# PREDICTION OF INTERNODE LENGTH IN *PINUS RADIATA* STANDS

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## ABSTRACT

Internode length is an important variable in determining the amounts of clearwood which can be obtained from unpruned logs. An empirical model has been developed for predicting stand mean internode length for variable log lengths for forest sites in New Zealand. The model, applicable for both unimproved and genetically improved *Pinus radiata* D. Don, predicts internode length from mean annual rainfall, altitude, and "level of genetic improvement".

**Keywords**: internode length; modelling; *Pinus radiata.*

## INTRODUCTION

Internode length is defined as the vertical distance on a tree stem between the top of one cluster of branches and the base of the next higher cluster of branches (*see* Fig. 1). A knowledge of how internode length varies with breed, site, and management is important to the forest manager, since internode length is an important variable in determining the amounts of clearwood (known as clear cuttings) which can be obtained from unpruned logs.

On an individual tree, internode length is under strong genetic control once the juvenile phase is passed (Carson & Inglis 1988; Lavery 1986). Tree breeders have taken advantage of this fact in developing a special-purpose "long-internode" breed (Carson 1987), while selection for improved growth rate and stem form in a general-purpose "growth and form" breed has produced a correlated response of reduced internode lengths.

The length of internodes will also depend on annual height growth, the number of branch clusters, and their relative position within the annual cycle.

The number of internodes in the annual shoot varies between one and six (Bannister 1962). Data collected at Pigeon Valley near Nelson indicated that where there are two internodes in the annual shoot, the first is the longest; where there are more, the internodes are longest about the middle of the annual shoot. However, work in Australia (Fielding 1960) found that internode length varied from a maximum at the base of the annual shoot to a minimum at the top. Bannister (1962) suggested that these differences might be a reflection of the effects of dry summers in Australia in contrast to generally moist summers in New

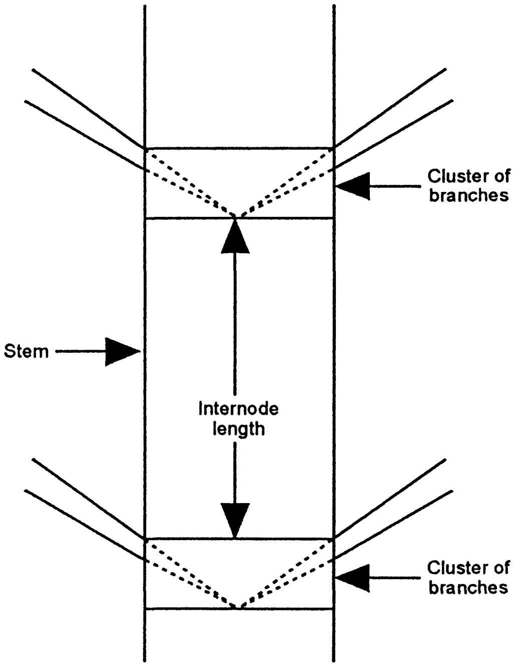


FIG. 1–Method of measuring internode length.

Zealand. This seems logical as Fielding's data indicated reduced internode lengths during a period of drought.

The mean number of internodes in the annual shoot varies with age. At Whakarewarewa Forest near Rotorua and at Pigeon Valley the mean number of internodes in the annual shoot increased from about 1.5 to 3.5 between ages 4 and 15 years (Bannister 1962). After 15 years the mean number of internodes in the annual shoot remained fairly constant (Bannister 1962).

The effects of site factors on internode length in New Zealand are not well understood. There is some evidence that internodes are longer at more southerly latitudes, and shorter where site fertility is limiting (Carson & Inglis 1988).

Information on the influence of management practices on internode length is scarce. An analysis of a thinning experiment (Siemon *et al.* 1976) indicated that stand density had a negligible effect on stem mean internode length (averaged over the whole stem, rather than stem sections formed at a given stocking after thinning). The thinning experiment was planted at a nominal stocking of 1700 stems/ha, first thinned at age 15 years (stand mean height approx. 21 m), and then received different thinning treatments to give stockings of between 163 and 1312 stems/ha at age 23 years (stand mean height approx 28 m).

Data on internode index

$$\frac{\sum \text{length (m) of internodes} \geq 0.6 \text{ m}}{\text{log length}}$$

for second logs (approx. 5.7–11.2 m) were collected by D. McFarlane from sites (in Kaingaroa Forest) at various stockings (89–583 stems/ha) and site indices (27, 29, 35 m). An analysis of these data indicated that, for a given site index, internode index increased with stocking. However, the correlation coefficient was significant at the 5% level at only one site index. In data collected for the current study, stocking did not significantly affect internode length at three out of four forest sites (*see* Appendix 1).

To date there has been no model available for predicting internode length or internode index. STANDPAK, a stand evaluation package developed by the Forest Research Institute, requires the user to enter the internode index for fixed log lengths. STANDPAK generates medium to long-term yield predictions for *P. radiata* by simulating growth, harvesting, and processing on a stand basis. A table of internode index values for unimproved *P. radiata,* derived from measurements by C. Inglis (Forest Research Institute 1988), is available on a regional basis. Values for improved *P. radiata* have been estimated recently (Carson 1988; Carson & Inglis 1988; N.G.Woods & Carson unpubl. data).

The objective of this study was to develop a model, using currently available data, for predicting stand mean internode length in variable log lengths from stands of both unimproved and improved *P. radiata.* The limited time-frame of the study precluded the collection of additional data, such as soil factors, which may affect internode length.

