Assessing interactions between initial stand stocking and genotype on growth and form of 17 year old *Pinus radiata* in Canterbury

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Abstract

Influences of initial stand spacing and genotype on physical properties of 17-year-old *Pinus radiata* growing in a Nelder stocking design experiment in Canterbury were examined. Physical characteristics, including diameter at breast height, tree height, green crown height and stem slenderness were investigated for 385 trees, whilst internode length and branch index were examined for 65 trees. No significant interactions between breed and stocking were found, indicating that relatively simple adjustments to existing silvicultural models could represent impacts of stocking on a variety of tree breeds.

Diameter at breast height decreased from 41.1 cm to 17.7 cm as stand stocking increased from 209 stems ha^{-1} to 2551 stems ha^{-1}. Green crown height increased from 1.8 m to 10.2 m with increasing stand stocking, whilst stem slenderness also increased with increasing stand stocking. Tree height was not significantly influenced by genotype. As expected the 870 long internode breed had significantly longer internode lengths than other breeds, demonstrating its defining physical characteristic.

Branch index (BIX) was significantly and positively correlated with tree diameter (r^2= 0.80), with BIX ranging from 35 mm at 364 stems ha^{-1} to 13 mm at 2551 stems ha^{-1}. After correction had been made for tree diameter, BIX exhibited a significant positive relationship with mean internode length which when included in the analysis increased the r^2 from 0.80 to 0.90. Tree diameter and mean internode length accounted for the effects of stocking and genotype on BIX.

The results provide considerable insight into how stocking and genotype regulate stem geometry and as such provide managers with a demonstration of the effect of a wide range of operationally used stockings on these important external tree characteristics.

Introduction

Do tree breeds and genotypic series behave differently with respect to stand stocking? This question is important, because managers wish to model growth, stem geometry and branch diameter of differing genotypes of trees. If tree genotype has the same overall effect on, say, diameter at breast height (dbh) growth at a range of stockings, then relatively simple adjustments to models can be made to represent the behaviours of different genotypes. If, on the other hand, genotypes respond quite differently to varying stocking (i.e.: there is an interaction between genotype and stocking), then different breeds and series may require substantially different models. The study described here addressed this question with respect to stem geometry and branch diameter.

During the establishment of a forest plantation, two of the most important decisions are the selection of appropriate genetic material and a suitable initial stand stocking. Whilst considerable research has focussed on how genetic material and initial stand stocking impact on the external characteristics of growth and form (Fries 1984, Carson *et al.* 1999, Land *et al.* 2003), no reported studies have examined the interaction of these factors on *Pinus radiata.*

Tree morphology is markedly affected by intra-specific competition (Smith *et al.* 1996). Intra-specific competition is a function of initial stand stocking and the growth rate of trees and subsequently influences diameter, green crown height, taper or stem slenderness, and branch size.

While tree diameter has been found to exhibit a strong negative relationship with stand stocking (Cromer and Pawsey 1957, Sjolte-Jorgensen 1967), tree height appears to be relatively unaffected by stand stocking, except in extreme situations (Siemon *et al.* 1976, Hocker 1979, Cremer *et al.* 1982). However, in a review of experiments by Sjolte-Jorgensen (1967), it was found that in most cases for conifers, the mean top height of the stand positively increases with stocking. This observation has also been noted by Mason (1992), Maclaren *et al.* (1995) and Carson *et al.* (1999). As with diameter, green crown height and stem slenderness are significantly correlated with stocking.

Branch size as measured by branch index (BIX)[3] has been found to decline with increasing stocking (Tombleson *et al.* 1991, Ballard and Long 1988, Cromer and Pawsey 1957). Research also suggests that mean internode length may influence BIX. In a study which included trees of the 850[4] and 870 series of the growth and form and long internode breeds grown at a stocking of 400 - 450 stems ha^{-1}, Watt *et al.* (2000) found that after correction was made for tree diameter, internode length exhibited a significant positive relationship with BIX. Although tree diameter and mean internode length accounted for a large proportion of the differences in BIX between the 850 and 870 series, there was still significant differences in BIX between breeds after

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[3] *BIX is the mean of the largest branch in each of the four quadrants for the nominated log length.*

[4] *The number "850", "268" and "870" is a prefix number denoting a particular series of breed, with the first digit referring to the regional origin of the breed and the last two digits referring to the year of selection (Vincent and Dunstan, 1989).*

accounting for these two factors. To date these findings have not been tested for breeds or genetic series with contrasting internode length growing across a range of stockings.

