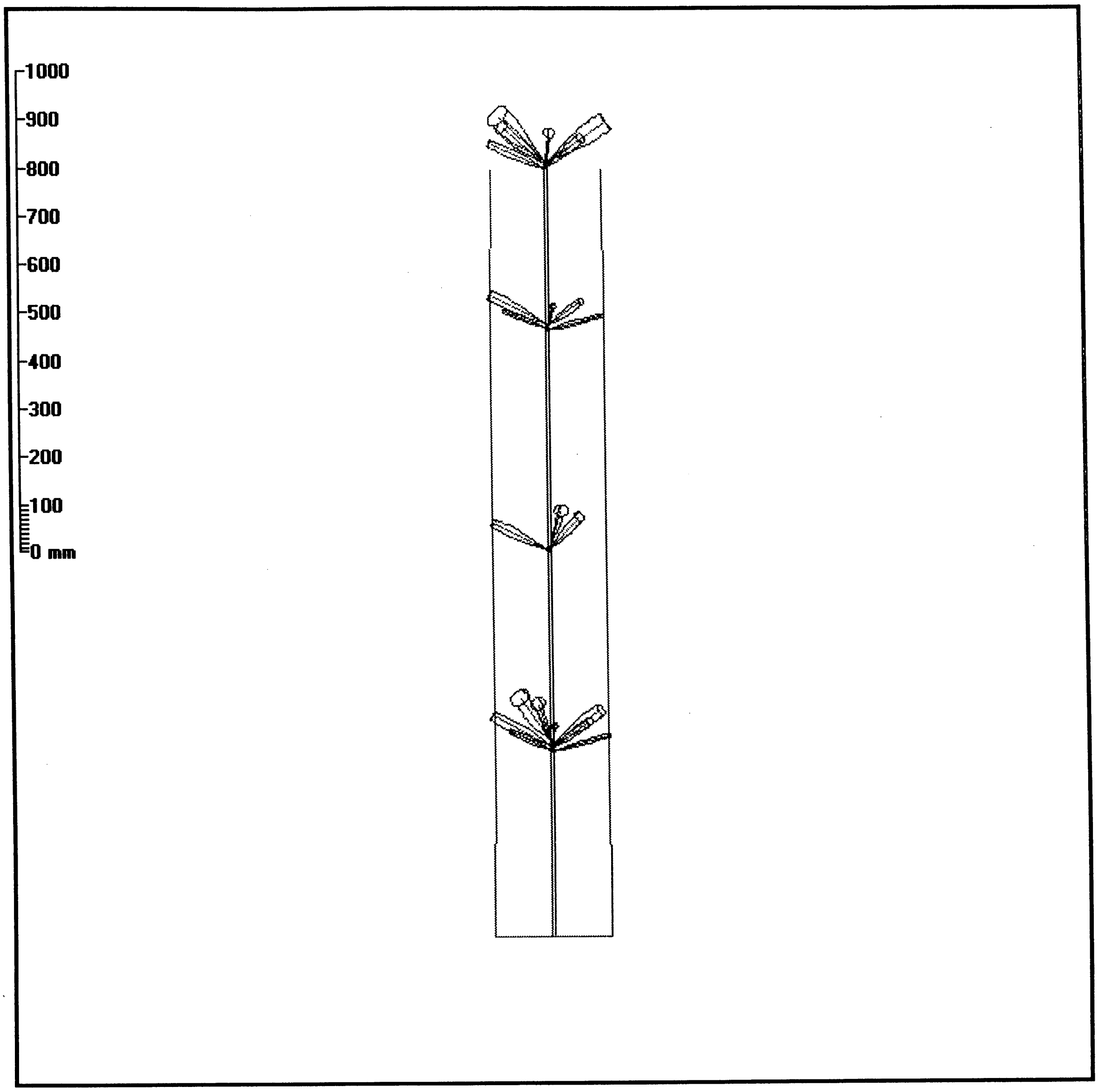

Figure 2. Tree age 20, annual shoot 6. A circle at the end of each branch represents its current diameter at the surface of the stem. Curved lines at the upper and lower extent of the branch within the stem delineate the shape of the knot.

