Volume functions for Douglas-fir

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NZ Douglas-fir Cooperative

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VOLUME FUNCTIONS FOR DOUGLAS-FIR

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ABSTRACT

This study describes and compares existing tree-level and stand-level volume functions for Douglas fir, and develops an improved stand level function for use within the Douglas-fir calculator and other decision support systems.

The tree level models T120, T136, T228, T273, T274, T275 and T428 are compared against a nationwide sample plot data set. In terms of volume prediction, T428 predicts the highest volumes, followed by T136. T274 predicts only slightly more volume than T273, with T275 following. These three functions are not significantly different from each other. T120 and T228 are not recommended for use as they are based on restricted data sets

Existing national stand-level volume functions were compared with the same models with new coefficients, and new functional forms. Coefficients were also fitted for the North Island, upper South Island, Canterbury and the lower South Island regions to investigate issues in using national models regionally.

New Formula 1 was selected as the best function in terms of the trade off between complexity and accuracy. The formula with its coefficients is:

$$V = \exp\left(-0.639 + 0.976\ln(BA) + 0.909\ln(MTH)\right)$$

Alternatively, this can be expressed as $V = 0.5278{*}BA^{0.976}{*}MTH^{0.909}$

Refitting this function to regional data sets gave an increase in accuracy especially at volumes above 1000 m^3/ha, and particularly for the upper South Island. A separate stand-level volume function for this region may not be necessary however, as this effect appears to be an artefact of the characteristics of the particular mix of sample plots available for analysis from this region.

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INTRODUCTION

With some 112,000ha, Douglas fir currently makes up six percent of New Zealand's exotic forest resource, making it the second most important species behind *Pinus radiata*. Commercial plantations of Douglas fir are located from Tokoroa south. The timber is predominantly used as a stiff and stable structural lumber (Cown, 1999).

The primary purpose for growing Douglas fir in New Zealand is to produce quality timber that provides a financial gain. Accurate estimation of the volume of wood in a stand allows for the valuation of the resource. The prediction of volume also assists in the planning and control of a resource for management purposes.

Tree-level volume functions are applied is situations where individual tree diameters and heights are available, for example within the permanent sample plot system, and within tree-level growth models. By aggregating volumes for all the trees in a plot or stand, volume per hectare can be obtained using these functions. These aggregated volumes can in turn be regressed against stand parameters such as basal area, mean top height, and stocking to obtain stand-level volume functions for application in stand-level models such as the calculator.

In an ancillary project, the data sets used to derive the existing tree-level volume functions will be pooled to develop a new '3P' tree level volume function which hopefully will be widely applicable to Douglas-fir throughout New Zealand, similar to the '3P' function already developed for radiata pine (Gordon and Budianto, 1999).

This study describes and compares existing tree-level and stand-level volume functions for Douglas fir, and develops an improved stand level function for use within the Douglas-fir calculator and other decision support systems.

The tree level models T120, T136, T228, T273, T274, T275 and T428 are compared against a nationwide sample plot data set. Existing national stand-level volume functions were compared with the same models with new coefficients, and new functional forms. Coefficients were also fitted for the North Island, upper South Island, Canterbury and the lower South Island regions to investigate issues in using national stand-level models regionally.

COMPARISON OF TREE-LEVEL VOLUME FUNCTIONS

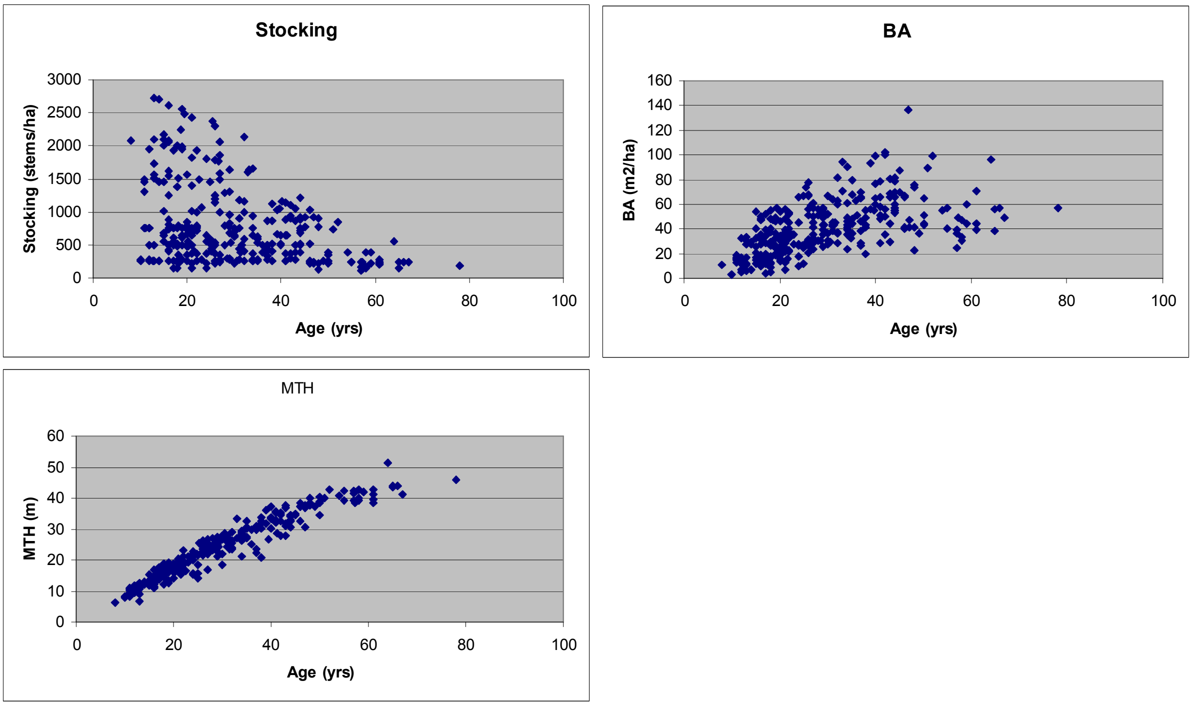
Permanent Sample Plots (PSPs, Dunlop 1995) were used as the basis for this part of the study. A random selection of measurements from 298 sample plots was used as the basis for comparison of the tree level functions. Comparisons using larger selections showed no advantage. For each sample plot measurement, the under-bark volume was estimated using all the available tree level volume/taper functions. A list of these functions, and the data sets they are based on, are shown in Table 1.