## METHODS

In the absence of a well-designed experiment to determine the influence of silviculture on internode length, it has been assumed that stocking and silviculture do not have an effect (*see* Introduction and Appendix 1). It was also assumed that the time of measurement was sufficiently late in the rotation for any changes in internode length due to branch growth to have ceased.

### Data Available

Data on internode length were collected during a previous study of branching in *P. radiata* (Inglis & Cleland 1982; Inglis in prep.). In 27 forests throughout the country several variables were measured on a sample of crop trees (usually 24) within a plot. The trees were free of leader malformation, and generally at least 17 years old. Some improved trees were younger than this.

The variables pertinent to this study were:

- height to bottom of whorl
- height to top of whorl

which were measured on each tree for each whorl below 16.7 m.

These data were converted to:

- height to base of internode = height to top of previous whorl
- internode length.

Climatic data from meteorological stations at or near the sampled forest sites were obtained from "Summaries of Climatological Observations to 1980" (New Zealand Meteorological Service 1983). Only commonly measured climatic variables were considered. No attempt was made to adjust for differences in climate between the plots and the meteorological stations at which the climatic variables were measured.

## Alternative Modelling Approaches

Three different approaches were considered.

(1) An approach suggested by H.A.I.Madgwick (pers. comm.) was to develop a model which would predict the lengths of internodes as a function of the number of internodes within the annual shoot and annual height growth. In order to utilise this approach it was necessary to identify the annual shoots for each tree within the dataset.

An attempt was made to identify annual shoots for trees within a plot in Ashley Forest using the fact that the largest reduction in internode length within the annual shoot appears to be between the second-to-last and last internodes (Bannister 1962, Fig. 12). This approach was abandoned because there was no way of checking for errors introduced in ageing the shoots.

(2) A proposed model which directly predicted length of internodes greater than or equal to 0.6 m was not developed because of difficulties in deriving a logically sound variable similar to internode index which would be applicable to variable log lengths.

(3) The approach finally taken was to investigate how internode length varied with height from the ground, without taking any account of the position of the internode within the annual cycle.

## DATA ANALYSIS

The first step was to develop a model to predict internode length for unimproved *P. radiata*. Using the criteria set out below, 16 plots of unimproved *P. radiata* at different locations were selected from a dataset that had been collected by C. Inglis and others.

- Internode lengths of trees in the plot measured from close to ground level to a height of 17 m
- Plots covering the site range for *P. radiata* in New Zealand and not biased towards a particular region
- Reasonable proximity to a meterological station—within 0.1° of latitude.

The first criterion was relaxed in order to include plots in particularly important forest areas. Location of and data for the 16 plots are given in Fig. 2 and Table 1 respectively. Nine of the 11 forest areas not selected were from the South Island. Inclusion of those data would have biased the model.

When individual tree values of internode length were plotted against height from the ground, any pattern in the data was difficult to discern (Fig. 3).

Stand mean internode length was calculated for each 1-m height zone as follows:

$$\frac{\Sigma \text{ length (m) of internodes starting within that 1-m zone}}{\text{number of internodes starting within that 1-m zone.}}$$

When these stand mean internode lengths were plotted against height, a pattern became apparent (Fig. 4—note that the y axis is at a different scale from that in Fig. 3). An appropriate function describing this pattern was:

$$y = x / (a + b\,x + c\,x^2) \qquad (1)$$

where: y is the mean internode length at height x
a,b,c are regression coefficients

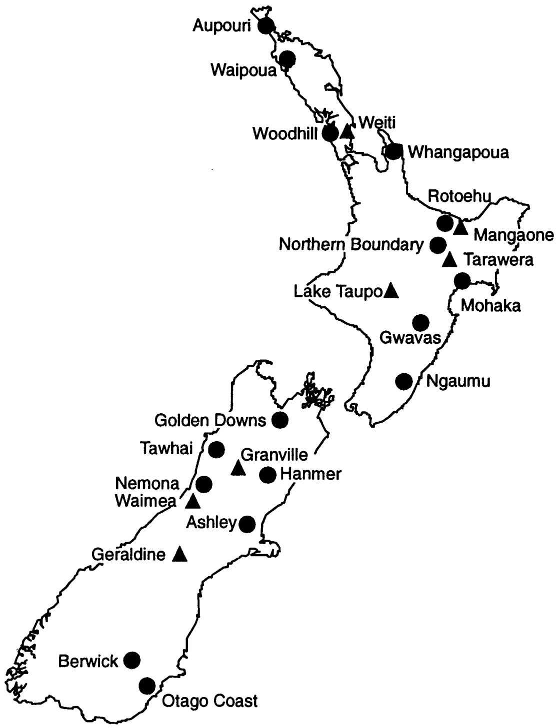


FIG. 2–Location of forest sites. Areas labelled ▲ used for validation.