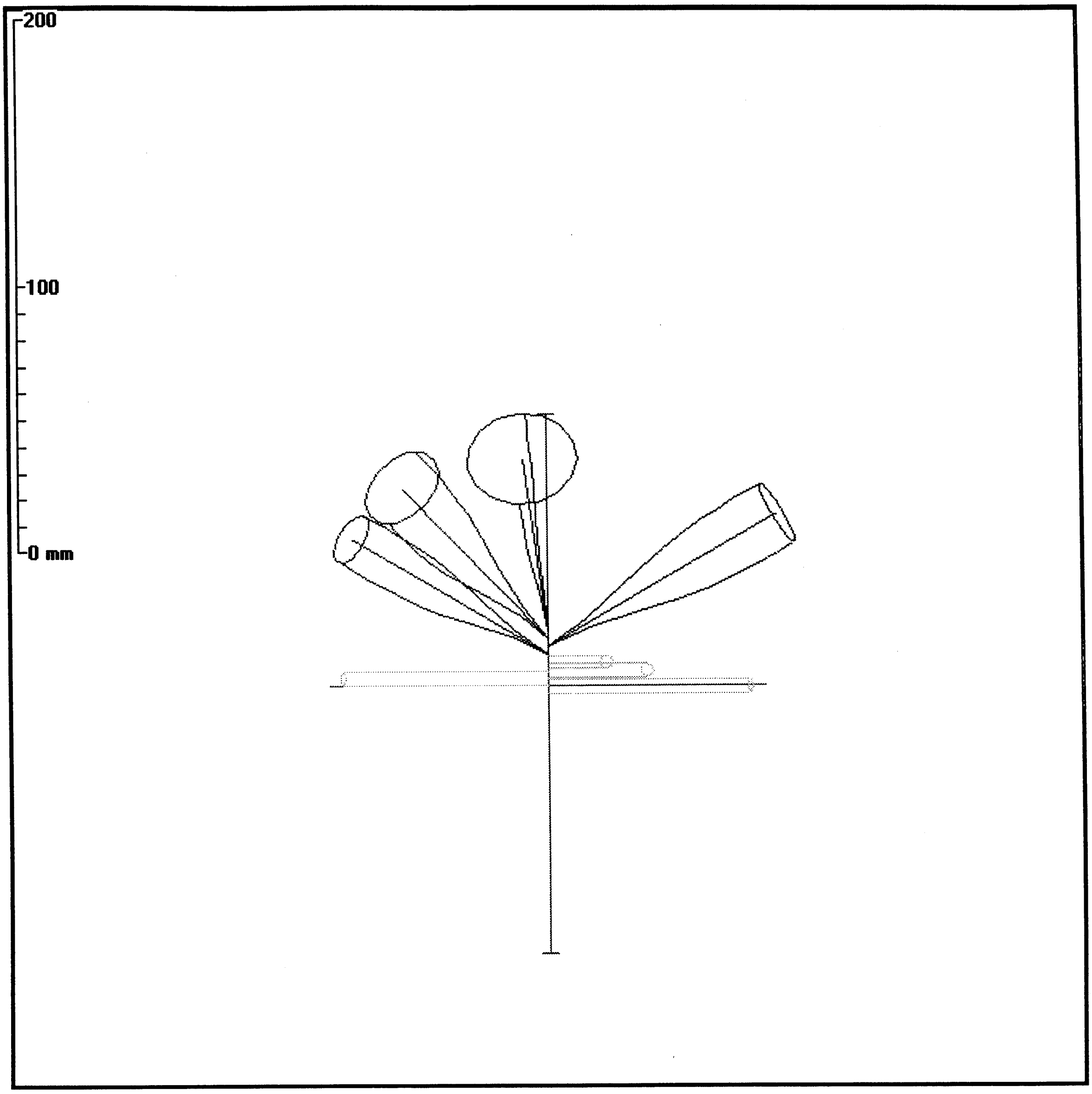

Figure 3. Tree age 20, annual shoot 12, cluster 2.