Table 1. Tree-level volume functions for Douglas-fir in New Zealand

	Thin/ Unthinned	Yr	No of trees	Min ht (m)	Max ht (m)	Min DBH (cm)	Max DBH (cm)	Mean vol (m^3)
T136 All NZ	T,U	1977	996	9	49	5	150	1.20
T120 Ashley	U	1973	207	9	23	8	30	0.28
T228 Longwoods	U	1986	89	14	31	11	61	0.71
T273 Nelson	T	1992	75	10.4	39.9	14	56	0.73
T274 Otago/Southland	T	1992	153	3.0	37.8	3	65	0.54
T275 Canterbury	T	1992	359	3.0	42.7	4	82	0.43
T438 Central North Is.	T	2002	128	15	45	14	81	1.45

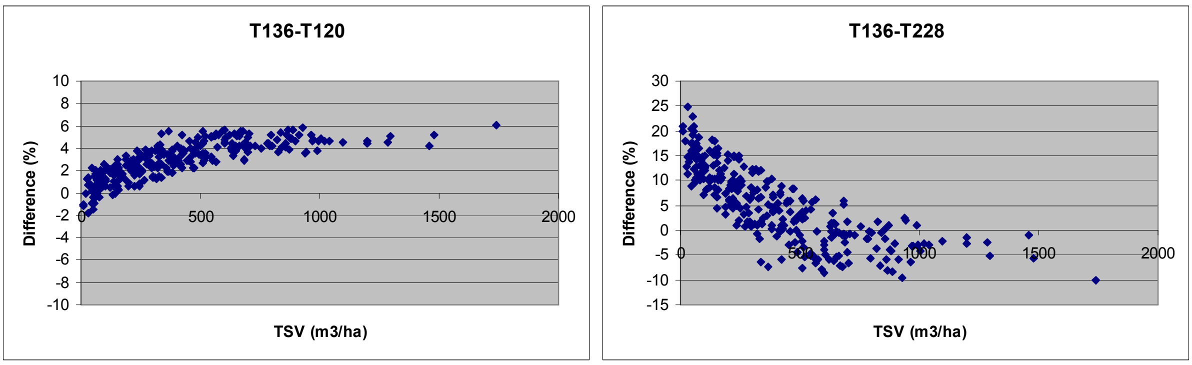
Tree level volume function 'T 136' was made in 1977 and is applicable New Zealand wide. The table is based on 996 trees and has a standard error of 8.9% (Dunlop, 1995). The function T120 is limited to trees from Ashley forest of less than 23m height and 30cm DBH, so has obvious limited applicability. Function T228 is based on a sample of trees from Longwoods forest of maximum height 31m. The other three functions T273, T274 and T275 were made for the regions Nelson, Southland and Canterbury respectively and are based on a sample set of 597 trees, which includes some of the data sets used in T120, T228, and T136 (Temu, 1992).

The characteristics of the random set of 296 sample plot measurements from throughout New Zealand are illustrated in Figs 1-3. These show that this data set covers a wide range of stockings, basal areas, and mean top heights.



Figs 1-3. The range of stockings, basal areas, and mean top heights in the sample plots used to compare the tree-level volume functions

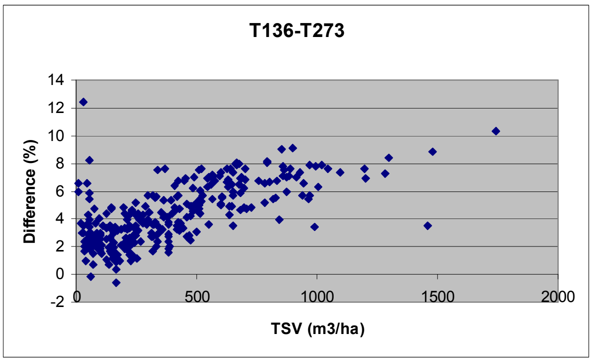
All the above functions were applied to this data set to obtain tree volumes, which were then aggregated as volume/hectare. To enable comparisons of these aggregated volumes, the volumes derived from each function were subtracted from the volumes derived from T136, and the differences expressed as a percentage of that predicted by T136. A negative value shows the selected function to be predicting a higher volume than T136, and a positive value shows prediction of a lower value. These results are illustrated in the following figures.

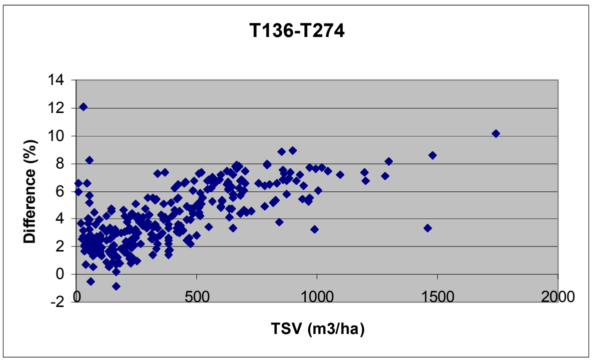


Figs 4-5. Difference in volume/ha predicted by T136 and T120 (left) and T136 and T228 (right).

