Incorporating thinning responses into a branch diameter model

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Plantation Management Cooperative

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EXECUTIVE SUMMARY

INCORPORATING THINNING RESPONSES INTO A BRANCH DIAMETER MODEL

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The Kimberley/Knowles model is widely used to predict branch diameter for radiata pine in New Zealand. It is shown that this model can be converted into a form that predicts branch diameter as a function of Site Index, 300 Index and stocking, in unthinned or early-thinned stands. By combining this model with a newly developed crown height model, the effects of late and/or multiple thinnings on final branch diameter can be predicted. Branch diameters corresponding to the initial stocking, and to the stocking levels following each thinning are firstly predicted. These are then distributed along the stem of the tree using the crown height model to determine the appropriate stem heights for each branch diameter. A simple interpolation procedure is used to connect these diameters. The model has been tested against branch measurement data from ten late-thinned stands and generally appears to perform well. However, it will need more validation before it can become fully accepted.

BACKGROUND

Branch size has always been recognised as one of the more important quality variables for *Pinus radiata* unpruned logs, particularly if they are to be sawn into framing timber (Cown et al, 1987). Models for predicting branch diameter reliably are therefore important.

Inglis and Cleland (1982) developed a model for predicting branch index (BIX) using data from 628 trees across 25 site/treatment combinations. They found that BIX could be predicted using site index (SI - mean top height at age 20), mean DBH at age 20 years (DBH20), predominant mean height at the time of last thinning (HTTHIN), and log height class. Using these variables, the derived an empirical regression model that explained 92% of the variation in their data. This model has been found to work well on traditional forest sites at moderate to high stockings. However, Knowles and Kimberley (1993) found that it under-predicted BIX at stockings less than 200 stems/ha, especially on more fertile ex-pasture sites.

A model was subsequently developed by Kimberley and Knowles (1993) using new data, from 899 trees in 26 stands, including many from fertile ex-pasture sites. This model predicted BIX for 2nd logs (5.7 - 11.2 m stem height). It used many of the same variables used by Inglis and Cleland, (SI, DBH20, HTTHIN), but also attempted to explain genetic effects on BIX by including GF rating in the equation. This 2nd log BIX model, which explained 98.5% of the variation in the data, is:

$$[1] \qquad \mathrm{BIX} = 3.0 + b \times \ln(1 + \exp((0.985 + 0.356 \times \mathrm{DBH20} - 0.354 \times \mathrm{SI} - 0.212 \times \mathrm{GF} - 0.321 \times \mathrm{HTTHIN}) / b))$$

with $b = 3.52$

This model was validated against the Inglis/Cleland data by Middlemiss & Knowles (1994). Their analysis showed that it consistently over-predicted BIX by about 0.7 cm. This over-prediction has never been fully explained although there are several possibilities as discussed by Middlemiss & Knowles. One is that the validation data was generally from stands planted at much higher initial stockings than the modelling data. Another possibility is that the GF term in the model overstates the genetic effect. The stands in the validation set were all assumed to have a GF of 7. The model predicts that GF 7 trees will have branches about 1 cm greater in diameter than GF 14 trees, a difference of about 20%. However, Shelbourne and Briscoe (1983) found that a felling-select seedlot had 2nd log branches on average only 0.15 cm larger in diameter than an ‘850’ seedlot (about GF 14). Taking account of the lesser stem diameter growth of unimproved seedlots which will therefore produce a smaller DBH20, the appropriate branch diameter adjustment for GF 7 compared with GF 14 appears to be less than +10%, or about half the Kimberley/Knowles value.

The Kimberley/Knowles model was later extended to predict BIX in butt logs and upper logs (Kimberley & Knowles, 1996; Hansen et al., 2004). This model uses Equation [1] to predict 2nd log BIX, and then predicts BIX in the butt and upper logs by multiplying this predicted 2nd log BIX with ratios predicted using HTTHIN and post-thin stocking as input variables. This model also has an override that reduces BIX in the upper part of the stem to account for branches that are still growing and have therefore yet to reach their final diameter. When applied to very early-thinned stands, the model tended to over-predict, and to overcome this problem, HTTHIN is restricted to be no less than 8 m.

The Inglis/Cleland and Kimberley/Knowles models are similar in that they use empirical regression equations to predict final branch size by means of a single summary statistic (BIX) for each 5.5 m log. However, an alternative branch modelling approach which involves predicting position, size and other attributes of individual branches has also been explored by Ensis (Grace et al., 1998). This has led to the development of the Branch Location, Orientation and Size Simulator (BLOSSIM), which is based on a detailed knowledge of crown morphology. However, we believe that the simpler empirical final branch diameter models still have a place, and they are currently the only models available in the forest stand simulation programmes STANDPAK, FORECASTER and the Radiata pine Calculator. Therefore, any improvements that can be made to these models should be pursued.

One area where there appears to be room for improvement is in modelling the response to thinning of branch size against stem height. Although both the Inglis/Cleland and Kimberley/Knowles models incorporate variables such as HTTHIN to predict response to thinning, they cannot predict the effects of multiple thinnings accurately. Also, because they predict BIX only for standard 5.5m logs (although BIX for alternative log lengths can be derived from these), they can not predict changes in branch size against height with any great detail. This report describes a method of improving predictions of branch diameter in response to thinning.

OBJECTIVE

Modify the Kimberley/Knowles branch index model to improve its ability to predict the effects of late and/or multiple thinnings on final branch diameter against stem height.

DEVELOPMENT OF THE MODEL

Kimberley et al. (2000) demonstrated that in unthinned or early-thinned stands, branch size in radiata pine remains almost constant to a height equal to about 60% into the green crown from the top of the tree. Above this height, which defines the point where branches cease growing and become moribund, branch diameters decrease towards the top of the tree. This constant relationship between branch diameter and height appears to hold, at least while trees are still growing strongly in height, i.e., up to a height of at least 40 m on typical sites. This result together with the branch modelling work described above, lead to the following hypotheses concerning final branch diameter in radiata pine:

1. Branches become moribund at a distance of about 60% into the green crown from the top of the tree.
2. In unthinned or early-thinned stands, branch diameter remains constant from the base of the tree to the moribund branch height.
3. In unthinned or early-thinned stands, final branch diameter can be predicted from Site Index and DBH20.
4. In late-thinned stands, branches developing above the height at which the thinning occurred will have the same final diameter as branches in an unthinned stand of the same stocking on that site.
5. In late-thinned stands, branches below moribund height at the time of thinning will not respond to the thinning.

As discussed above, Hypotheses 1, 2 and 3 have been demonstrated to be correct, at least to a reasonable level of precision. The last two hypotheses are not proven, but do not seem unreasonable. Based on these hypotheses, Kimberley (2000) suggested an approach that might be used for modelling final branch diameter against stem height, which would account for the effects of late or multiple thinnings. This approach is as follows:

In unthinned or early-thinned stands in which final stocking is established at a young age:

1. Predict height to base of green crown and from this, derive height of moribund branch growth (e.g., at 60% into the green crown from the top of the tree).
2. Predict BIX up to this height using the Kimberley/Knowles 2nd log model from DBH20, SI and a possible genetic adjustment.
3. Reduce BIX above this height to be zero at total tree height, using a simple function (e.g., a straight line).

For late-thinned or multiple-thinned stands:

1. Predict D_1, the DBH20 that would have occurred if the pre-thinning stocking had been maintained to age 20.
2. Predict D_2, the DBH20 that would have occurred if the stand had been thinned early to the post-thinning stocking.
3. Predict BIX_1 with the 2nd log model from D_1, SI and a possible genetic adjustment.
4. Predict BIX_2 with the 2nd log model from D_2, SI and a possible genetic adjustment.
5. For the thinning age, predict H_1 the height where branch growth becomes moribund, and H_2 the total tree height.
6. Assign BIX_1 to the stem below H_1, BIX_2 to the stem above H_2, and use a transition function (e.g., a straight line) to interpolate BIX between H_1 and H_2.
7. Predict moribund height H_3, and total height H_4 at the clearfell age.
8. Reduce BIX above H_3 to be zero at H_4, using a simple function (e.g., a straight line).

Graphically, predicting branch diameter versus stem height using this approach is shown in Fig. 1 for early-thinned stands, and in Fig. 2 for late-thinned stands.