Stem cones are shown below the branch cluster. The vertical separation of branch and cone origins at the stem pith can be seen, and the increase in branch size and angle from the base of the cluster. Note that as this is a 2-D projection of the 3-D cluster, branch angles can appear steeper than they are.

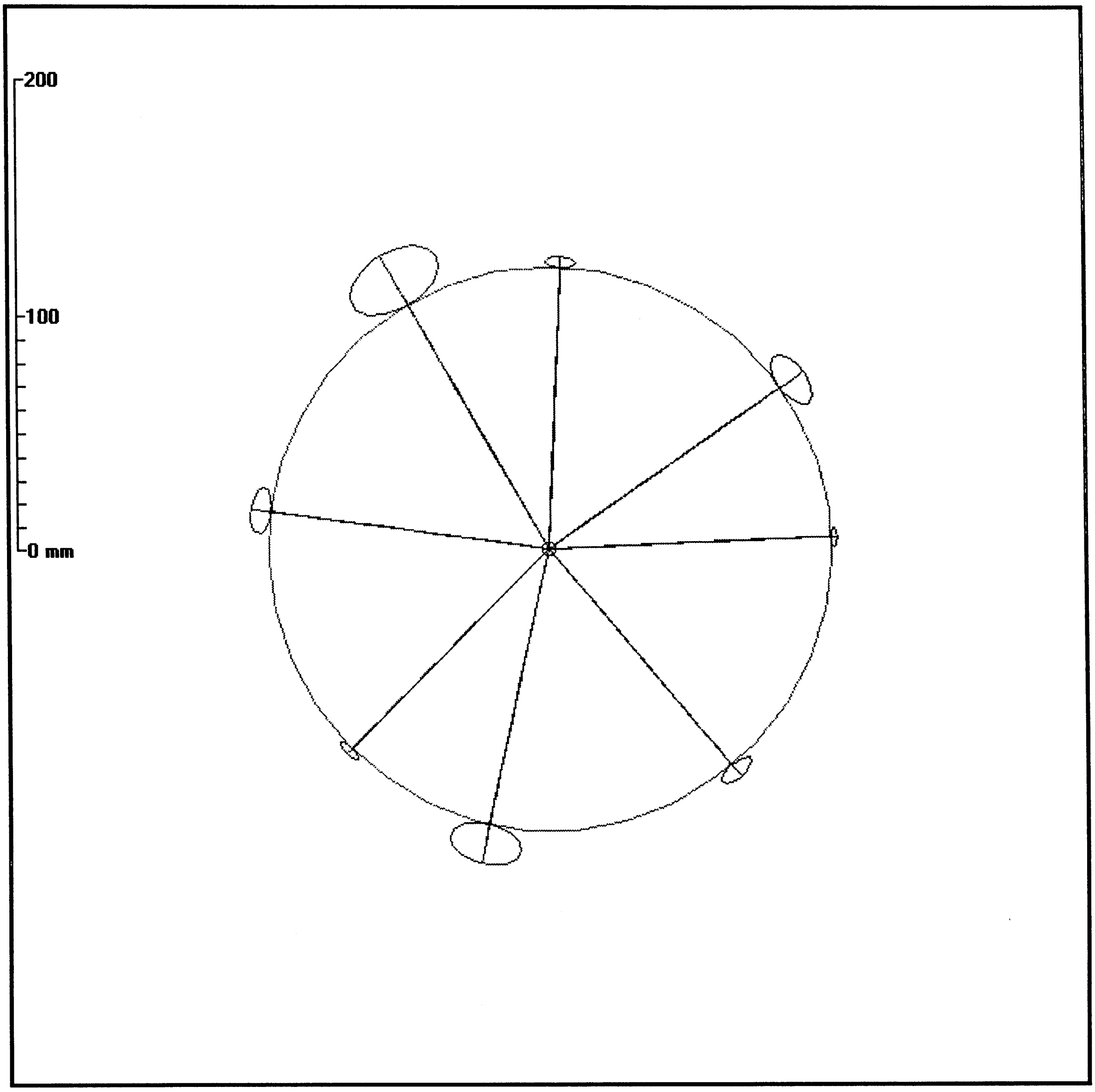

Figure 4. Tree age 20, annual shoot 6, cluster 1.