Whilst stocking has been shown to have an impact on BIX, previous research found no correlation between stocking and internode length (Siemon *et al.* 1976, Grace and Carson 1993). The study reported here offered an opportunity to corroborate this finding across a wide range of stockings and breeds that could be expected to differ in internode length.

New Zealand has a longstanding genetic improvement program for *Pinus radiata*. The breeding program as described in numerous publications (e.g. Shelbourne *et al.* 1986, Jayawickrama *et al.* 1997a) has produced planting stock with altered external features such as internode length and branch diameter. The five "genotype/propagation treatments" used within the experiment reported here come from two breeds (870 is a long internode breed, whilst the 850 and 268 series are from the same growth and form breed). Within the 268 series there were one and three year old cuttings.

The 850 series had a growth and form (GF) rating of 14, whilst the seedlings, one-year-old cuttings and three-year-old cuttings from the 268 series had GF ratings of 22, 19 and 17 respectively (Shelbourne *et al.*, 1986). These GF breeds were devised to produce structural timber and, when pruned, knot-free timber. However, the development of the 850 and 268 series resulted in a reduction of the average internode length below that of unimproved plantations. This led to the development of the 870 breed (Jayawickrama *et al.* 1997b).

The 870 breed is the first generation long internode breed developed to obtain long clear sections from unpruned trees and has been found to have significantly longer mean internode lengths than the 850 and 268 series (Carson and Inglis 1988). Other than longer internode lengths, the 870 breed has larger diameter branches than the GF breed (Jayawickrama *et al.* 1997b).

In New Zealand many relationships between stocking and stem geometry are represented in software such as the Standpak modelling system and web-based models on the School of Forestry's website (http://www.forestry.ac.nz) at the University of Canterbury, however, these stocking/stem geometry relationships may vary with genotype. Effects of genotype have not been fully incorporated into software packages and in some cases are unknown. Where genotype influences the level of a relationship it is easy to apply adjustments to existing software. If an interaction between genotype and stocking exists, adjustments become more complex and must be made to coefficients within models represented by the software.

The objective of this study was to examine the influence of initial stand stocking and genotype on physical stem characteristics of differing breeds and series of *Pinus radiata,* identifying where significant interactions between breed and stocking exist.

Materials and Methods

Site Location

Measurements were taken from 17-year-old *Pinus radiata* trees that had been grown in a Nelder experiment (Nelder 1962) located at Burnham, approximately 18 km south-west of Christchurch (latitude 43°36.5'S, longitude 172°17.75'E, altitude 70 m a.s.l.). The trial was situated on Lismore stony silt loam soil (N.Z.S.B. 1968) and experienced a mean annual precipitation of 650 mm, in which seasonal water deficits occur during January to March, when evapotranspiration exceeds rainfall (G. Furniss, pers. comm.).

Experimental Plot

The experiment comprised five genotype/propagation treatments (850, 870, 268, cuttings taken from one-year-old parents and cuttings taken from three-year-old parents. Cuttings were both from the 268 series.). The Nelder trial contained 45 spokes separated by 8 degree intervals in 10 circular rings (Figure 1) with high initial stocking rates present at the centre of the Nelder and low initial stocking rates present on the outer ring of the Nelder (Table 1). Each genotype/propagation treatment occupied nine of the spokes split in a group of five spokes on one side of the plot and a group of four spokes on the other side of the plot, making two randomised complete blocks.

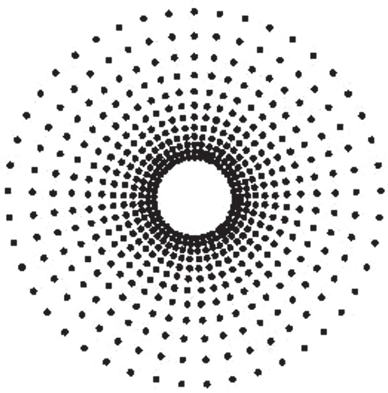
The trees were not thinned prior to examination. Due

Table 1. Nelder design

Circle number	Radii of planting circles(m)	Equivalent square spacing(m)	Initial stocking (stems ha^{-1})
Buffer	12.35	/	/
1	14.20	1.98	2551
2	16.31	2.28	1924
3	18.75	2.26	1457
4	21.54	3.00	1111
5	24.75	3.46	835
6	28.44	3.97	635
7	32.68	4.56	481
8	37.56	5.24	364
9	43.16	6.03	275
10	49.59	6.92	209
Buffer	56.99	/	/

to natural mortality, windthrow or malformation, 385 of the original 450 trees were suitable for examination. A total of 182 trees had a complete set of neighbours. The 65 trees assessed for BIX and internode length were selected from this population.