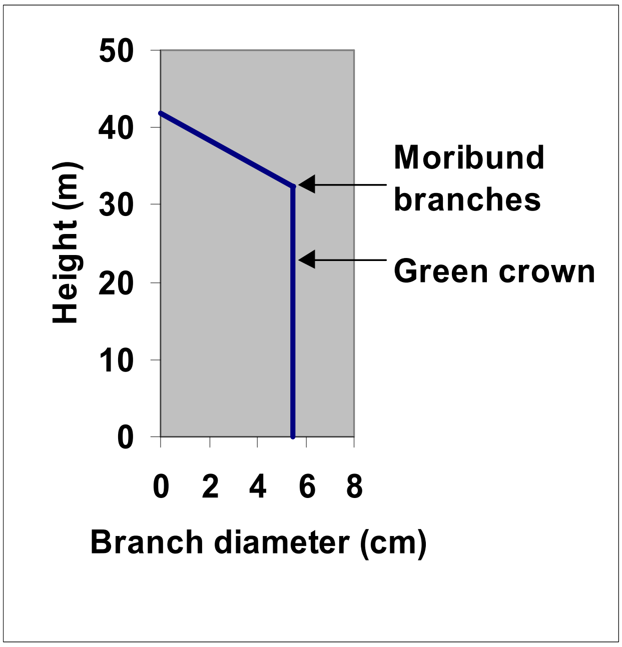

Fig. 1. BIX versus height in a stand thinned to final stocking at an early age.

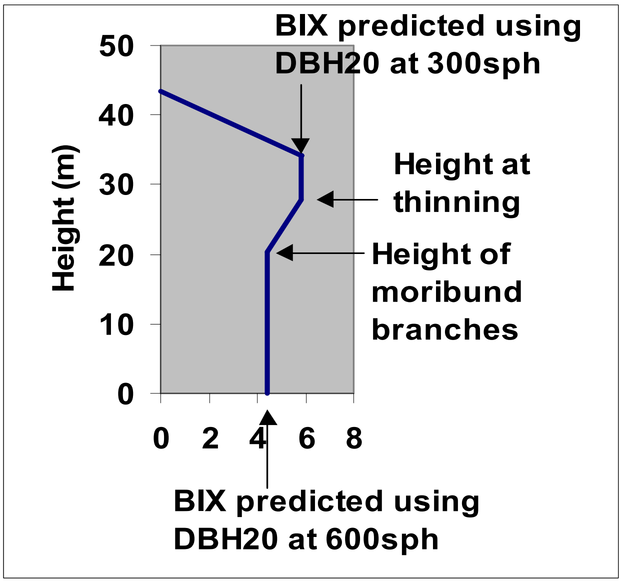

Fig. 2. BIX in a stand thinned from 600 to 300 stems/ha at a height of 28 m.

Although it appeared that this model might work, there were difficulties in implementing it. In particular, at the time the approach was suggested, there was no reliable way of carrying out steps 1 and 2 for late-thinned stands because growth models could not readily predict DBH at age 20 years for any specified stocking. However, this can now be performed very easily using the 300 Index Growth Model. Once the 300 Index and Site Index have been estimated, which can be done using any plot measurement, DBH20 can be predicted using this model for any final crop stocking. Effectively with this approach, branch size for an early-thinned stand is predicted from SI, 300 Index and stocking. The calculation of DBH20 from these variables is only an interim step required to use the Kimberley/Knowles model, and the model could be re-expressed in terms of these three variables. This is shown in Figs 3-5 where the predicted BIX is plotted against stocking for a range of Site Indices and 300 Indices. One conclusion from these charts is that it is very difficult to control branch size when the Site Index is low and the 300 Index is high (Fig. 3). Conversely, when the Site Index is high, branch size is controlled at moderate stockings, even when the 300 Index is quite high (Fig. 5), although it increases rapidly at stockings below 300 stems/ha.

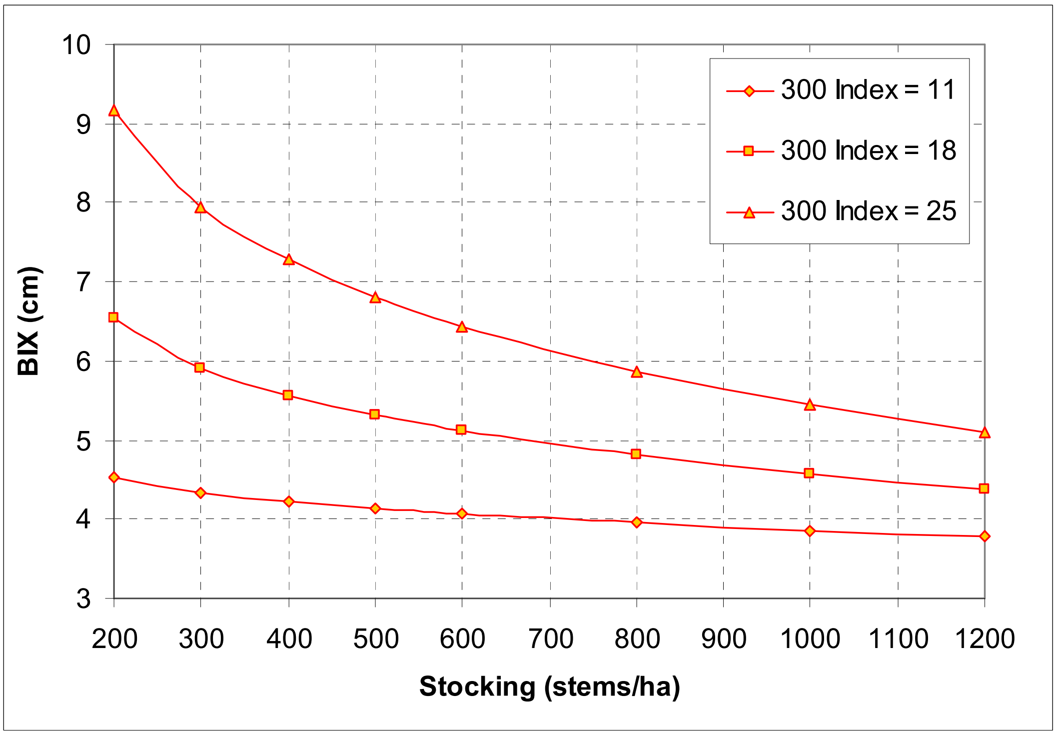

Fig. 3. Branch Index predicted using the Kimberley/Knowles model versus stocking for a range of 300 Indices at a Site Index of 23 m.

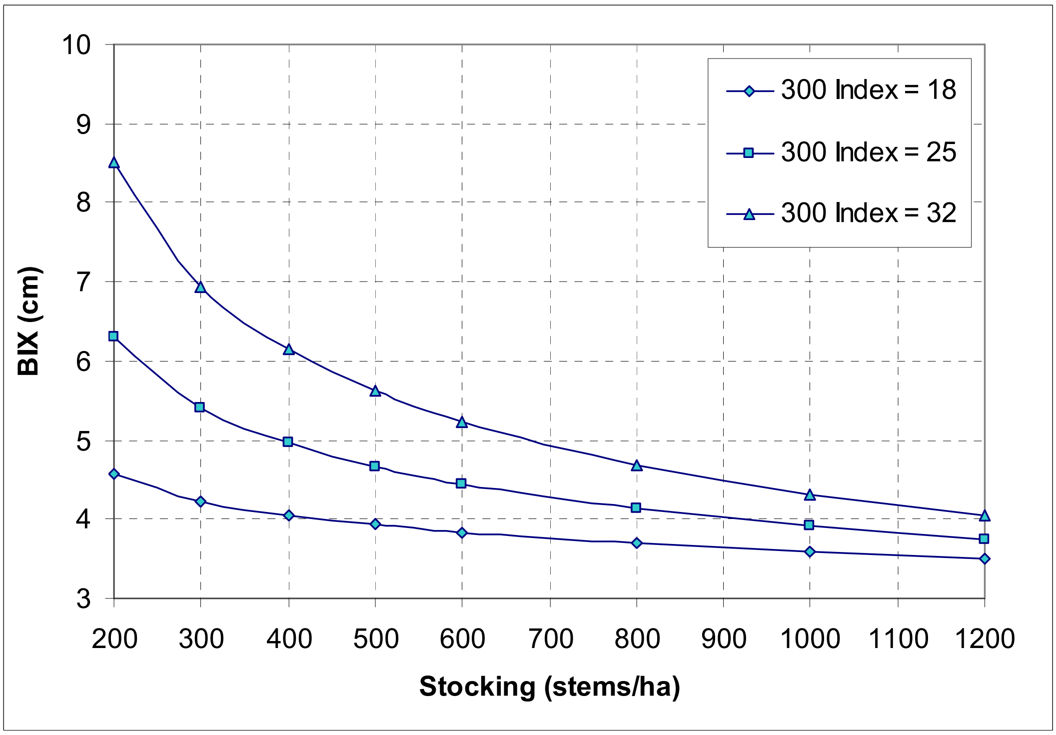

Fig. 4. Branch Index predicted using the Kimberley/Knowles model versus stocking for a range of 300 Indices at a Site Index of 30 m.