TABLE 1–Location and meteorological data for forest sites

| Site | Latitude (°) | Altitude of met. station (m) | Annual rainfall (mm) | Mean annual temp. (°C) | Average daily max. for hottest month (°C) | Average daily min. for coldest month (°C) | Average days ground frost | Average days air frost | Site index (m) |
|---|---|---|---|---|---|---|---|---|---|
| Ashley | 43.2 | 107 | 825 | 11.4 | 21.2 | 2.2 | 48.9 | 16.9 | 25.0 |
| Aupouri | 35.0 | 69 | 1187 | 16.0 | 23.7 | 9.4 | 1.2 | 0.0 | 19.0 |
| Berwick | 46.0 | 18 | 734 | 10.3 | 20.6 | 0.3 | 84.9 | 52.5 | 22.0 |
| Golden Downs | 41.5 | 274 | 1307 | 10.5 | 21.9 | –1.1 | 117.6 | 73.6 | 27.0 |
| Gwavas | 39.5 | 335 | 1257 | 11.2 | 22.6 | 1.1 | 75.6 | 46.1 | 31.0 |
| Hanmer | 42.5 | 387 | 1163 | 10.2 | 22.3 | –1.3 | 139.5 | 81.7 | 21.0 |
| Mohaka | 39.0 | 286 | 1659 | 12.8 | 22.8 | 3.4 | 55.4 | 11.3 | 29.5 |
| Nemona | 42.6 | 4 | 2451 | 12.3 | 19.7 | 4.4 | 26.0 | 1.9 | 27.0 |
| Ngaumu | 41.0 | 244 | 1173 | 11.4 | 22.6 | 1.8 | 102.0 | 48.0 | 27.0 |
| Otago Coast | 46.1 | 18 | 739 | 10.1 | 20.4 | 0.1 | 93.2 | 53.0 | 24.0 |
| Northern Boundary | 38.0 | 544 | 1483 | 10.7 | 21.6 | 0.9 | 99.5 | 50.3 | 33.0 |
| Rotoehu | 38.0 | 72 | 1641 | 13.0 | 23.5 | 2.3 | 44.0 | 28.9 | 35.0 |
| Tawhai | 42.2 | 198 | 1963 | 11.1 | 22.8 | 0.1 | 68.2 | 52.0 | 20.0 |
| Waipoua | 35.7 | 88 | 1651 | 14.1 | 23.3 | 5.7 | 10.3 | 3.1 | 22.0 |
| Whangapoua | 36.5 | 4 | 1875 | 14.6 | 24.3 | 5.5 | 21.9 | 11.4 | 32.0 |
| Woodhill | 36.5 | 30 | 1328 | 14.6 | 23.2 | 6.6 | 12.7 | 4.6 | 24.0 |

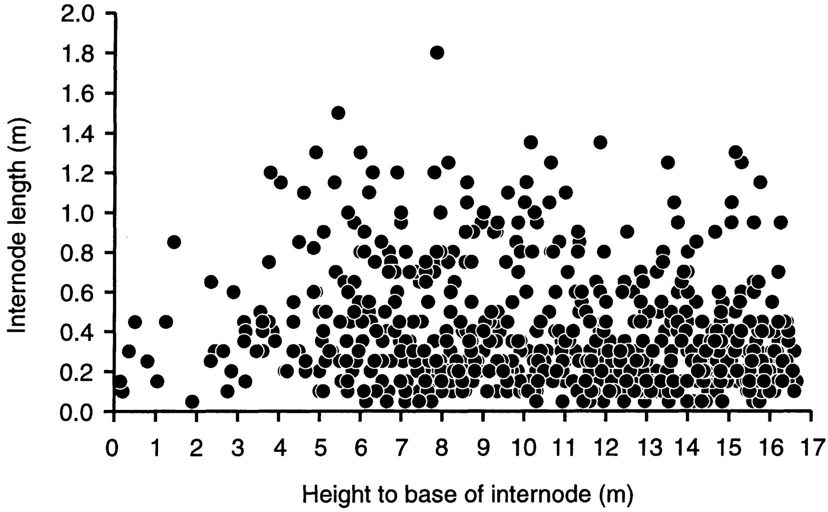


FIG. 3–Individual within-tree internode length against height to base of internode, at Ashley Forest.

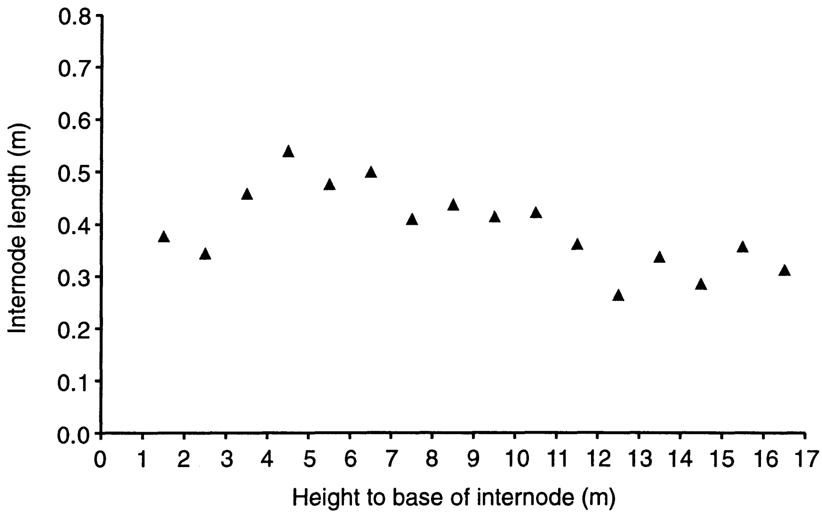


FIG. 4–Stand mean internode length in 1-m height zones against height to base of internode, at Ashley Forest.

This curve was fitted to the values of stand mean internode length for each plot and the values of a, b, and c were examined. In all but three of the datasets, b was not significantly different from zero (at the 5% level). It was therefore decided to fit the function:

$$y = x / (d + e x^2) \qquad (2)$$

where: y is the mean internode length at height x

d and e are regression coefficients

The advantage of this function is that the maximum internode length (IMX) and the location (height on the stem) of the maximum internode length for a site (LOC) (*see* Fig. 5) can be described in terms of d and e, and vice versa.

$$LOC = \sqrt{(d/e)} \quad (3)$$

$$IMX = LOC / (2.0\ d) \quad (4)$$

The predicted values of d, e, LOC, and IMX are shown in Table 2a.