Figure 1. Plan of the Nelder stocking design experiment used. Trees are planted at each spot.



Measurements

Measurements of diameter at breast height, tree height and crown height were taken from 385 trees representing the five genotype/propagation treatments and ten initial stand stockings within the Nelder plot. Dbh was measured in centimetres (cm) using a tree diameter tape, whilst tree height and green crown height were measured in metres (m) using a vertex height instrument. Slenderness was calculated as height/dbh. Green crown height was measured as the height of the first live branch. Branch diameter and internode length were measured on 65 trees which were felled. The 65 trees selected represented all five genotype/propagation treatments and seven of the initial stand stockings. The largest branch in each quadrant of every whorl in the second log (6.0 - 12.0 m) was measured using calipers in millimetres (mm). Measurements were taken at a distance of two centimetres from the trunk to avoid node swelling. Quadrant 1 always faced true north. Internode lengths for each log (6.0 - 12.0 m) were obtained from internodes that were completely within the log length described above by measuring the vertical distance from the top of one whorl to the base of the whorl above.

Analyses

Analyses on height, green crown height, slenderness and dbh were initially restricted to those trees, 182 in total, that were completely surrounded by neighbouring trees and thus not affected by the mortality of neighbouring trees. In addition, analyses were conducted using all trees to see whether or not the results differed. The latter analysis had the advantage of being more balanced, and it is debatable whether or not trees surrounded by a complete set of neighbours properly represent treatments in an initial stocking experiment, because mortality is a feature of highly stocked stands. The analyses reported for internode length and BIX used 65 trees.

All analyses were undertaken using SAS (SAS-Institute-Inc., 2000). Mean values of the stocking and genotype within block level data were used for all analyses unless otherwise indicated. An analysis of variance examined the main and interactive effects of stocking and breed on four separate variables: diameter, height, slenderness and green crown height. The mean was determined for all variables to assess the impact stocking and breed had on the variables and a Student-Neuman-Keuls (SNK) test was used to determine if the means were significantly different.

Taking into account repeated measures within trees a linear mixed model (proc MIXED) was used to assess the effect of height to the base of the internode on internode length. As internode length was not found to vary with internode height, subsequent analyses were undertaken at the block level using mean internode length. In this analysis internode length was transformed using scaled power transformations (Cook & Weisberg 1999) to improve the linear fit:

$$X^{(\lambda)} = \begin{cases} (x^{\lambda}-1)/\lambda & \lambda \neq 0 \\ \log(x) & \lambda = 0 \end{cases}$$

The value of λ ranges typically between -1 and 3 to produce a variety of curvilinear shapes.

Analyses of diameter, height, slenderness and length of canopy were also conducted specifying stocking as a continuous variable, with the latter variable transformed using scaled power transformations.

The effects of stocking and genotype on BIX were initially assessed using analysis of variance. Variation in BIX was modelled using stocking and genotype, as well as tree diameter and average internode length. Curvilinear relationships were represented by variables transformed using scaled power transformations (Cook & Weisberg 1999).

Results

Interactions between stocking and genotype/propagation treatment were not statistically significant for height, dbh, slenderness and crown length.

Initial stand stocking had a highly significant ($P<0.0001$) influence on tree diameter at breast height with diameter increasing as stand stocking declined (Table 2). A scaled transformation of stems ha^{-1} using a λ value of -0.5 provided the best fit to a model of dbh vs stocking. The influence of genotype/propagation treatment on diameter was marginally significant ($P = 0.0418$) (Table 3), and only the three-year-old cuttings treatment and 850 series differed significantly from one another. Tree height was not significantly affected by stocking or genotype/propagation methods.

Green crown height was significantly affected by stocking ($P<0.0001$, $\lambda=-0.1$) and genotype ($P<0.0007$) (Figure 2). The 850 series had a green crown height of 6.0 m compared to 7.1 for the other genotype/propagation treatments.