T120 generally predicts up to 5% less volume than T136, with minimal differences at low volumes per hectare. T228 predicts substantially less volume at low volumes/ha, with similar predictions around 500-700 m^3/ha. Predictions for stand volumes above this are higher than

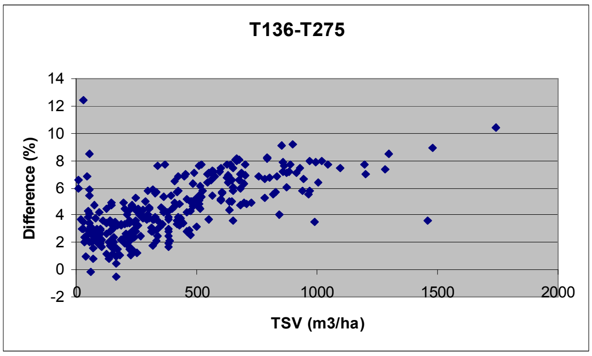
T136. Given that both these functions are based on data from just one forest, and other limitations, (see table 1) these functions should obviously only be used with caution.

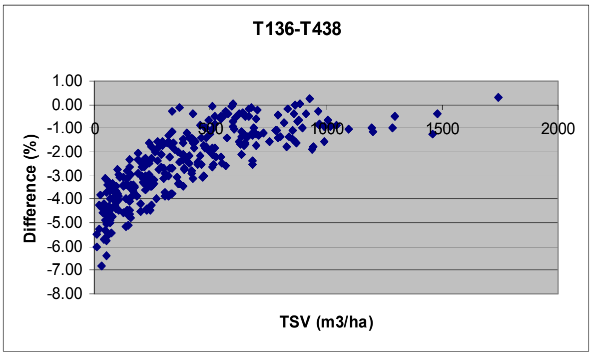




Figs 6-7. Differences between T136 and T273 (left) and T136 and T274 (right).

Both T273 and T274 predict less volume than T136, with the difference as a percentage increasing at higher volumes/ha. Both T273 and T274 seem to be behaving identically.





Figs 8-9. Difference between T136 and T275 (left) and T136 and T438 (right).

T275 predicts less volume than T136, and behaves similarly to T273 and T274. Comparisons of the predicted volumes by T273, T274 and T275 show only very small differences, with T273 intermediate between T274 which predicts the most and T275 which predicts the least. Differences between all three functions are of the order of ± 0.3% maximum, which is probably not significant at a practical level. T438 predicts more volume than T136, especially at low volumes per hectare. These differences are of the order of less than 1% at volumes above around 800m3/ha. Analysis shows that the differences are in proportion to MTH (see fig 9).

Given that no trees were included in T438 of less than 15m height, it can be seen that this function is predicting around 4% more volume at the lower end of its range, and is behaving similarly to T136 at mean top heights of around 45m

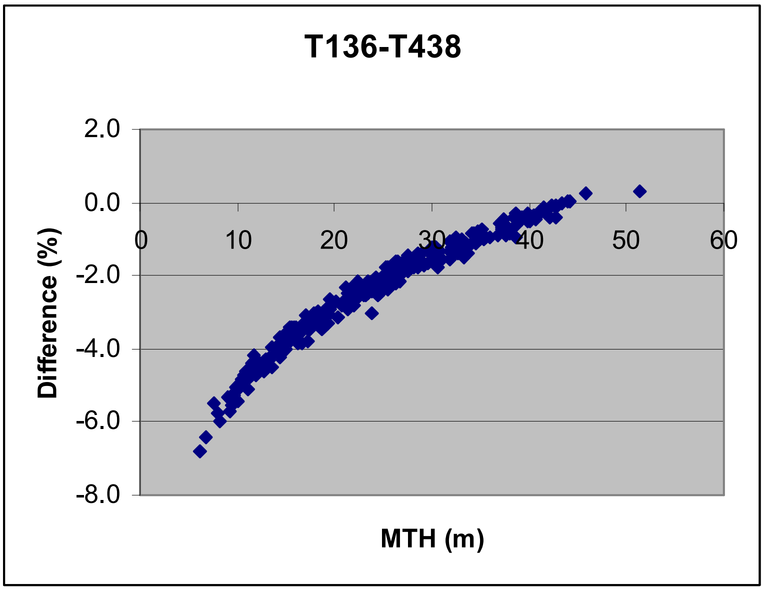


Fig 10. Difference between T136 and T228, plotted against mean top height.

In an ancillary project, the data sets used to derive the existing tree-level volume functions will be pooled to develop a new '3P' tree level volume function which hopefully will be widely applicable to Douglas-fir throughout New Zealand, similar to the '3P' function already developed for radiata pine (Gordon and Budianto, 1999).

STAND-LEVEL VOLUME FUNCTIONS

Introduction

The Beekhuis (1966) stand volume function was originally derived for radiate pine. It is simple but robust and has withstood the test of time. It can apply to a wide range of situations, including the volume prediction of other species (Maclaren, 2000). The Beekhuis stand volume model currently used in the Douglas fir calculator is as follows (Knowles, 2005):

$$V/B = 0.928 + 0.3208H$$

where	V	=	stand volume per hectare
	B	=	basal area per hectare
	H	=	mean top height
	0.928, 0.3208	=	coefficients

In 1986 the Stand Growth Modelling Co-operative identified the need for a growth model for Douglas fir in the South Island (SIDFIR), with work beginning in 1989. The data used in the construction of the model came from forests throughout the South Island (Law 1990). The SIDFIR stand volume function was similar to the Beekhuis function but the coefficients were revised and it had an extra parameter that took into account stocking (N). MTH and BA were also used. It was concluded that the SIDFIR model behaved logically and well for the range of data analysed (Law 1990).

The Douglas fir calculator V2 is a stand level modelling system, which has been constructed as a joint venture between the New Zealand Farm Forestry Association and the Douglas fir Cooperative. Where possible the calculator utilises functions that are appropriate for the whole country, rather than for one particular forest of region (Knowles *et al*., 2004).

This project aims to compare all existing available national stand-level volume functions for Douglas fir against the regional data sets, and a combined national data set. The data set has been produced from the Forest Research permanent sample plot (PSP) system. Improvements will be made to the existing functions by refitting the coefficients, and new functional forms will also be investigated.