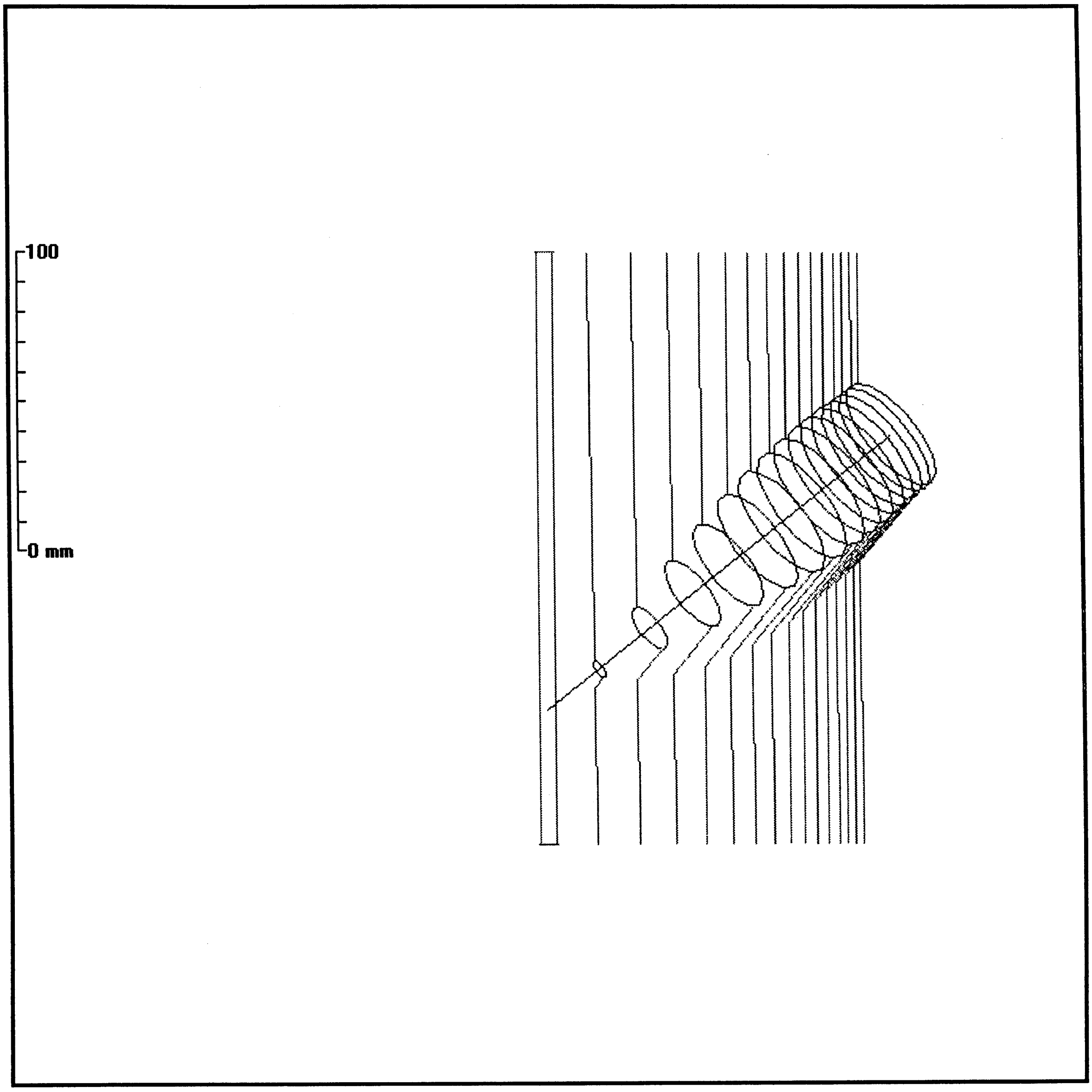

Figure 5. Tree age 20, annual shoot 6, cluster 1, largest branch.

Bark encasement is predicted on this branch from ring 14 onwards.