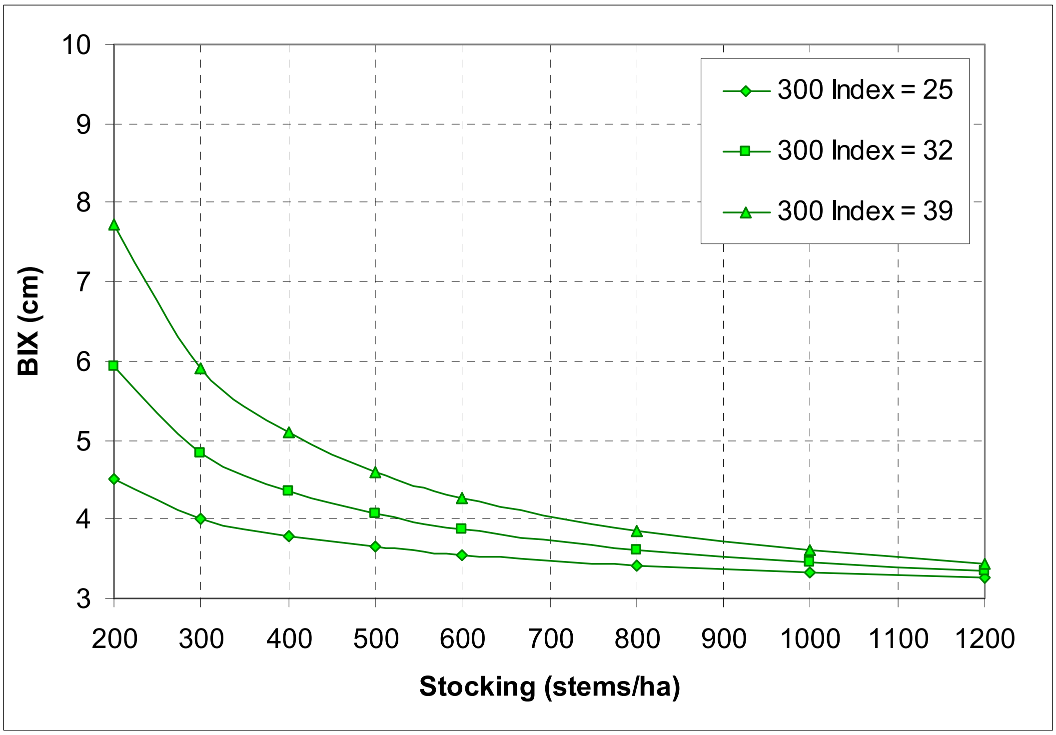

Fig. 5. Branch Index predicted using the Kimberley/Knowles model versus stocking for a range of 300 Indices at a Site Index of 37 m.

Crown height model

One requirement for the branch modelling approach suggested above is an accurate means of predicting crown height. There are two currently available crown length or crown height models for radiata pine in New Zealand, one developed by Beekhuis (1965), and the other by Turner (1998). Although both models appear to perform well at most ages, they were found to be less accurate at young ages. As the proposed branch model requires good crown height predictions at very young ages, it was decided to fit a new crown height model using data from 20 Final Crop Stocking trials.

Mean height to the base of the green crown (HTCROWN), mean height (HT), stocking (N), SI and 300 Index were extracted for each measurement from these trials using the PSP system. Measurements with mean crown heights less than 10 m were discarded because below this level, crown height measurements can be artificially raised by pruning treatments. In Fig. 6, mean crown height is shown plotted against mean height for different stocking classes. Within each stocking class, the relationship between crown height and total height is approximately linear with the ratio of crown height to total height increasing with tree height. For example, in the highest stocking class, this ratio is 0.48 at a mean height of 25 m, and 0.68 at a mean height of 45 m.

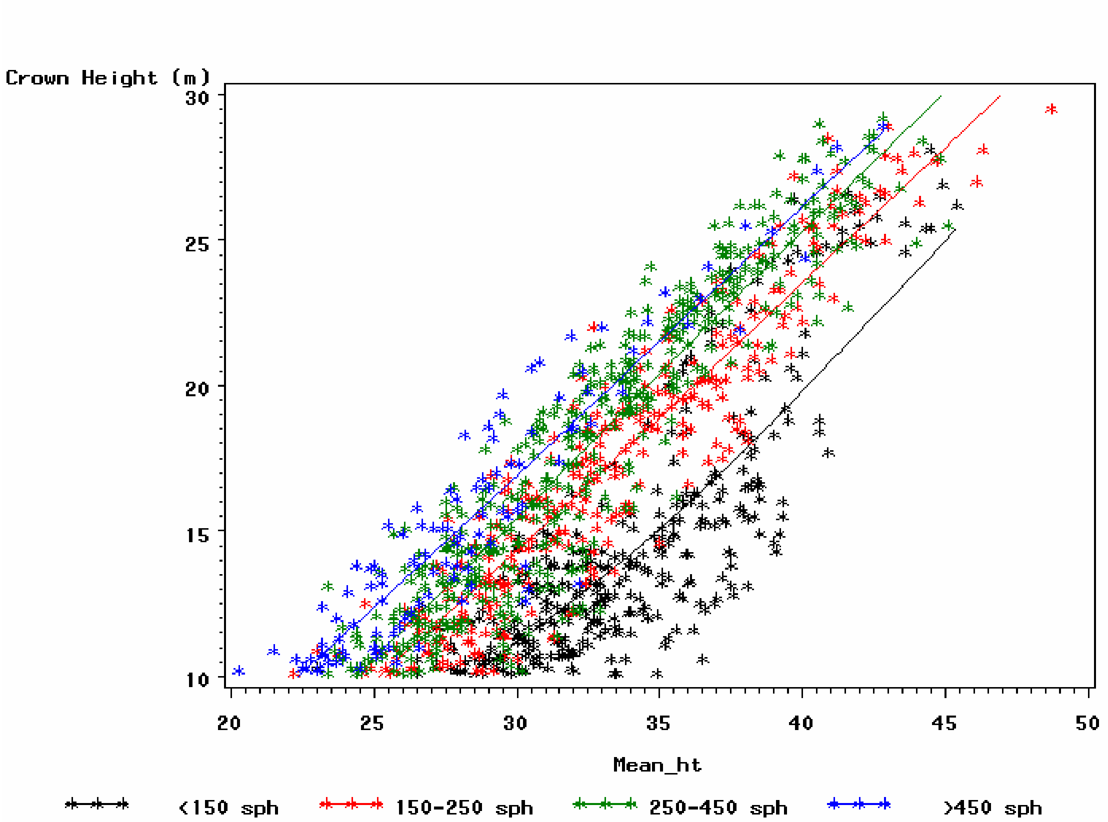

Fig. 6. Mean crown height versus mean tree height by stocking in 20 final crop stocking trials. Lines are smoothing splines fitted to each stocking class.

The following regression function was fitted to this data:

[2] $\text{HTCROWN} = a + b \times \text{HT} + c \times \ln(N) + d \times \text{HT} \times \ln(N)$

The parameter estimates are given in Table 1. This model had an R^2 of 0.85 and a root mean square error of 1.9 m implying that it predicts mean HTCROWN for an average plot measurement to within 3.8 m, 95% of the time. Figs. 7 & 8 show that after accounting for HT and N, there is no trend in HTCROWN against either SI or 300 Index. However, there is consistent model bias in some trials, especially in the two Nelson trials where the model over-predicts HTCROWN by an average of 5.0 m (NN 525/1) and 2.4 m (NN 545/4) respectively. Average bias in all other trials is no more than 2 m, and less than 1 m in sixteen of the 20 trials. Plots of residuals against stocking, mean height and age show no trend indicating that the model accounts well for these variables.