The results of the comparison are presented as mean error and mean bias values between predicted and observed values. Mean error is estimated as the root mean square residual (RMSR) and bias is estimated as the mean actual deviation (MAD).

METHODS

Existing national functions

Volumes for some 1500 sample plots from throughout NZ were estimated using the selected regional tree-level volume functions, and placed into a file together with the stand-level parameters of basal area, mean top height (MTH) and stocking. Volumes produced by this method are referred to throughout the report as 'observed' volume. The data set was split into a 'model' data set (approximately 1000 sample plots) and a 'validation' data set (approximately 500 sample plots).

Several existing national volume functions were investigated in order to compare their prediction of stand volume for Douglas fir. These functions are shown below:

$$V = BA(a + bMTH) \qquad \text{(Beekhuis)}$$

$$V = BA\left(a + bMTH + cN\frac{MTH}{BA}\right) \qquad \text{(S36)}$$

$$V = BA\left(a + bMTH + c\frac{MTH}{\sqrt{N}} + dN\frac{MTH}{BA}\right) \qquad \text{(NZ1)}$$

Where V is predicted volume,
MTH is plot mean top height,
N is stocking (stems/ha),
And BA is plot basal area (m^2/ha)

The Beekhuis equation was originally developed by Beekhuis (1966) and was used nationally for radiata pine (*Pinus radiata* D. Don.). The second model, called 'S36" is currently in use for Douglas fir New Zealand wide (Katz *et al*., 1984, Law 1990). The third model has previously been used for radiata pine New Zealand wide under the name 'NZ1' or 'S38' (Law and Knowles, 1994). The coefficients for these three existing models are shown in Appendix 1.

Volumes were estimated using each function against the model data set. The residuals (difference between observed and predicted values) were used to calculate the root mean square residual (RMSR) and mean actual deviation (MAD) values. The RMSR values were converted into mean % error values by dividing them by mean observed volume. Similarly MAD values were also converted into mean % bias values by dividing them by mean observed volume.

Each model was primarily assessed on the amount of error that was produced. Mean bias was also taken into consideration because it illustrated how significantly the model was under or over predicting. The whole data set was assessed for overall fit, then placed into 500 m^3/ha volume classes to investigate the error and bias of each class.

The models were analysed nationally, then the data was split into four regions based on the tree level function that had been used to calculate the observed volume. The regions were then analysed in exactly the same manner. These regions were:

- North Island (Tree level volume function '136')
- Upper South Island (Tree level volume function '273')
- Canterbury (Tree level volume function '275')
- Lower South Island (Tree level volume function '274')

The validation data set was used to confirm the results from the model data set, with the same analysis as described above being carried out on each function.

Refitted existing national functions

The existing national functions had their coefficients refitted. This process involved minimising the sum of the residuals squared for each function, using the 'Solver' function in EXCEL®. Each model was then analysed against the whole data set and for the 500m^3/ha volume classes, nationally and regionally. Each function was ranked on mean error, and mean bias. These results were then substantiated by the validation data set.

New functional forms

Four new formulas have been developed in order to predict stand volume for Douglas fir. These formulas are very similar with each consecutive model retaining the parameters of the previous but being slightly more complex. The coefficients for these functions were generated in SAS® and can be viewed in Appendix 1. The four new formulas are shown below:

$$V = \exp\left(a + b\ln(BA) + c\ln(MTH)\right) \qquad \text{(New Formula 1)}$$

$$V = \exp\left(a + b\ln(BA) + c\ln(MTH) + d\ln(N)\right) \qquad \text{(New Formula 2)}$$

$$V = \exp\begin{pmatrix} a + b\ln(BA) + c\ln(MTH) + d\ln(N) + e\ln(BA)^2 \\ + f\ln(MTH)^2 + g\ln(N)^2 \end{pmatrix} \qquad \text{(New Formula 3)}$$

$$V = \exp\begin{pmatrix} a + b\ln(BA) + c\ln(MTH) + d\ln(N) + e\ln(BA)^2 \\ + f\ln(MTH)^2 + g\ln(N)^2 + h\ln(BA)\ln(MTH) \end{pmatrix} \qquad \text{(New Formula 4)}$$

Each new formula was evaluated over the whole data set and for the 500m^3/ha volume classes, nationally and regionally, following the same process as described above. The results were then verified by the validation data set. New formula 1 is of the same form as used by Temu (1992) to predict stand volumes.

Regionally refitted coefficients

The function that bests fitted the trade off between accuracy and complexity was chosen to have its coefficients regionally refitted, using the 'Solver' function in EXCEL®. Analysis of the mean error and mean bias for each region was then completed following the same procedure as described above.

RESULTS

Existing national coefficients

Model data

a) Beekhuis

The line in figure 10 demonstrates where the predicted values coincide perfectly with the observed values. The majority of the predicted values are above this line at higher volumes illustrating that the Beekhuis function, with its current coefficients, is showing bias at volumes above 1500m^3/ha. This observation is confirmed in Table 3 with significant bias being recorded for volume classes above 1500m^3. The existing Beekhuis model at currently used in the calculator predicts volume with little bias at volumes of less than 1500m^3/ha (Table 3).