In order to predict how mean internode length varies with forest site (as well as height), it was necessary to see if the values of d and e from Equation 2 were in any way related to site variables. As IMX and LOC can be derived from d and e, and are more meaningful variables, the correlation coefficients between LOC and IMX and the site variables (Table 1) were calculated (Table 2b) and graphs were plotted for pairs of variables with high correlation coefficients.

LOC and IMX were obviously associated with some site variables although one site, Hanmer, appeared to behave as an outlier. Examination of the data for this plot showed that some unusually long internodes of over 0.5 m and up to 3 m had been recorded at stem heights of less than 5 m. Some trees had received three prunings and it is suspected that pruned whorls were not visible at the time of measurement. For this reason, data from Hanmer were excluded from subsequent analyses.

Regression equations were developed to predict IMX and LOC from the site variables shown in Table 1. Initially the site variable most highly correlated with IMX and LOC was used as the independent variable. Other variables which were not highly correlated with the original independent variable were then added to see if more of the variability could be accounted for.

The most appropriate regression equations were considered to be:

$$LOC = f + g\ ALT \quad (5)$$

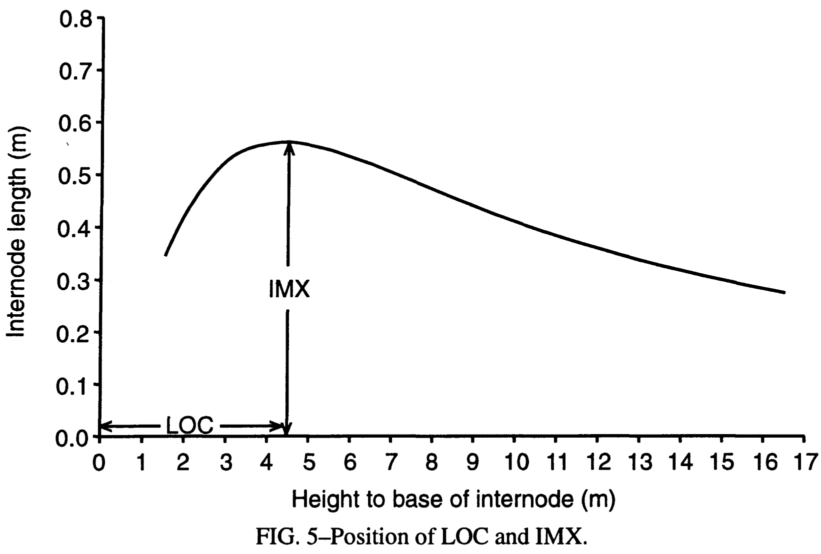


FIG. 5–Position of LOC and IMX.

TABLE 2a–Estimated values of d, e, IMX, and LOC for plots with unimproved *Pinus radiata*

| Site | d | e | IMX | LOC |
|---|---|---|---|---|
| Ashley | 4.54 | 0.208 | 0.515 | 4.67 |
| Aupouri | 3.57 | 0.295 | 0.487 | 3.48 |
| Berwick | 3.60 | 0.172 | 0.635 | 4.57 |
| Golden Downs | 7.78 | 0.138 | 0.483 | 7.51 |
| Gwavas | 6.81 | 0.180 | 0.452 | 6.15 |
| Hanmer | 0.32 | 0.345 | 1.505 | 0.96 |
| Mohaka | 3.32 | 0.199 | 0.615 | 4.08 |
| Nemona | 2.60 | 0.175 | 0.741 | 3.85 |
| Ngaumu | 5.11 | 0.189 | 0.509 | 5.20 |
| Otago Coast | 2.43 | 0.227 | 0.673 | 3.27 |
| Northern Boundary | 7.91 | 0.114 | 0.527 | 8.33 |
| Rotoehu | 3.62 | 0.184 | 0.613 | 4.44 |
| Tawhai | 2.41 | 0.144 | 0.849 | 4.09 |
| Waipoua | 3.18 | 0.304 | 0.509 | 3.23 |
| Whangapoua | 3.48 | 0.247 | 0.539 | 3.75 |
| Woodhill | 5.37 | 0.221 | 0.459 | 4.93 |

TABLE 2b–Correlation coefficients between LOC, IMX, and site variables (15 sites)

| | IMX | LOC |
|---|---|---|
| Site index (m) | –0.20 | 0.45 |
| Annual rainfall (mm) | 0.41 | –0.13 |
| Mean annual temperature (°C) | –0.31 | –0.47 |
| Average daily max. temp. in hottest month (°C) | –0.37 | –0.13 |
| Average daily min. temp. in coldest month (°C) | –0.30 | –0.50 |
| Average days ground frost | 0.08 | 0.64 |
| Average days air frost | 0.12 | 0.59 |
| Altitude (m) | –0.22 | 0.80 |
| Latitude (degrees) | 0.51 | –0.006 |

which explained 60.8% of the variance, and

$$IMX = -p + q\,LAT + r\,RAIN \qquad (6)$$

which explained 61.9% of the variance

where: f, g, p, q, r are regression coefficients
ALT is the altitude in metres
LAT is the latitude in degrees
RAIN is the mean annual rainfall in millimetres.

Correlation coefficients between the residuals and the other variables listed in Table 1 were all less than 0.4. The addition of site index as an independent variable did not significantly improve the fit for either LOC or IMX. A major advantage of the above equations is that one does not need to know how trees grow on a specified site before internode length can be estimated. It is also an advantage when modifying the model for improved breeds since site index tends to increase with level of improvement (S.Carson & O.García pers. comm.).