Table 1. Regression coefficients for Model [2]

Parameter	Estimate	Standard error
a	-7.41	3.48
b	0.153	0.106
c	-1.11	0.62
d	0.142	0.019

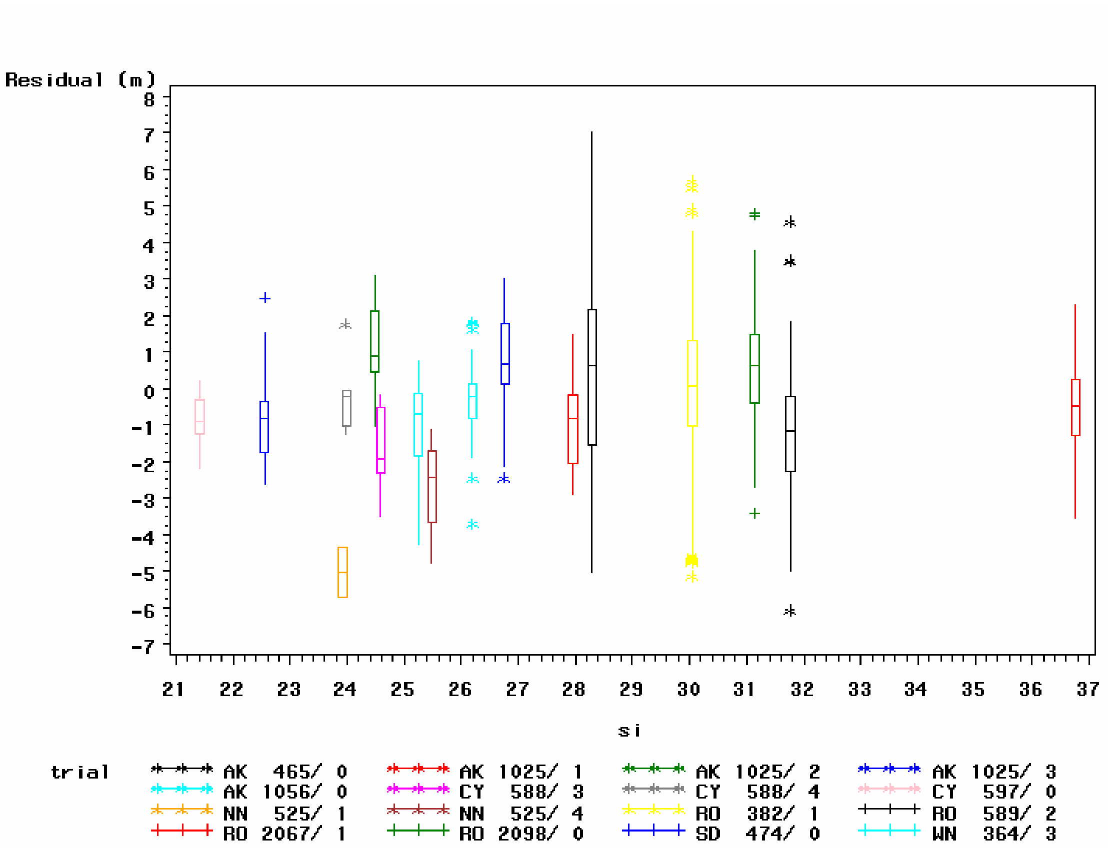

Fig. 7. Box plots of residuals from Model [2] versus SI for each trial.

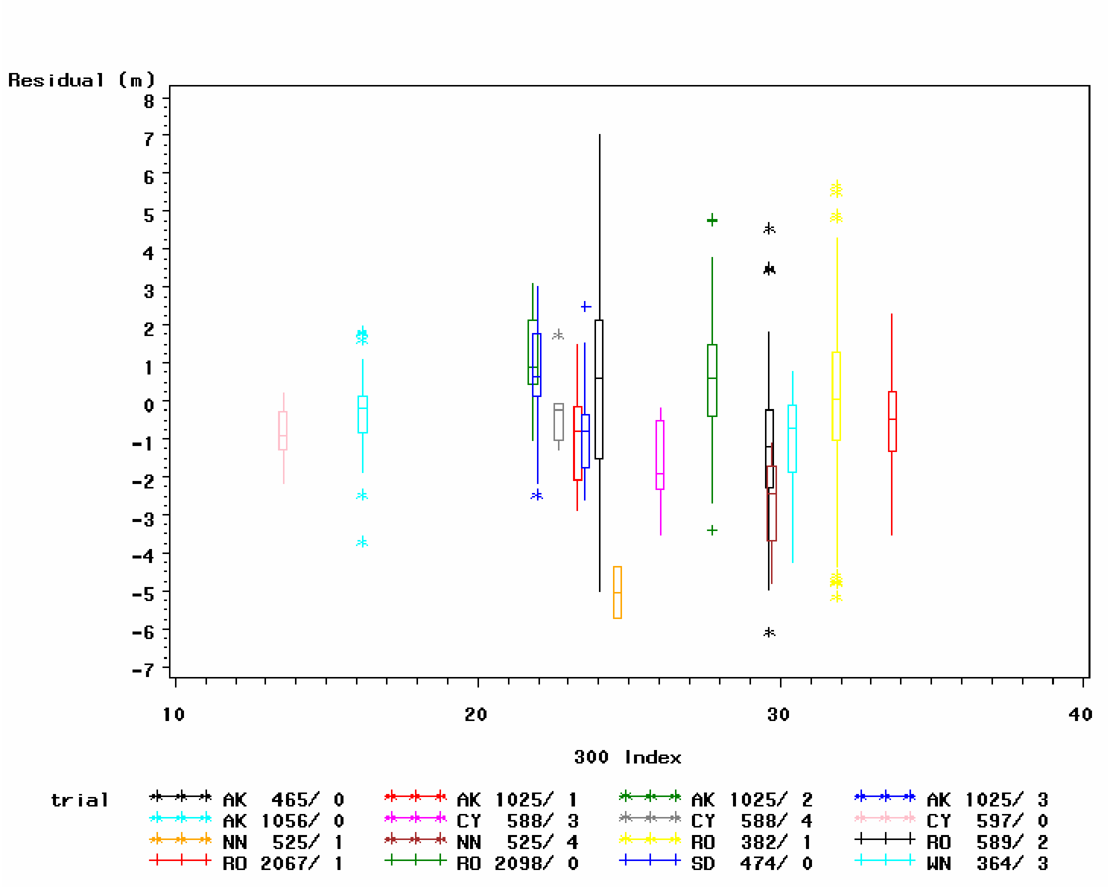

Fig. 8. Box plots of residuals from Model [2] versus 300 Index for each trial.

Implementation of the branch diameter model

A prototype version of the branch model described above has been implemented in Microsoft Excel using VBA (Visual Basic for Applications) code. It incorporates the original Kimberley/Knowles 2nd log BIX model (Equation [1] with GF set at 14 and HTTHIN set at 8 m to represent an early thinning), the 300 Index Growth Model to predict DBH20, and the crown height model described above. The user can specify a genetic calibration factor, which is used as simple multiplier to adjust predictions from the standard model. The model assumes that branches become moribund at a height corresponding to 60% into the green crown from the top of the tree, and uses simple straight-line interpolation as illustrated in Figs. 1 & 2. Note that the crown length model is allowed to produce 'negative' crown heights in the early period of growth. The model predicts the mean largest branch per metre of stem. Analysis of the branch database indicated that a multiplier of 0.94 can be used to convert BIX for a 5.5 m log into mean largest branch per metre of stem.

Examples of model predictions for three basic regimes on three site types are given in Figs. 9-11. The regimes are: early-thinning (750 to 300 stems/ha at 10 m height); late-thinning (750 to 300 stems/ha at 20 m height); and multiple thinning (1,200 to 600 stems/ha at 8 m, 300 stems/ha at 18 m, and 175 stems/ha at 26 m). The site types shown are a typical coastal sand site (300 Index = 18 m^3/ha/yr, SI = 25 m); a typical 'Forest' site (300 Index = 25 m^3/ha/yr, SI = 30 m); and a typical 'Farm' site (300 Index = 30 m^3/ha/yr, SI = 30 m). The predictions indicate that for stands thinned at 10 m height, branches in all logs respond to the thinning, fully so above the 2nd log. For stands thinned at 20 m height, branches in the lower two logs do not to respond to the thinning, while branches in the 3rd log only partly respond.

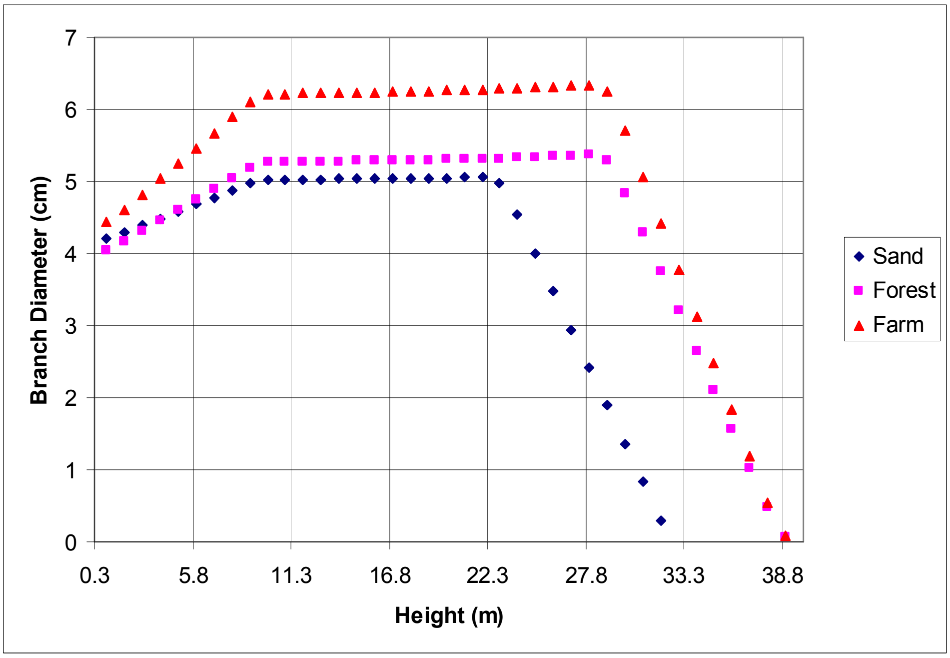

Fig. 9. Predictions from the model of average largest branch diameter per metre of stem at age 30 years on three site types of stands thinned from 750 to 300 stems/ha at a height of 10 m.