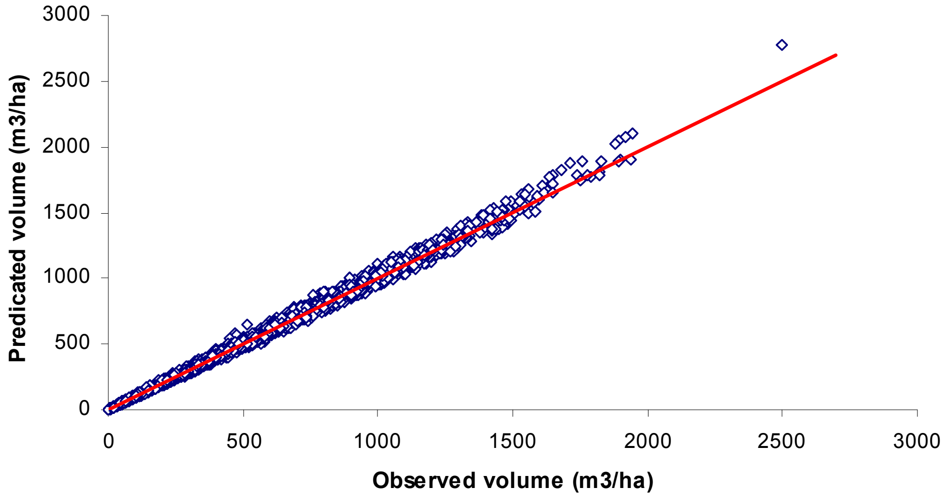


Figure 11: Observed vs. predicted volume values for the national (model) data set using the Beekhuis volume function with existing coefficients.

b) S36

Figure 12 shows that the S36 function is over predicting, with the majority of values above the 1:1 line. This bias is clearly visible at higher volume levels. Table 3 clearly shows that this model shows overall bias and that the level of bias increases with volume/ha.

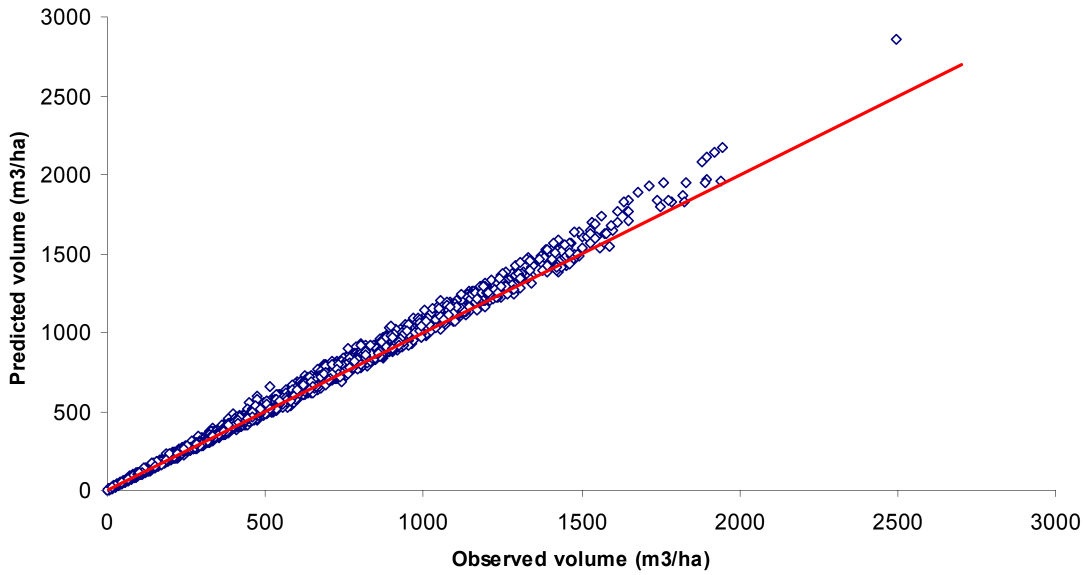


Figure 12: Observed vs. predicted volume values for the national (model) data set using the S36 volume function with existing coefficients.

c) NZ1

The NZ1 function under-predicts volume and again the error is more pronounced at higher volumes/ha (Figure 13). This trend is illustrated in Table 3 with bias apparent in all volume classes.

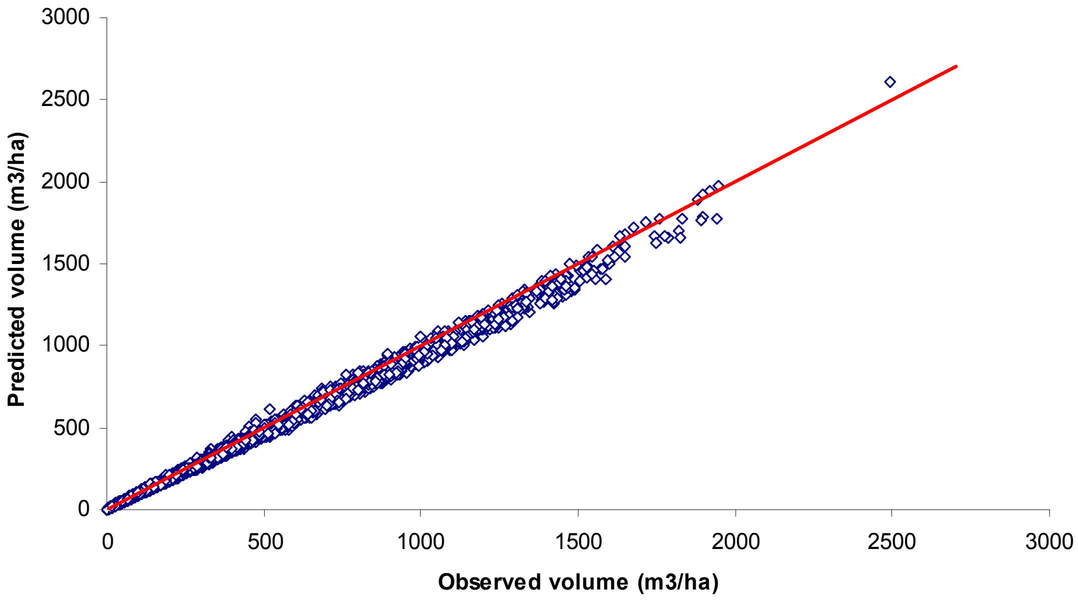


Figure 13: Observed vs. predicted volume values for the national (model) data set using the NZ1 volume function with existing coefficients.

The values for the mean error give an indication of the fit of each function providing an estimate of the accuracy with which the model will predict volume. The value is calculated by dividing the root mean square residual by the average observed volume (398 m^3/ha). The Beekhuis function has the lowest value showing that nationally, it can predict volume with greater accuracy in comparison to the other two functions (Table 2). It should be noted that the coefficients used in this formula have been revised recently (Knowles, 2005).