Stem slenderness was significantly ($P<0.0001$, $\lambda=0.3$) influenced by stocking (Table 2) and marginally ($P=0.0211$)

Table 2. Mean diameter, height, green crown height and slenderness by initial stand stocking.

Initial stocking (stems ha^{-1})	Mean diameter (cm)	Mean height (m)	Green crown height (m)	Slenderness (m/cm)
209	36.6	16.6	1.8	0.46
275	34.7	17.5	2.7	0.51
364	35.0	17.7	3.4	0.51
481	31.8	18.4	5.4	0.59
635	28.6	18.0	6.8	0.64
835	24.9	17.7	7.8	0.74
1111	24.0	17.8	8.8	0.77
1457	21.9	17.6	9.3	0.84
1924	18.9	16.8	9.4	0.95
2551	17.7	17.3	10.2	1.03

influenced by genotype (Table 3). The three-year-old cuttings were slightly more slender than other genotype/propagation treatments.

Internode length was significantly influenced by genotype ($P<0.05$) but not stocking or the interaction of the two. The 870 breed, with a mean internode length of 61 cm across all stand stockings, was significantly different from the four remaining genotype/propagation treatments, which had mean internode lengths between 37 and 47 cm. The distance from the ground to the base of the internode was found to have no influence on internode length ($P<0.05$). Internode length was not significantly correlated with dbh.

Figure 2. Relationship between initial stand stocking and green crown height for each genotype/propagation treatment; 3-year-old cuttings (black circle), 1-year-old cuttings (white circle), 850 breed (black square), 870 breed (white square) and 268 breed (black triangle).

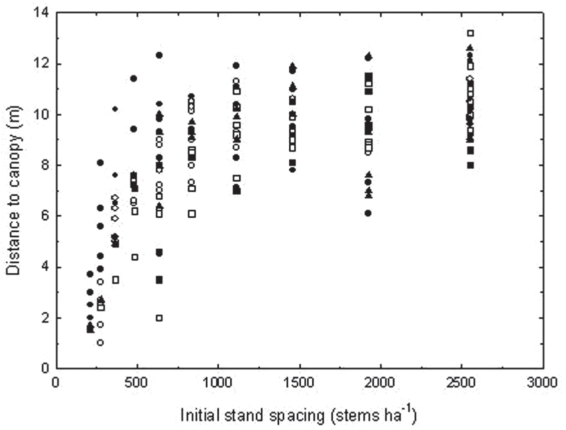
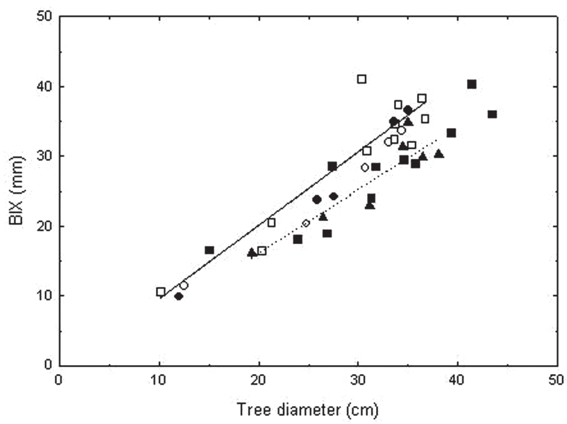


Table 3. Mean diameter, height, green crown length and slenderness by breed/propagation treatment

Breed/ propagation treatment	Mean diameter (cm)	Mean height (m)	Green crown height (m)	Slenderness (m/cm)
1-year-old	27.2	17.9	10.9	0.70
3-year-old	26.0	17.7	10.3	0.75
268	27.3	17.2	10.1	0.68
850	28.9	18.2	12.2	0.68
870	25.8	17.0	10.3	0.71

Initial stand stocking significantly influenced BIX ($P<0.0001$, $\lambda = -0.6$), with values for BIX ranging from 35 mm at 364 stems ha^{-1} to 13 mm at 2551 stems ha^{-1}. Neither genotype/propagation nor the interaction with initial stand stocking had a significant influence on BIX means when included in a model incorporating stocking effects. However, tree diameter exhibited a strong ($r^2=0.80$), significant ($P<0.0001$), and positive relationship with BIX (Figure 3). Inclusion of stem diameter at breast height in the analysis accounted for the stocking effect on BIX. The latter effect was found to be insignificant when added to the model with stem diameter. Moreover, genotype/propagation treatment was significant in the model that included diameter at breast height, indicating that treatments had different intercepts, but not different slopes in this latter model (Figure 3).