Another advantage of these equations is that altitude and latitude are easily measured from maps, and rainfall values can be obtained from the New Zealand Meteorological Service (1983).

The parameters d and e were described in terms of site variables using Equations 7–10 (Equations 7 and 8 are of the same form as Equations 5 and 6 respectively).

$$LOC = A + B\ ALT \quad (7)$$

$$IMX = C + D\ LAT + E\ RAIN \quad (8)$$

$$d = LOC / (2\ IMX) \quad (9)$$

$$e = d / (LOC^2) \quad (10)$$

where A, B, C, D, E are coefficients to be estimated by regression.

These formulae for d and e were substituted into Equation 2 and the coefficients (A, B, C, D, E) were estimated using a non-linear regression routine.

When actual and predicted values of stand mean internode length were compared, it was found that the model tended to under-estimate stand mean internode length at heights between 0 and 1 m. It was thought that some early whorls may not have been visible at time of measurement owing to damage or to suppression by weeds. In order to improve the relationship for more important zones higher in the tree it was decided to ignore the data between heights of 0 and 1 m. The value of $r^2$ from fitting the revised data set was 0.61. There were no obvious patterns when the residuals (errors in predicting stand mean internode length) were plotted against predicted stand mean internode length, altitude, latitude and rainfall, indicating that the model cannot be rejected as being unsuitable for predicting stand mean internode length.

For each site, the predicted and actual internode lengths were plotted against height in the tree. Agreement between actual and predicted values was considered to be reasonable (Fig. 6). The model was used to predict stand mean internode length for log lengths and the actual and predicted values are shown in Table 3a. The error in predicting stand mean internode length for a log was ≤0.05 m for 29 out of the 41 logs. For the other 12 logs the error was ≤0.11 m.

The model was used to predict stand mean internode length for logs at four other sites not included in the original dataset (Table 3b). The estimates of mean internode length were within 0.12 m of the true value for three of the four sites. One reason for the poor prediction of mean internode length for logs at Waimea may be that the mean annual rainfall there is higher than for any of the sites used in developing the model.

## Improved *Pinus radiata*

The effect of genetic improvement on internode length of *P. radiata* was considered using data from progeny trials established in 1969 and 1971 at sites in Woodhill Forest, Northern Boundary of Kaingaroa Forest, Golden Downs Forest, and Otago Coast Forest (Carson & Inglis 1988; Woods & Carson unpubl. data).

At each site, up to three different groups of progenies were sampled:

- an "850" series clonal seed orchard seedlot
- open-pollinated progeny of 23 plus-trees of the "268" clonal series
- open-pollinated progeny of eight long-internode trees.

TABLE 3a–Comparison of actual and estimated mean internode length (m) for logs (for datasets used to develop the model)

| Site | First log | | Second log | | Third log | |
|---|---|---|---|---|---|---|
| | Actual | Estimate | Actual | Estimate | Actual | Estimate |
| Ashley | 0.47 | 0.49 | 0.44 | 0.46 | 0.31 | 0.32 |
| Aupouri ◊ | 0.42 | 0.36 | 0.34 | 0.33 | | |
| Berwick ⊕ | 0.61 | 0.59 | 0.50 | 0.48 | 0.41 | 0.33 |
| Golden Downs | – | – | 0.48 | 0.52 | 0.41 | 0.38 |
| Gwavas ⊗ | 0.52 | 0.53 | 0.46 | 0.48 | 0.31 | 0.36 |
| Mohaka | 0.57 | 0.49 | 0.48 | 0.51 | 0.35 | 0.38 |
| Nemona | 0.63 | 0.70 | 0.53 | 0.60 | 0.40 | 0.41 |
| Ngaumu | – | – | 0.44 | 0.48 | 0.34 | 0.35 |
| Otago Coast | 0.58 | 0.56 | 0.43 | 0.48 | 0.35 | 0.33 |
| Northern Boundary ♦ | – | – | 0.53 | 0.50 | 0.46 | 0.40 |
| Rotoehu ⊕ | 0.59 | 0.53 | 0.47 | 0.44 | 0.39 | 0.31 |
| Tawhai | 0.72 | 0.61 | 0.66 | 0.60 | 0.51 | 0.43 |
| Waipoua | 0.42 | 0.44 | 0.33 | 0.40 | 0.29 | 0.28 |
| Whangapoua | 0.48 | 0.49 | 0.40 | 0.42 | 0.30 | 0.29 |
| Woodhill ⊕ | 0.46 | 0.45 | 0.37 | 0.37 | 0.30 | 0.25 |

Notes: First log is mean of internodes starting between 1 and 5.7 m (2 and 5.7 m for sites marked ⊕, 4 and 5.7 m for site marked ⊗)

Second log is mean of internodes starting between 5.7 and 11.2 m (5.7 and 11 m for site marked ◊).

Third log is mean of internodes starting between 11.2 and 16.7 m (11.2 and 16.0 m for site marked ♦)

TABLE 3b–Comparison of actual and estimated mean internode length (m) for logs in validation plots

| Site | First log | | Second log | | Third log | |
|---|---|---|---|---|---|---|
| | Actual | Estimate | Actual | Estimate | Actual | Estimate |
| Geraldine | 0.61 | 0.53 | 0.57 | 0.50 | 0.40 | 0.35 |
| Granville | 0.50 | 0.62 | 0.57 | 0.56 | 0.46 | 0.39 |
| Tarawera | 0.59 | 0.54 | 0.47 | 0.49 | 0.37 | 0.34 |
| Waimea | 0.53 | 0.75 | 0.43 | 0.66 | 0.35 | 0.45 |

Notes: First log is mean of internodes starting between 1 and 5.7 m.