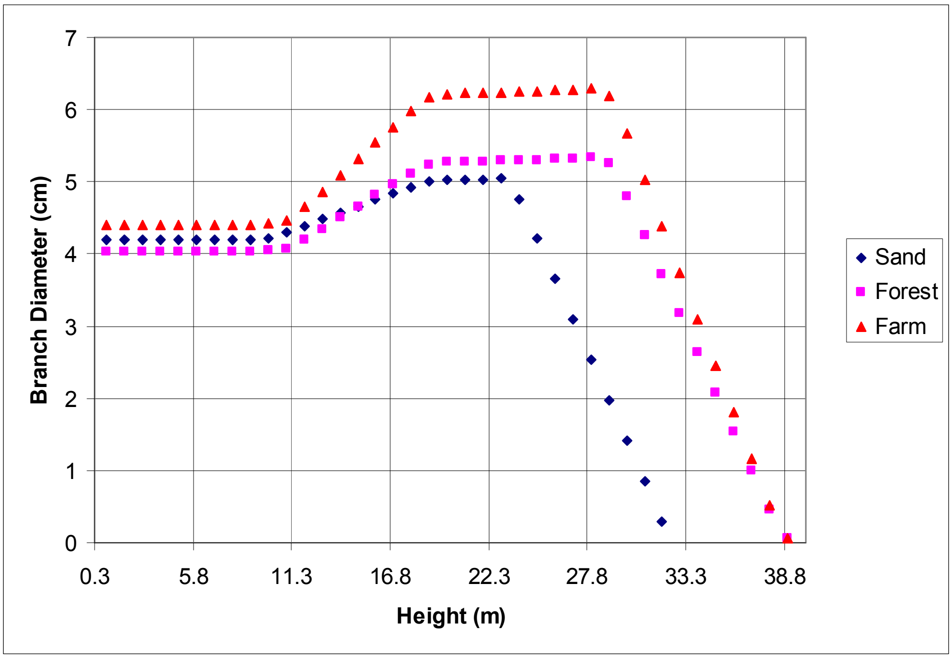

Fig. 10. Predictions from the model of average largest branch diameter per metre of stem at age 30 years on three site types of stands thinned from 750 to 300 stems/ha at a height of 20 m.

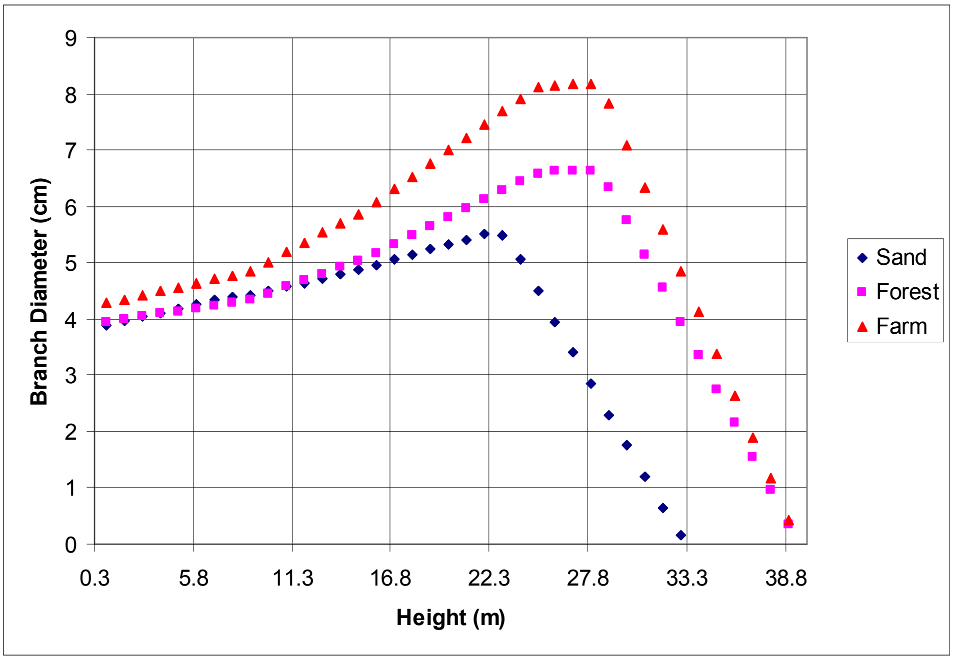

Fig. 11. Predictions from the model of average largest branch diameter per metre of stem at age 30 years on three site types of stands with initial stocking 1200 stems/ha and three thinnings: to 600 stems/ha at 8 m; 300 stems/ha at 18 m; and 175 stems/ha at 26 m.

Testing the model

The model was tested against data extracted from the 10 trial treatments in the branch database shown in Table 2. These included three treatments from a trial on a low site index (Berwick), two treatments from a coastal sand forest (Woodhill), and five treatments from two high Site Index Central North Island trials (Tarawera and Northern Boundary). Details of the regimes applied to these stands are shown in Table 3. Most of these treatments included a late thinning enabling the performance of the modelled response to thinning to be tested. Branches in all stands were measured to a height of about 17 m. Twelve to 25 trees were measured in each treatment.

Table 2. Details of plot data from the branch database used to test the model.

Location	Database Code	PSP plots	SI (m)	300 Index (m^3/ha/yr)
Berwick	b370	SD 371/0, plots 6, 7	22.2	17.9
	b370d	SD 371/0, plot 15	21.2	19.8
	ber250	SD 371/0, plots 4, 9	22.1	19.0
Northern Boundary	nb20c	RO 911/1, plot 2	34.8	31.0
	nb35c	RO 911/1, plot 8	31.3	30.3
Tarawera	Qtar2	RO 955/7, plots 31-33	36.9	29.4
	Qtar7	RO 955/6, plots 2, 4, 18	37.6	30.8
	Qtar8	RO 955/4, plots 6, 14, 18	38.3	30.8
Woodhill	wh200	AK 334, plot 4/2	23.0	16.3
	wh400	AK 334, plot 1/1	27.3	18.5

Table 3. Details of plot data from the branch database used to test the model.

Database Code	Thin age (yrs)	Thin height (m)	Initial stocking (stem/ha)	Post-thin stocking (stem/ha)	Measurement age (yrs)
b370	10	10.5	2315	370	22
b370d	14	14.5	2315	385	22
ber250	10	10.4	2315	247	22
nb20c	8/14	14.0/25.3	2315	455/203	19
nb35c	8/14	12.2/22.5	2315	457/204	19
qtar2	7/14	15.6/26.9	2267	499	17
qtar7	6/9	12.0/18.1	2454	1344/379	17
qtar8	6/9	12.3/18.5	4399	1351/379	17
wh200	9/16	12.2/20.0	2200	370/200	27
wh400	9	13.1	2200	400	27

Mean largest branch per metre of stem was predicted with the model using SI, 300 Index, stocking and HTTHIN for each treatment. No genetic adjustment was made and the model was therefore run at the equivalent of GF 14, even though all the stands had little genetic improvement and would probably best be regarded as GF 7.

The predicted and actual largest diameter branch per metre of stem averaged across all trees is shown in Figs. 12-21. The results are very promising with little bias overall in most treatments. The trend of increasing branch diameter with height in response to late thinning is predicted well in most stands, especially in the Berwick, Tarawera and Northern Boundary trials, and to a slightly lesser extent in the Woodhill trial. The reduction in branch diameter towards the top of the tree is also well predicted in the Berwick trial.