Figure 3. Relationship between BIX and tree diameter for the five genotype/propagation treatments; 3-year-old cuttings (black circle), 1-year-old cuttings (white circle), 850 series (black square), 870 breed (white square) and 268 series (black triangle). Linear lines have been drawn through those genotypes with the highest and lowest BIX for a given diameter; the 870 breed (solid line) and the 268 series (dotted line), respectively.

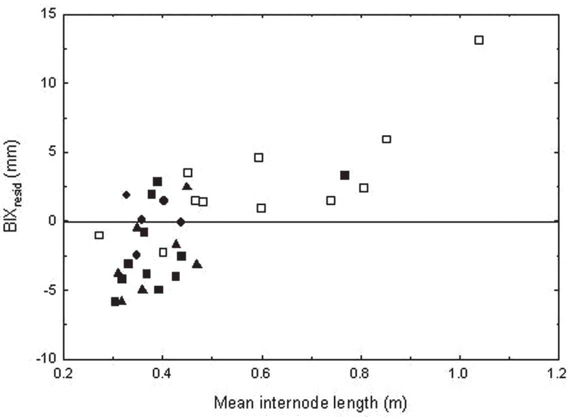


After correction had been made for tree diameter a plot of residual BIX against mean internode length revealed a positive relationship (Figure 4). Mean internode length was significant ($P<0.0001$) when included in the model with stem diameter (also $P<0.0001$) and improved the coefficient of determination of this model from 0.80 to 0.90. Inclusion of mean internode length in the model accounted for the genotype effect on BIX; the latter effect was found to be insignificant when added to the model with stem diameter and mean internode length, indicating that models of BIX based on diameter at breast height should have different intercepts for breeds with differing internode lengths. This result held when one extreme internode length was excluded from the analysis. If the 870 breed was excluded from the analysis, then the influence of internode length was not quite significant ($P<0.052$), and the class level genetic effect was similarly insignificant ($P<0.14$). The final branch index model was as follows:

$$BIX = -10.07 + 1.009\ DBH + 16.226\ IL$$

where BIX=branch index in mm, dbh=diameter at breast height in cm, and IL=mean internode length in m ($r^2=0.9$).

Figure 4. Relationship between residual BIX and mean internode length for the five genotype/propagation treatments; 3-year-old cuttings (black circle), 1-year-old cuttings (white circle), 850 series (black square), 870 breed (white square) and 268 series (black triangle).



Discussion

Perhaps the most important result of this study was the lack of any significant interaction between genotype and stocking on variables describing stem and branch geometry. This implies that simple adjustments to intercepts of equations in existing silvicultural models might account for differences in dbh, BIX and green crown height observed between genotypes. Genotype did not influence height significantly, and so no change in models of mean top height would be required. This was not a test of genetic by environment interactions, nor was it a test for differences in growth pattern between breeds or series. Managers wishing to apply existing models to new tree genotypes should be mindful of these other potential interactions.

Diameter, as one would expect, was considerably affected by initial stand stocking. There was a uniform increase in diameter with reduced stocking that resulted in over a two-fold increase in diameter as stocking decreased from 2551 stems ha^{-1} to 209 stems ha^{-1}. This relationship between stocking and diameter has been known for considerable time but it is still routinely confirmed, more recently from the Tikitere Agroforestry Trial (Knowles *et al.*, unpubl), and from work by Holley and Stiff (2003) and Land *et al.* (2003) using loblolly pine (*Pinus taeda*).

No relationship was found between tree height and initial stand stocking. This result corroborates previous observations (Siemon *et al*, 1976; Hocker, 1979; Cremer *et al.*, 1982; Lanner, 1985). However, it contradicts Sjolte-Jorgensen (1967), Mason (1992), Maclaren *et al.* (1995) and Carson *et al.* (1999), who all noted that either mean height or mean top height increased with stocking in their studies.

Green crown height showed a substantial change of over eight metres between the low and high stand stockings, with significant, large changes with stocking up to 1111 stems ha-1, after which changes in green crown height were less pronounced. Beekhuis (1965) noted that both Brown (1962) and Whiteside (1962) had observed an approximate one metre increase in green crown height for every 0.3 m increase in spacing, which was similar to results observed here.