Second log is mean of internodes starting between 5.7 and 11.2 m.

Third log is mean of internodes starting between 11.2 and 16.7 m

The "268" series group was subdivided into three groups:

- a highly multinodal group of eight progenies
- a group of seven progenies selected with emphasis on improved growth rate and stem form
- a group of eight progenies selected with emphasis on longer internodes.

For these datasets, d, e, LOC, and IMX were directly estimated using Equations 2–4. These values of LOC and IMX for improved *P. radiata* were then compared with the predicted values of LOC and IMX for unimproved *P. radiata* at the same site using Equations 7 and 8 respectively. The ratios LOC(improved) : LOC(unimproved-predicted) and IMX(improved) : IMX(unimproved-predicted) were calculated (Tables 4a and b). While it was expected that the ratio of IMX(improved) to IMX(unimproved-predicted) would vary with level of genetic improvement, it also appeared that the ratio varies with site (Table 4a).

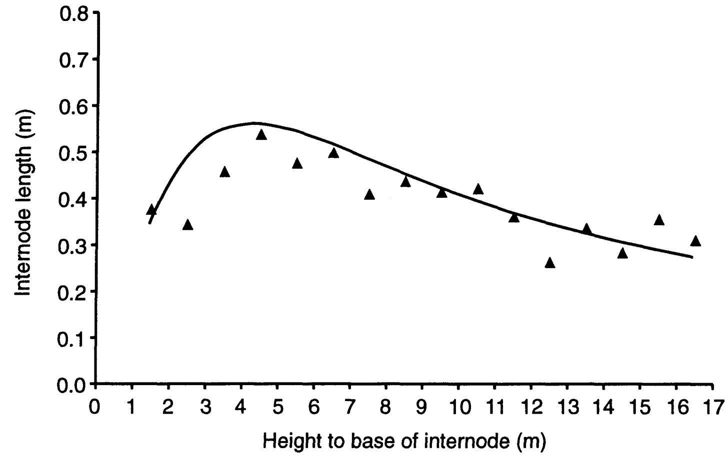


FIG. 6–Relationship between stand mean internode length and height to base of internode at Ashley Forest; ▲ denotes values of actual observations, curve represents predicted relationship.

TABLE 4a–Ratio of IMX(improved) to IMX(unimproved-predicted)

| | Forest | | | | Mean |
|---|---|---|---|---|---|
| | Northern Boundary | Golden Downs | Otago Coast | Woodhill | |
| "268" series | | | | | |
| Short internodes | 1.03 | 0.88 | 0.82 | 0.80 | 0.88 |
| Medium internodes | 1.24 | 1.05 | 0.93 | 0.95 | 1.04 |
| Long internodes | 1.42 | 1.14 | 0.95 | 0.97 | 1.12 |
| "850" series | – | 0.95 | 0.94 | 0.91 | 0.93 |
| Long internode | – | 1.30 | 1.22 | 1.07 | 1.20 |

TABLE 4b–Ratio of LOC(improved) to LOC(unimproved-predicted)

| | Forest | | | | Mean |
|---|---|---|---|---|---|
| | Northern Boundary | Golden Downs | Otago Coast | Woodhill | |
| "268" series | | | | | |
| Short internodes | 0.82 | 0.62 | 1.04 | 0.89 | |
| Medium internodes | 0.80 | 0.67 | 1.06 | 0.83 | |
| Long internodes | 0.74 | 0.60 | 1.09 | 0.82 | |
| "850" series | - | 0.65 | 1.14 | 0.88 | |
| Long internode | - | 0.67 | 1.17 | 0.73 | |
| Mean | 0.78 | 0.64 | 1.10 | 0.83 | 0.84 |

For the three "268" series groups, the ratio was correlated with altitude. However, given that sampling was from only four sites, any model developed to predict how the ratio varies with site may not be applicable throughout the country. It was therefore decided to assume that the ratio did not vary with site, i.e. to use mean ratio (Table 4a) for each level of improvement and investigate how that assumption would affect the prediction of internode length.

From Table 4b, it appears that the ratio of LOC(improved) to LOC(unimproved-predicted) did not vary much with level of genetic improvement. The ratio did vary with site. The low ratios for both Golden Downs and Northern Boundary Forests could be due to the fact that there were no data for unimproved stands below 5 m and 4 m respectively. The mean internode length for the lowest zone in both those forests was derived from one or two observations and appeared to be unusually low. This may have affected the prediction of LOC for the unimproved stands, and hence the ratio. There is no obvious reason why the position of the maximum internode length should vary with level of improvement. Given that there were data from only four sites, two assumptions were considered:

(a) LOC does not vary with improvement, i.e., ratio = 1.0. This implies that the maximum internode length occurs at the same height in the tree, regardless of level of improvement.

(b) A ratio of 0.84 (the overall mean, *see* Table 4b) applies. This implies that the maximum internode length occurs at a lower height in the tree in improved *P. radiata* than in unimproved *P. radiata*.