The mean bias is also a useful test. Negative values signify over-prediction and positive values signify under prediction. Table 2 demonstrates that nationally, the Beekhuis function over predicts by a very small amount (-0.4%). The other two models have much larger mean bias evident.

Table 2: Mean error (fit) and mean bias percentages for the national (model) data set using each of the existing functions.

Function	Mean error (fit) (%)	Mean bias (%)
Beekhuis	4.8	-0.4
S36	6.8	-3.4
NZ1	8.6	6.1

Table 3 clearly shows that large amounts of bias exist in all three functions when predicting volumes over 1500m³/ha. The Beekhuis model predicts volume with little bias up to 1500 m³/ha.

Table 3: Mean bias in 500m³/ha intervals for the national (model) data set using each of the existing functions.

Volume (m3/ha)	Mean bias (%)		
	Beekhuis	S36	NZ1
0-500	-0.1	-1.6	3.6
501-1000	-0.8	-6.2	10.2
1001-1500	-1.7	-10.9	17.0
1501+	-13.3	-26.9	14.5

Validation data

The mean errors of each function calculated from the validation data set are very similar to mean errors from the model data set (Table 4). This indicates that the calculated accuracy of each function is probably correct.

Table 4: Mean error for the national (validation) data set using each of the existing functions.

Function	Mean error (fit) (%)	
	Model	Validation
Beekhuis	4.7	4.7
S36	6.7	6.7
NZ1	8.5	8.7

The mean bias values calculated from the validation data set are also consistent with those from the model data set (Table 5). The Beekhuis function only slightly over predicts volume while the S36 function over predicts more severely. The NZ1 function has the greatest average deviation, under-predicting by six percent.

Table 5: Mean bias values for the national (validation) data set using each of the existing functions.

Function	Mean bias (%)	
	Model	Validation
Beekhuis	-0.4	-0.2
S36	-3.3	-3.2
NZ1	6.0	6.2

Table 6 confirms the findings from Table 3. Using the validation data set, the Beekhuis model has little error up to 1500 m^3/ha with bias increasing for all functions above 1500 m^3/ha.

Table 6: The mean bias in 500m^3/ha intervals for the national (validation) data set using each of the existing functions.

Volume (m3/ha)	Mean bias (%)		
	Beekhuis	S36	NZ1
0-500	0.0	-1.5	3.7
501-1000	0.0	-5.2	10.8
1001-1500	-3.6	-13.1	15.2
1501+	-10.6	-25.4	17.7

Regional effects of existing national functions

Model data

The data was split into four regions based on the tree level volume functions that were used to calculate the observed volumes. The regions are as follows:

- North Island (Tree level volume function '136')
- Upper South Island (Tree level volume function '273')
- Canterbury (Tree level volume function '275')
- Lower South Island (Tree level volume function '274')

Figure 14 shows that for the Beekhuis model applied to the North Island data, residuals are relatively unbiased, showing that the model predicts volumes with reasonable accuracy in this region. This is confirmed by a mean error of 4.1 percent and a mean bias of 1.5 percent from Table 7 and 8 respectively. The remaining three regions were over predicted by the Beekhuis model (Appendix 2).

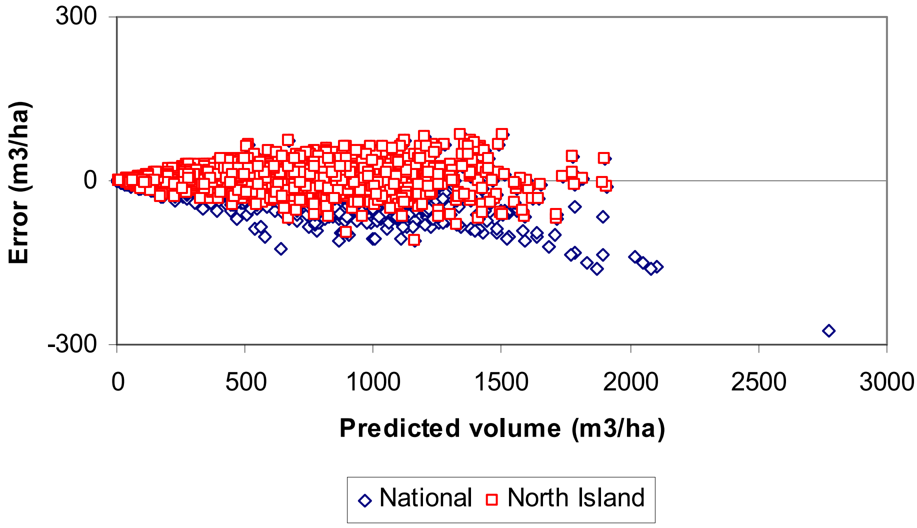


Figure 14: The residuals from the North Island region compared to the national residuals. The residuals are based on volume prediction using the Beekhuis function with its existing coefficients. Figure 15 demonstrates that the S36 function with its original coefficients is over predicting both nationally and for the North Island region. This trend can be observed for all regions (Appendix 2).

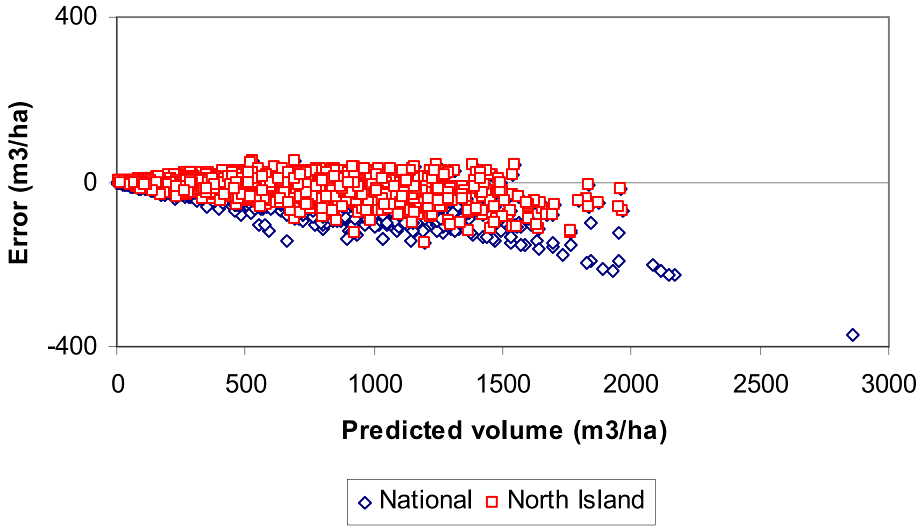


Figure 15: The residuals from the North Island region compared to the national residuals. The residuals are based on volume prediction using the S36 function with its existing coefficients.