Slenderness was also significantly influenced by stocking. It is well established that in general, in trees of the same age, slenderness decreases with increasing diameter (Sjolte-Jorgensen, 1967; Wang and Ko, 1998; Zhang *et al.*, 2002). In this trial, more than a two-fold increase in slenderness occurred between the lowest and highest stand stockings.

The significant influence of initial stand stocking on branch index for the second log in this trial corroborates findings by Tombleson *et al.* (1991) and Ballard and Long (1988). Findings demonstrate that variation in BIX between stockings was attributable to differences in diameter for a given genotype/propagation treatment. This is consistent with previous studies which show that diameter accounts for variation in stocking induced differences in BIX (Smith *et al.* 1996, Knowles and Kimberley unpubl., Woollons *et al.* 2002). For a given diameter the greatest difference in BIX between genotypes was between the 268 series and the 870 breed. The BIX for the 870 breed was found to be on average 5.5 mm larger than the 268 series after adjusting for stem diameter. This is supported by Carson and Inglis (1988), Jayawickrama *et al.* (1997b) and Watt *et al.* (2000) who have all found that for a given tree diameter the 870 breed tended to have larger diameter branches than GF breed. Carson and Inglis (1988) state that selection for long internodes increased average internode length and also tended to increase average branch size, which can be supported from observations made in this trial.

Mean internode length accounted for the within and between genotype effect on BIX. This is consistent with research by Watt *et al*. (2000), and extends these findings to a greater range of stockings and breeds. Analyses done at the tree level (data not shown), indicate that the relationship between mean internode length and BIX was strong. For the genotypes examined in this study our results suggest that inclusion of internode length in models of branch diameter may provide a useful means of quantifying within and between genotype variation in BIX.

The effect of stocking on internode length agrees with findings by Siemon *et al*. (1976) and Tombleson *et al*. (1991) who observed no obvious trend. Compared to many other conifers, a distinctive feature of *Pinus radiata* is the relatively long internodes which separate the whorls of branches (Lavery, 1986), that are under strong genetic control once the juvenile state of the tree is passed (Lavery, 1986; Grace and Carson, 1993). The effect of genotype was well demonstrated within this trial and compared favourable with results from Carson and Inglis (1988), who noted that the 870 breed had significantly longer mean internode lengths than the 850 series.

Carson and Inglis (1988) noted that the 268 series was extremely multinodal, but this observation was not consistent with results reported here. The 850 and 268 series had an essentially identical number of whorls per tree throughout the trial, whilst as expected, the 870 breed had considerably fewer whorls. Correlations in this study suggest that internode length of *Pinus radiata* may be relatively independent of tree size, which is in agreement with Woollons *et al*. (2002). In attempting to model internode length, Woollons *et al*. (2002) noted that 'it is evident internode length can be regarded as a random phenomenon'. Results from this study and previously from Carson and Inglis (1988) confirm that there is a large potential for exploiting genetic variation in internode length to dramatically increase the yields of clearwood, without unduly compromising growth rate. There are obvious advantages in growing clearwood in long pieces, namely, reducing the costs of re-cutting and increasing the versatility of the product for meeting a range of end uses.

Conclusions

No statistically significant interactions between stocking and genotype/propagation method were found for any of the variables examined.

Diameter, green crown height and slenderness were all significantly influenced by initial stand stocking. Stem diameter decreased from 36.7 cm to 17.7 cm as stand stocking increased from 209 stems ha^{-1} to 2551 stems ha^{-1}. Green crown length decreased from 1.8 m to 10.2 m with increasing stand stocking, whilst stem slenderness increased from 0.46 to 1.03 with increasing stand stocking.

The 850 series had a higher green crown height than any of the other genotype/propagation treatments, and also had the largest mean dbh, although the effect on dbh was only marginally significant statistically and could only be shown to be different from the 870 breed and the cuttings taken from one-year-old parents.

BIX was positively correlated with tree diameter. After adjustment for tree diameter, BIX was positively correlated with internode length, and the two together explained 90% of variation in BIX.

The 870 breed had significantly longer internode lengths than other genotypes demonstrating its defining physical characteristic. The 870 breed had a mean internode length of 61 cm, whilst the remaining four breed/propagation treatments had mean internode lengths between 37 cm and 47 cm.

Acknowledgements

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