The predicted estimates of IMX and LOC for a given site were multiplied by the appropriate ratios for a given level of genetic improvement, and stand mean internode length at these sites was estimated for two stem sections (Table 5). With a ratio of 1.0, the error in predicting mean internode length for a log was ≤0.05 m in 16 out of 36 estimates and ≤0.1 m

TABLE 5–Actual and estimated mean internode length (m) for improved *P. radiata*

| Site | First log Internode starting between 1.0 and 5.7m | | | Second log Internode starting between 5.7 and 11.2m | | |
|---|---|---|---|---|---|---|
| | Actual | Ratio = 1.0 | Ratio = 0.84 | Actual | Ratio = 1.0 | Ratio = 0.84 |
| "268" series—short internodes | | | | | | |
| Northern Boundary | 0.45 | 0.38 | 0.40 | 0.46 | 0.47 | 0.46 |
| Golden Downs | 0.46 | 0.47 | 0.48 | 0.40 | 0.49 | 0.47 |
| Otago Coast | 0.43 | 0.52 | 0.53 | 0.47 | 0.45 | 0.43 |
| Woodhill | 0.33 | 0.39 | 0.40 | 0.29 | 0.34 | 0.33 |
| "268" series—medium internodes | | | | | | |
| Northern Boundary | 0.53 | 0.42 | 0.43 | 0.57 | 0.51 | 0.50 |
| Golden Downs | 0.54 | 0.51 | 0.52 | 0.45 | 0.53 | 0.51 |
| Otago Coast | 0.49 | 0.57 | 0.57 | 0.48 | 0.49 | 0.47 |
| Woodhill | 0.39 | 0.43 | 0.43 | 0.30 | 0.37 | 0.35 |
| "268" series—long internodes | | | | | | |
| Northern Boundary | 0.62 | 0.43 | 0.45 | 0.59 | 0.53 | 0.51 |
| Golden Downs | 0.60 | 0.53 | 0.54 | 0.44 | 0.55 | 0.53 |
| Otago Coast | 0.49 | 0.59 | 0.59 | 0.48 | 0.51 | 0.48 |
| Woodhill | 0.40 | 0.44 | 0.45 | 0.30 | 0.39 | 0.37 |
| "850" series | | | | | | |
| Golden Downs | 0.49 | 0.48 | 0.49 | 0.41 | 0.50 | 0.48 |
| Otago Coast | 0.49 | 0.54 | 0.54 | 0.49 | 0.46 | 0.44 |
| Woodhill | 0.37 | 0.40 | 0.41 | 0.30 | 0.35 | 0.33 |
| Long internode | | | | | | |
| Golden Downs | 0.68 | 0.54 | 0.56 | 0.52 | 0.57 | 0.55 |
| Otago Coast | 0.62 | 0.61 | 0.62 | 0.67 | 0.53 | 0.50 |
| Woodhill | 0.44 | 0.46 | 0.46 | 0.32 | 0.40 | 0.38 |

in 31 out of the 36. With a ratio of 0.84, the error in predicting stand mean internode length for a log was ≤0.05 m in 19 out of 36 estimates and ≤0.1 m in 33 out of the 36. For both ratios, no error was greater than 0.2 m.

The model was used to predict stand mean internode length for logs from stands at three sites, not included in the dataset, planted with improved *P. radiata* seed (Table 6). Improved seedlots are rated with a "Growth and Form" (GF) number to indicate their relative performance (Vincent 1987). The seedlots (Table 6) each contain progeny of a mix of several parent genotypes, which, on average, perform at the GF rating shown. Since the GF14 seedlot was of "850" series origin and the GF16 seedlot was of "268" series origin, it was considered appropriate to use the relevant internode ratios. Mangaone and Weiti were ex-farm sites rather than forest sites. The "actual mean internode lengths" (Woods & Carson unpubl. data) were mean internode length for fixed log lengths while estimated values are for all internodes starting within that length. The slight differences in definition should, however, make little difference. The error in estimating stand mean internode length was ≤0.06 m for the first log. The errors were much larger for all second logs. The larger error may be due to the fact that the stands were measured when young and the branches may not have stopped growing.

TABLE 6–Actual and estimated mean internode length (m) for improved *P. radiata* (validation plots)

| Site | First log (0.2–5.7 m) | | Second log (5.7–11.2 m) | |
|---|---|---|---|---|
| | Actual | Estimated | Actual | Estimated |
| Mangaone | | | | |
| GF14 | 0.42 | 0.45 | 0.61 | 0.43 |
| Taupo | | | | |
| GF14 | 0.32 | 0.36 | 0.62 | 0.47 |
| GF16 | 0.32 | 0.38 | 0.59 | 0.49 |
| Weiti | | | | |
| GF14 | 0.38 | 0.38 | 0.42 | 0.36 |

Given that similar predictions of stand mean internode length for logs were obtained using ratios of 1.0 and 0.84, and that there is no obvious reason for the position of the maximum internode length to vary with level of genetic improvement, it is suggested a ratio of 1.0 should be used.

## DISCUSSION

The model described here predicts stand mean internode length for variable log lengths from forest sites within New Zealand. It will not predict variation within a forest unless meteorological data are available for different locations within the forest. Comparison of actual and predicted values for internode length in test and validation plots suggests that the model gives reasonable predictions of stand mean internode length for both unimproved and improved *P. radiata*.

The model is empirical, i.e., there is no known underlying biological reason why rainfall, altitude, and latitude should affect internode length. However, the variables are not unrealistic since internode length has been observed to be reduced during a period of drought (Fielding 1960) and increases with latitude in New Zealand. Site index decreases with increasing altitude on central North Island pumice soils (Mountfort 1979). Even so, the model should be used with caution at sites where values for mean annual rainfall, altitude, and latitude fall outside the range used in developing the model (*see* Table 1).