The residuals produced by the NZ1 model show considerable bias with the model under predicting (Figure 16). The national and North Island residuals both give clear evidence of this. Appendix 2 reveals this trend is consistent throughout all the regions.

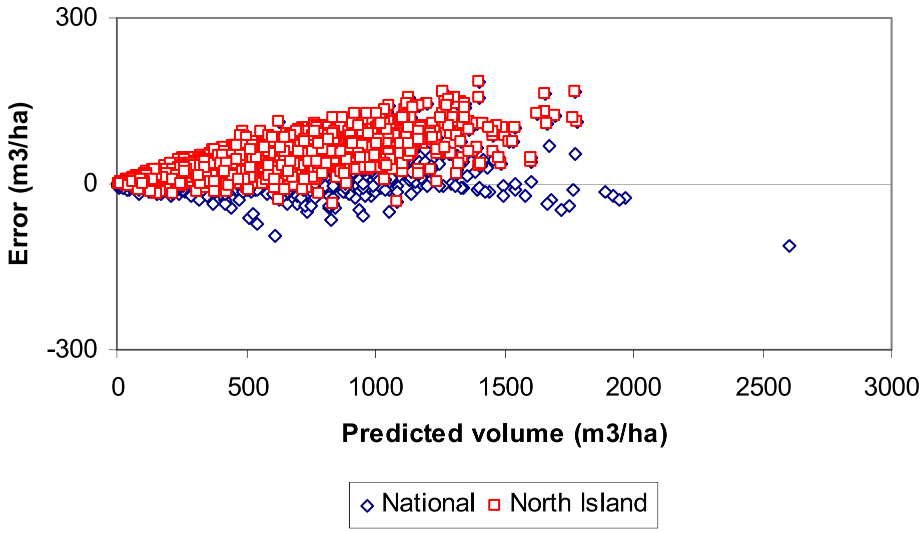


Figure 16: The residuals from the North Island region compared to the national residuals. The residuals are based on volume prediction using the NZ1 function with its existing coefficients.

Table 7 illustrates the mean error for the three functions in each region. The Beekhuis function has the lowest mean error value in the North Island and the lower South Island. However, the NZ1 function is more accurate in the upper South Island and Canterbury.

Table 7: The mean error value for each region within the national (model) data set for each function.

Region	Mean error (fit) (%)		
	Beekhuis	S36	NZ1
North Island	4.1	4.5	10.8
Upper South Island	6.3	10.0	5.0
Canterbury	4.6	7.2	4.3
Lower South Island	4.9	7.9	5.1

Table 8 shows that the upper South Island has a comparatively larger mean bias value compared to the other three regions using the Beekhuis function. The Beekhuis function has the lowest mean bias value for every region except the upper South Island.

Table 8: The mean bias value for each region within the national (model) data set for each function.

Region	Mean bias (%)		
	Beekhuis	S36	NZ1
North Island	1.5	-1.7	8.4
Upper South Island	-3.5	-6.7	3.2
Canterbury	-1.9	-3.9	3.0
Lower South Island	-2.3	-4.8	3.6

Appendix 3 illustrates the mean error and mean bias for each region in 500 m^3/ha classes for each function. It is clearly shown that the Beekhuis model has a good fit and little bias in the North Island at all volume levels. The S36 and NZ1 models have a reasonably good fit at low volumes (<500 m^3/ha) across all regions. The NZ1 function has a good fit and only a small percentage of bias in the upper and lower South Island regions across all volume classes.

Validation data

Table 9 illustrates that the Beekhuis model predicts stand volume most accurately in the North Island and lower South Island regions while the NZ1 model has the lowest RMSR in the upper South Island and Canterbury regions. These finding are consistent with those from the model data set (Table 7).

Table 9: The mean error values for each region for the validation data set. Volume is predicted using the original functions.

Region	Mean error (fit) (%)		
	Beekhuis	S36	NZ1
North Island	4.1	5.0	10.6
Upper South Island	5.5	8.9	5.1
Canterbury	6.8	9.7	5.1
Lower South Island	3.4	6.0	5.3

The Beekhuis model has the lowest mean bias for each region. The upper South Island has relatively high mean bias for each function (Table 10). These results are similar to those calculated from the model data set in Table 8.

Table 10: The mean bias values for each region for the validation data set. Volume is predicted using the original functions.

Region	Mean bias (%)		
	Beekhuis	S36	NZ1
North Island	1.3	-2.0	8.3
Upper South Island	-3.0	-5.9	3.2
Canterbury	-2.1	-4.2	2.9
Lower South Island	-1.7	-4.0	3.9

Appendix 4 shows the mean error and mean bias for the validation data set in each region in 500 m^3/ha classes for each function. It confirms that the Beekhuis function is accurate at predicting stand volume in the North Island and has very similar results as shown for the model data set in appendix 3.

Effects of the refitted national functions and new functional forms

Model data

In this section, revised coefficients were fitted to each of the three functions used to date, and four additional functions are introduced — New Formula 1 (2 variables, 3 coefficients), New Formula 2 (3 variables, 4 coefficients), New Formula 3 (3 variables, 7 coefficients) and New Formula 4 (three variables, 8 coefficients). The coefficients of these new functions, along with the three refitted functions from the previous section, were fitted using the 'Solver' function in EXCEL®.