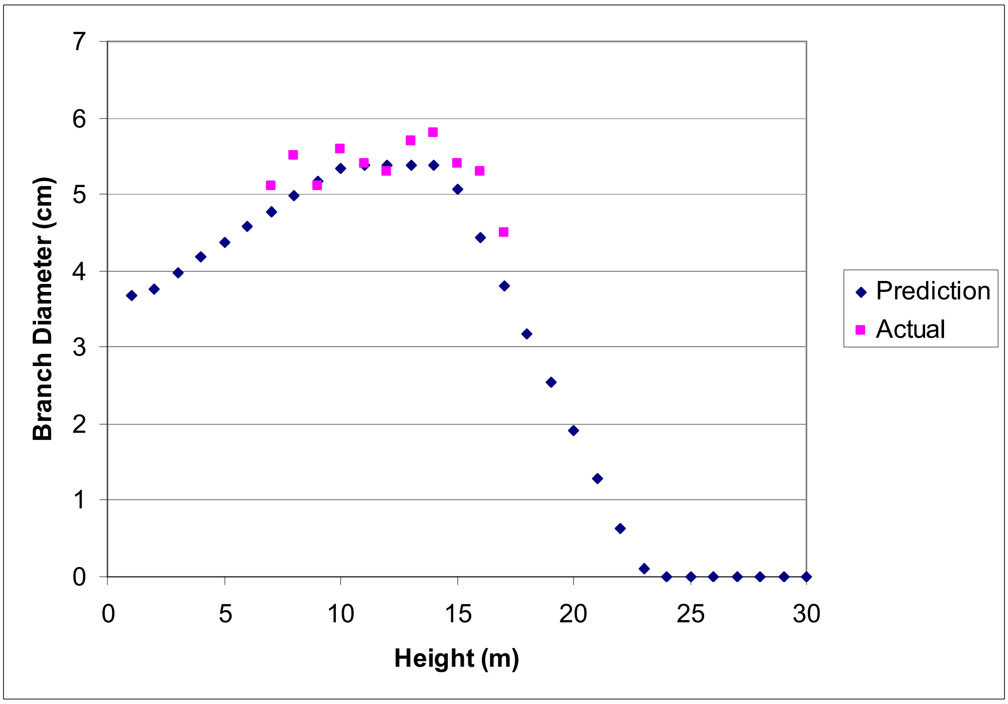

Fig. 12. Predicted versus actual mean largest branch per metre of stem for stand b370.

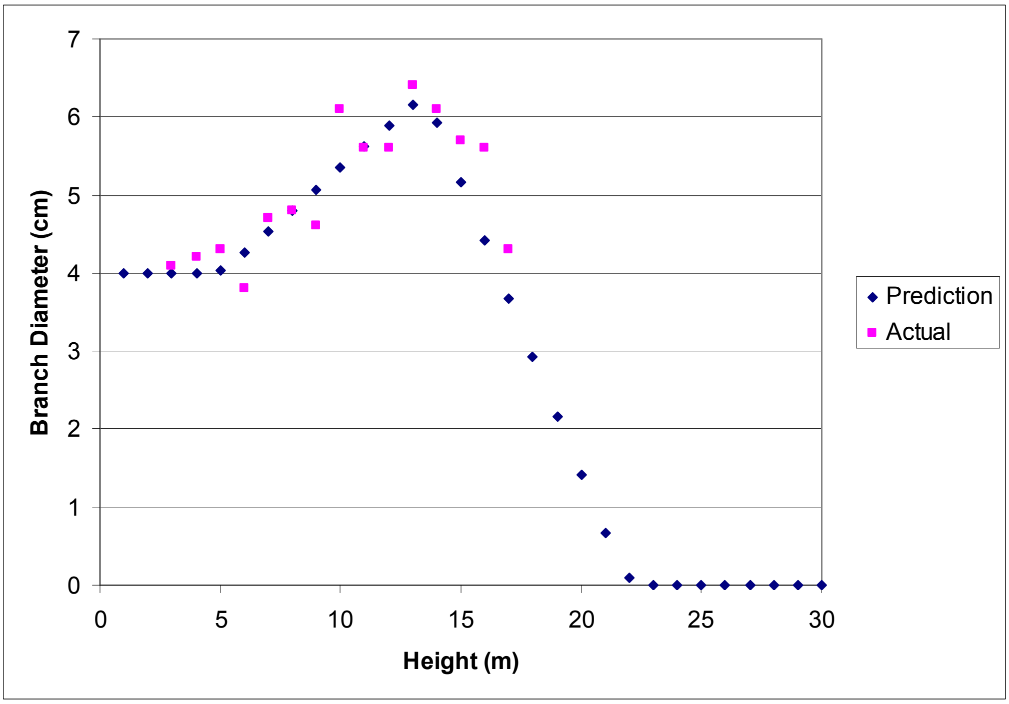

Fig. 13. Predicted versus actual mean largest branch per metre of stem for stand b370d.

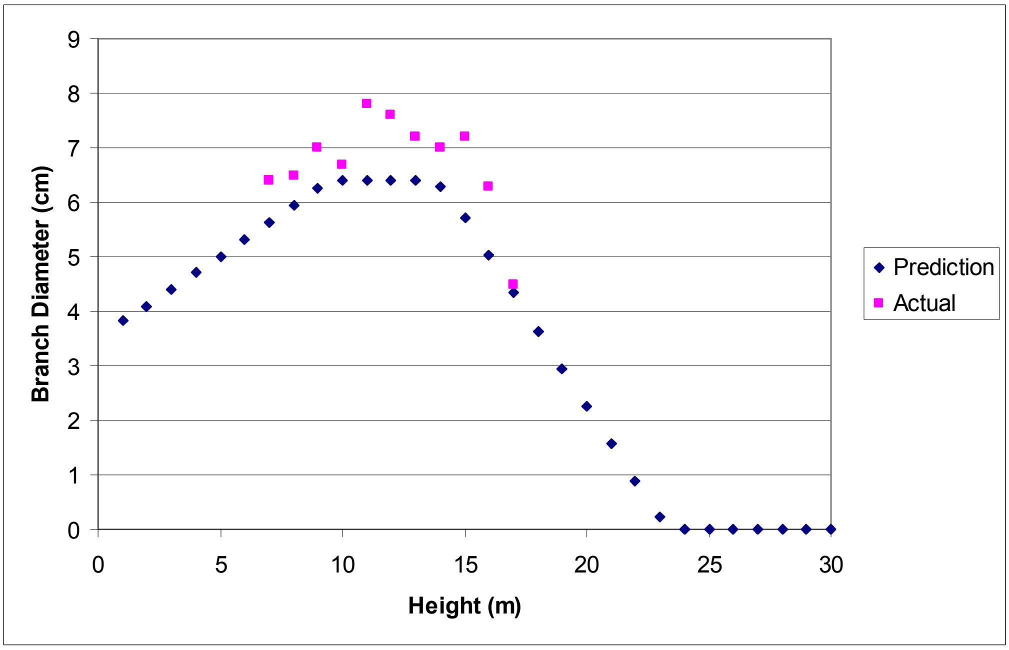

Fig. 14. Predicted versus actual mean largest branch per metre of stem for stand ber250.

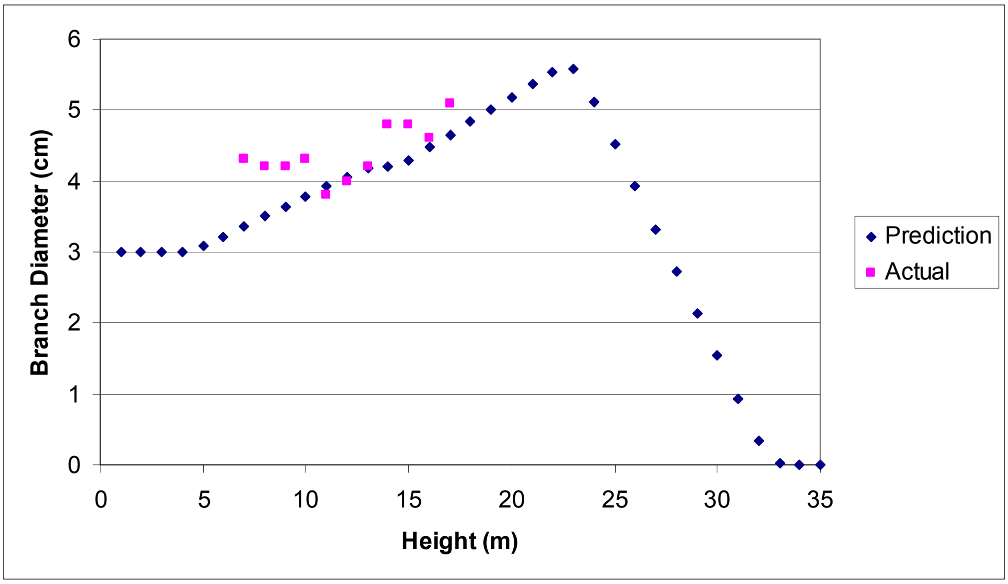

Fig. 15. Predicted versus actual mean largest branch per metre of stem for stand nb20c.