It is also important to know the sensitivity of the model to small changes in the independent variables. For a given site, there will probably be little error in measuring altitude and latitude as these variables can be obtained from maps. Within the range of altitude and latitude for the sites used to develop the model, a 10% change in rainfall produced a corresponding change in stand mean internode length of less than 6%. This means small errors in estimating mean annual rainfall will not produce absurd estimates of internode length.

In this study it has been assumed that internode length does not vary with age of measurement. However, when internode length was measured before branches ceased growing in some of the improved *P. radiata* plots, errors in predicting stand mean internode length were larger. Experimental work is therefore needed to check whether internode length varies as branches grow.

Further improvements to the model may be achievable by considering the influence of soil properties on internode length as there is some evidence that soil fertility may affect internode length (Carson & Inglis 1988). This would be best investigated by measuring internode length on pairs of sites with similar climate and location but different soil types.

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## REFERENCES

BANNISTER, M.H. 1962: Some variations in the growth pattern of *Pinus radiata* in New Zealand. *New Zealand Journal of Science 5*: 342–70.

CARSON, M.J. 1987: Improving log and wood quality: The role of the radiata pine improvement programme. *New Zealand Forestry 32(2)*: 26–30.

——1988: Long-internode or multinodal radiata pine—A financial analysis. *New Zealand Ministry of Forestry, FRI Bulletin No. 115.*

CARSON, M.J.; INGLIS, C.S. 1988: Genotype and location effects on internode length of *Pinus radiata* in New Zealand. *New Zealand Journal of Forestry Science 18*: 267–79.

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

FOREST RESEARCH INSTITUTE 1988: "User Guide for STANDPAK". Ministry of Forestry, Forest Research Institute, Rotorua.

INGLIS, C.S.: Predicting branch index in managed *Pinus radiata* stands—A revised model (in prep.)

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

LAVERY, P.B. 1986: Plantation forestry with *Pinus radiata. University of Canterbury, School of Forestry, Review Papers, Paper No. 12.*

MOUNTFORT, C.J. 1979: *Pinus radiata* site index/altitudinal relationships for forests established on pumice soils. Pp. 217–26 *in* Elliot, D.A. (Ed.) "Mensuration for Management Planning of Exotic Forest Plantations". *New Zealand Forest Service, Forest Research Institute Symposium No. 20.*

NEW ZEALAND METEOROLOGICAL SERVICE 1983: Summaries of Climatological Observations to 1980. *New Zealand Meteorological Service Miscellaneous Publication No. 177.*

SIEMON, G.R.; WOOD, G.B.; FORREST, W.G. 1976: Effects of thinning on crown structure in radiata pine. *New Zealand Journal of Forestry Science 6*: 57–66.

VINCENT, T.G. 1987: Certification system for forest tree seed and planting stock. *New Zealand Ministry of Forestry, Forest Research Institute, FRI Bulletin No.134.*

# APPENDIX 1

## DOES STOCKING AFFECT INTERNODE LENGTH?

In order to investigate whether stocking affected internode length, plots at the same site location, but with different stockings, were selected from the dataset collected by C. Inglis. Another criterion was a reasonable length of stem for which the internodes had been formed while the trees were at different stockings. Equivalent sections had to be used since internode length varies with height.

The plots which were considered suitable for testing are described below.

### *Berwick Forest*

Two plots were thinned to their final stockings of 250 and 370 stems/ha at a predominant mean height of 10.5 m. For each plot, the mean internode length for all internodes starting above 10.5 m was calculated (*see* Table A1). The means were not significantly different from zero.

### *Gwavas Forest*

Two plots were thinned to their final stockings of 200 and 400 stems/ha at predominant mean heights of 11.9 and 12.5 m respectively. For each plot, the mean internode length for all internodes above 12.5 m was calculated (*see* Table A1). The means were not significantly different.

### *Tawhai Forest*

Three plots were planted at two different initial stockings (1760 and 3086 stems/ha). These three plots received their first thinning at or above predominant mean height 13.5 m. For each plot, the mean internode length for all internodes starting below 13 m was calculated (*see* Table A1). There was a significant difference with stocking. As thinning is carried out at a given predominant mean height, some of the internodes included may have been formed after the thinning, particularly on smaller trees.

### *Tarawera Forest*

Nine plots were planted at various initial stockings. All plots received their first thinning above predominant mean height 11.8 m. For each plot, the mean internode length was calculated for all internodes starting below 11 m (*see* Table A1). Mean internode length was plotted against initial stockings for these plots. There was no obvious pattern. The correlation coefficient between stocking and mean internode length was not significant.

TABLE A1–Stocking and mean internode length

| Site | Stems/ha | Mean internode length (m) | Standard deviation | Number of observations |
|---|---|---|---|---|
| Berwick | 250 | 0.367 | 0.263 | 243 |
| | 370 | 0.376 | 0.246 | 253 |
| Gwavas | 200 | 0.314 | 0.199 | 205 |
| | 400 | 0.338 | 0.214 | 187 |
| Tawhai | 3086 | 0.559 | 0.363 | 249 |
| | 1760 | 0.652 | 0.403 | 793 |
| | 3086 | 0.558 | 0.419 | 391 |
| Tarawera | 2100 | 0.519 | 0.365 | 306 |
| | 2267 | 0.582 | 0.381 | 325 |
| | 2267 | 0.567 | 0.405 | 307 |
| | 2267 | 0.547 | 0.317 | 307 |
| | 2389 | 0.455 | 0.269 | 341 |
| | 1367 | 0.521 | 0.387 | 291 |
| | 2455 | 0.561 | 0.389 | 295 |
| | 4662 | 0.585 | 0.367 | 301 |
| | 2273 | 0.514 | 0.286 | 311 |