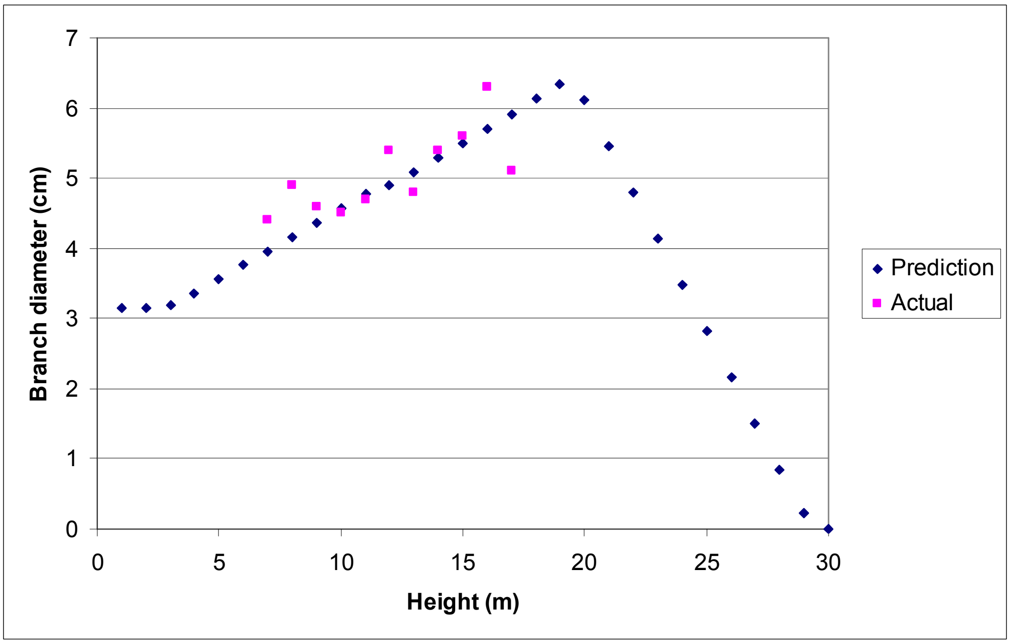

Fig. 16. Predicted versus actual mean largest branch per metre of stem for stand nb35c.

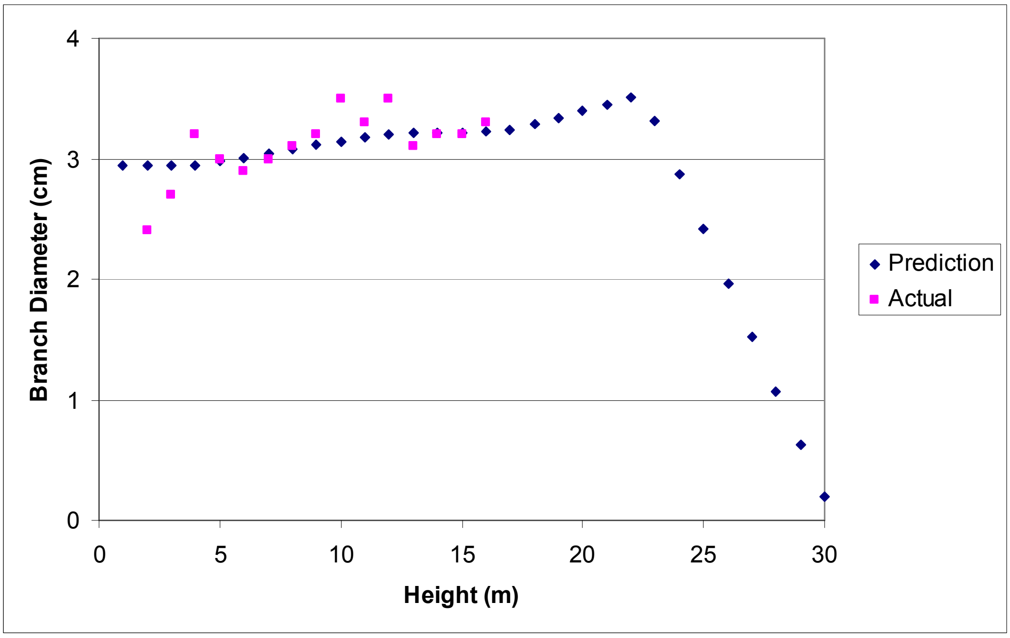

Fig. 17. Predicted versus actual mean largest branch per metre of stem for stand qtar2.

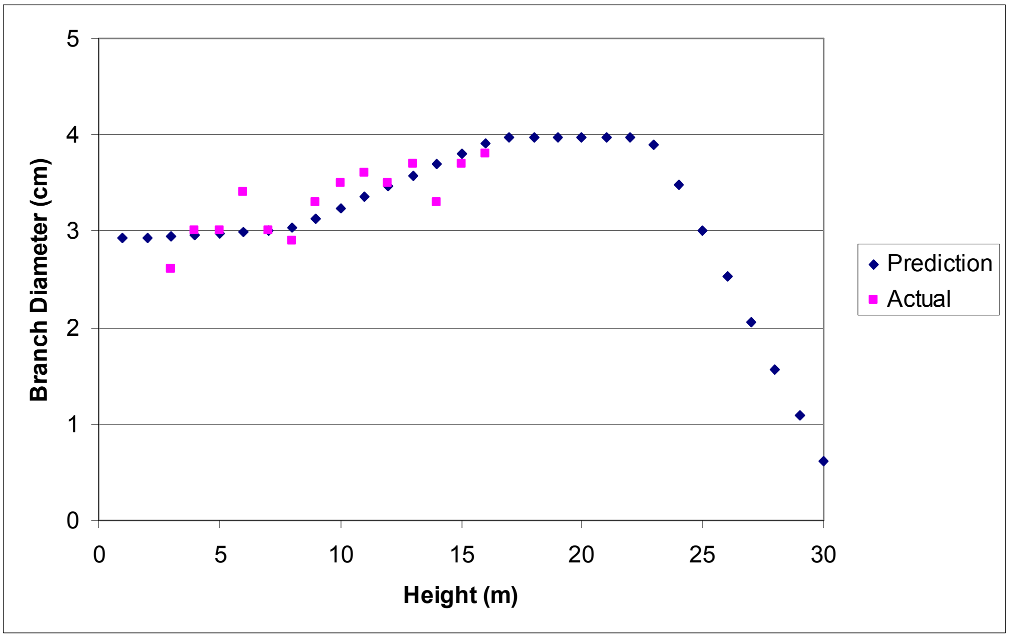

Fig. 18. Predicted versus actual mean largest branch per metre of stem for stand qtar7.

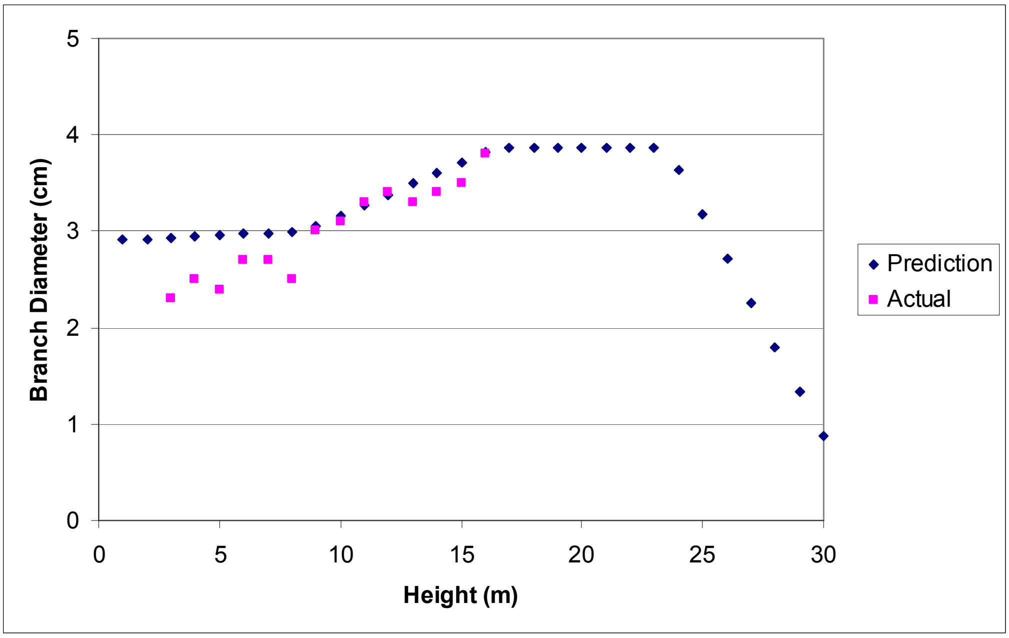

Fig. 19. Predicted versus actual mean largest branch per metre of stem for stand qtar8.

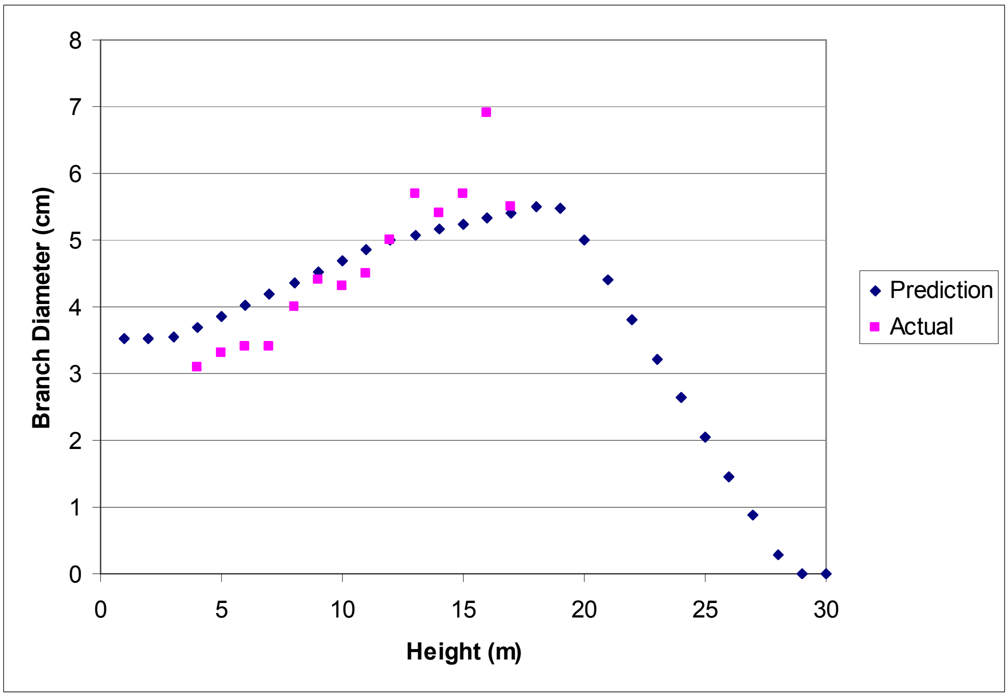

Fig. 20. Predicted versus actual mean largest branch per metre of stem for stand wh200.

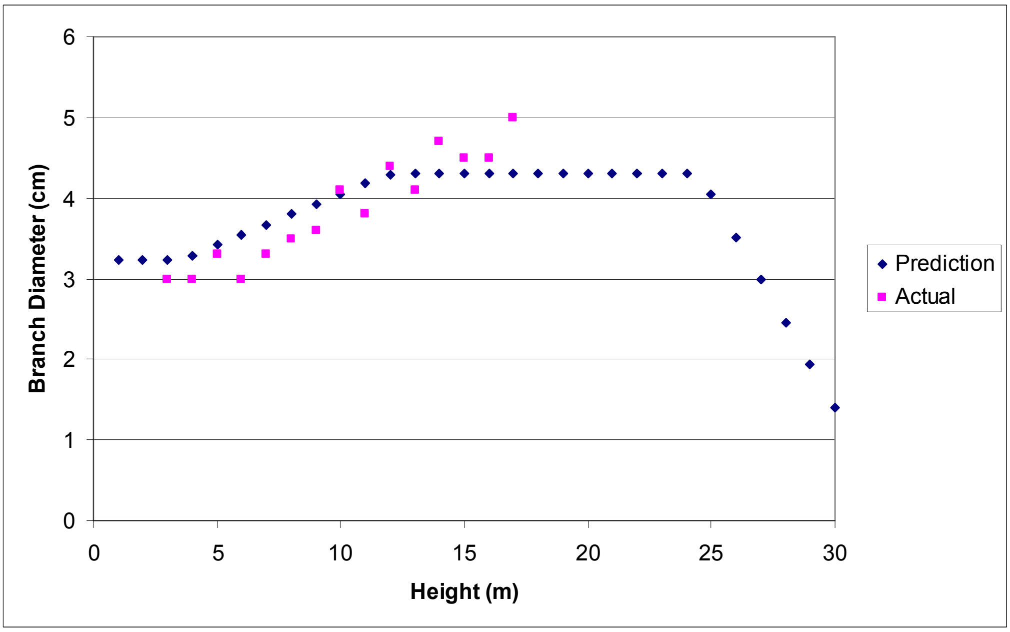

Fig. 21. Predicted versus actual mean largest branch per metre of stem for stand wh400.

Although the model performs well against the validation stands, more validation is required before the model can be used with complete confidence. This will require collection of new data as few late-thinned stands in the database other than those included in this report, are measured to a sufficient height to enable a comprehensive validation. Also, stand records for some of the historical data in the branch database are not sufficiently detailed to enable the model to be accurately applied. This validation of the model should concentrate on late-thinned stands. It would also be timely to confirm that the relationship between branch diameter and stocking, 300 Index and SI shown in Figs. 3-5 is accurate. This could be performed using existing data from the branch database.

As the model has been developed using historical data, it is also important to test it against newer genotypes to determine appropriate calibration factors for current breeds. As noted above, Shelbourne and Briscoe (1983) found little difference in branch size between a felling-select seedlot and an '850' seedlot. However, they reported that 2nd log branches in "268" series trees averaged 0.45 cm less than the "850" seedlot, suggesting that the adjustment against the "850" seedlot for this series might be about minus 15%. A long internode "870" seedlot had branches 0.6 cm larger than the "850" seedlot, and assuming poorer DBH growth for this seedlot, an adjustment of perhaps plus 20% would seem appropriate.

CONCLUSIONS

The Kimberley/Knowles model can be converted to predict final branch diameter in radiata pine as a function of stocking, 300 Index and Site Index in early-thinned or unthinned stands. By combining this model with a crown height model, the effects of late and/or multiple thinnings on final branch diameter can be predicted. This model has been tested against several late-thinned stands and generally appears to perform well. Ideally, it should be further validated so that it can be used with complete confidence.

REFERENCES

Beekhuis, J. 1965. Crown depth of radiata pine in relation to stand density and height. NZJForestry, 10(1), 43-61.

Cown D.J., Kimberley, M.O. and Whiteside, I.D. 1987. Conversion and timber grade recoveries from radiata pine logs. InKininmonth, J.A. (editor) Proceedings of the Conversion Planning Conference. Ministry of Forestry. FRI Bulletin pp147-161.

Hansen, L.W., Knowles, R.L, Kimberley, M.O. 2004. Functionality contained in the New Zealand Farm Forestry Association Radiata Pine Calculator Version 2. Forest & Farm Plantation Management Cooperative Report No. 91.

Inglis, C.S. and Cleland, M.R. 1982. Predicting final branch size in thinned radiata pine stands. NZ Forest Service, FRI Bulletin No. 3.

Grace, J.C., Blundell, W., Pont, D. 1998. Branch development in *Pinus radiata* - model outline and data collection. NZJFS 28(2), 182-194.

Kimberley, M.O. 2000. Dynamic branch modelling. Forest & Farm Plantation Management Cooperative. November 2000 Proceedings, 39-48.

Kimberley, M.O., Knowles, R.L. 1993. A model to predict branch index in radiata pine direct sawlog regimes. Forest & Farm Plantation Management Cooperative Report No. 1.

Kimberley, M.O., Knowles, R.L. 1996. Modelling branch size. Forest & Farm Plantation Management Cooperative. May 1996 Proceedings, 31-36.

Kimberley M.O., Barr, B., Knowles, R.L. 2000. Progress in modelling branch size including recent Tikitere data. Forest & Farm Plantation Management Cooperative. June 2000 Proceedings, 21-36.

Knowles, R.L. and Kimberley, M.O. 1993. The effects of site, stocking, and genetics on second log branching in Pinus radiata. NZFRI Project Record No. 3662.

Middlemiss, M., Knowles, R.L. 1994. Validation of the model to predict branch index in direct sawlog regimes. Forest & Farm Plantation Management Cooperative Report No. 4.

Shelborne, C.J.A, Briscoe, D. 1983. Gains from selection for branching characteristics in *P. radiata*. FRI Production Forestry Division Project Record No. 314.

Turner, J. 1998. Predicting green crown length in radiata pine. Forest & Farm Plantation Management Cooperative Report No. 51.