The S36 function with refitted coefficients has an approximately even spread of data on either side of the 1:1 line (Figure 17). A similar result is reflected in the other six refitted functions.

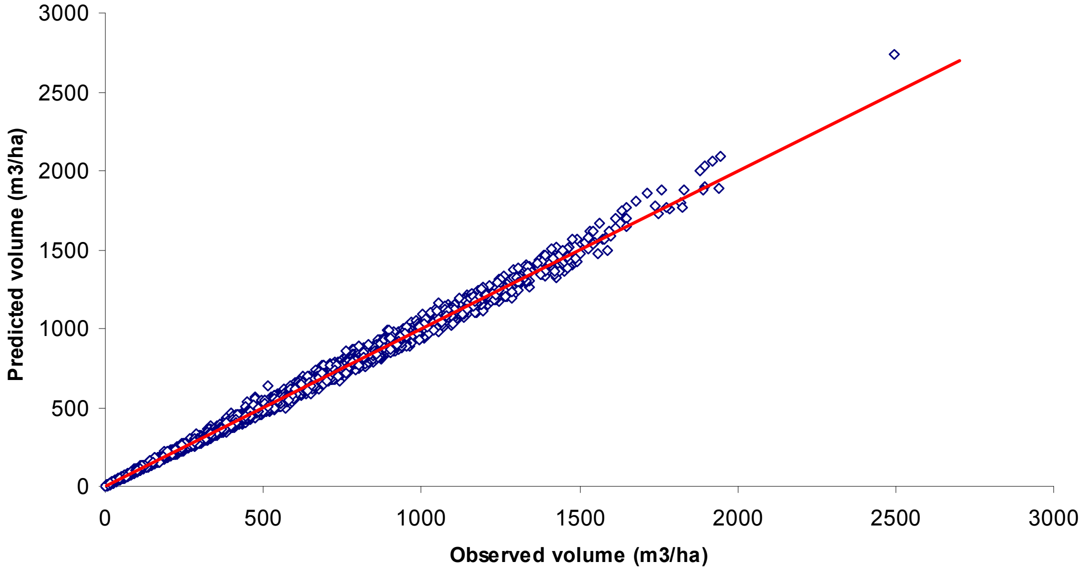


Figure 17: Observed vs. predicted volume values for the national (model) data set using the S36 volume function with revised coefficients.

The mean error of the seven functions ranged from 4.7 to 4.5 percent (Table 11), with the new formulas having the lowest values. The refitted coefficients resulted in a significant decrease in the mean error for the S36 and NZ1 functions. The mean bias values were at or very close to zero for all of the functions (Table 11). This means that on average these functions are not showing any clear bias.

Table 11: The mean error and mean bias values for the national (model) data set for each function. Volume is predicted using the refitted coefficients and the new formulas.

Function	Mean error (%)	Mean bias (%)
Beekhuis	4.7	0.24
S36	4.7	0.24
NZ1	4.6	0.07
New Formula 1 (3 coefficients)	4.5	0.00
New Formula 2 (4 coefficients)	4.5	0.00
New Formula 3 (7 coefficients)	4.5	0.00
New Formula 4 (8 coefficients)	4.5	0.03

Appendix 5 details the mean error and mean bias for the model data set for 500 m^3/ha classes for each function. It is clear that both the refitted models and the new formulas predict volume with less accuracy at higher volume levels (>1000 m^3/ha). However, the new formulas are clearly more accurate and have less bias at high volume levels. There are a relatively small number of PSPs for analysis containing more than 1000 m³/ha.

Validation data

The mean error for the seven functions ranged from 4.76 to 4.14 percent (Table 12). New Formula 4 (8 coefficients) was ranked first with the lowest mean error, followed consecutively by New Formula 3 and New Formula 1. The mean error for the NZ1 function was higher than both the Beekhuis and S36 functions. As with the model data the mean error of the new formulas was lower than the mean error of the Beekhuis, S36 and NZ1 functions. The mean bias ranged from 0.22 to 0.44 percent (Table 12). This indicates that there is no significant bias for any of the seven functions. These results are consistent with those from the model data.

Table 12: Mean error and mean bias values for the national (validation) data set for each function. Volume is predicted using the refitted coefficients and the new formulas.

Function	Mean error (%)	Mean bias (%)
Beekhuis	4.62	0.43
S36	4.62	0.44
NZ1	4.76	0.24
New Formula 1 (3 coefficients)	4.36	0.22
New Formula 2 (4 coefficients)	4.39	0.22
New Formula 3 (7 coefficients)	4.33	0.25
New Formula 4 (8 coefficients)	4.14	0.33

Appendix 6 details the mean error and mean bias for the validation data set for 500 m³/ha volume classes for each function. The trends are on the whole consistent with those from the model data set. The volumes for the 1001-1500 m³/ha volume class are less accurately predicted, with highest mean error values for all functions. That this may be a regional effect, contributed mainly by the Nelson data, is explored in the following section.

Regional effects of the refitted national functions and new functional forms

Model data

Regional mean error values from the new formulas were consistently lower than the original Beekhuis, S36 and NZ1 functions (Appendix 7). The North Island, Canterbury and lower South Island regions had mean error values lower than the national mean error. There was a significant increase in the mean error for the upper South Island region compared to the national value, illustrating that none of the national functions predict volume particularly well in this area.

Analysis of the mean bias revealed that over or under prediction patterns were consistent across all functions for each individual region (Appendix 7). The upper South Island region had larger mean bias values (approx. 3%) for each function compared to the other regions.

Figure 18 shows that in the North Island there is very little bias, with a trend towards slight under prediction. This is confirmed with a positive mean bias of 1.94 percent for the region. New Formula 4 predicted volume in this region with the greatest accuracy (mean error 4.45%), however the more simple new formula 1 comes very close with a mean error of 4.48%.

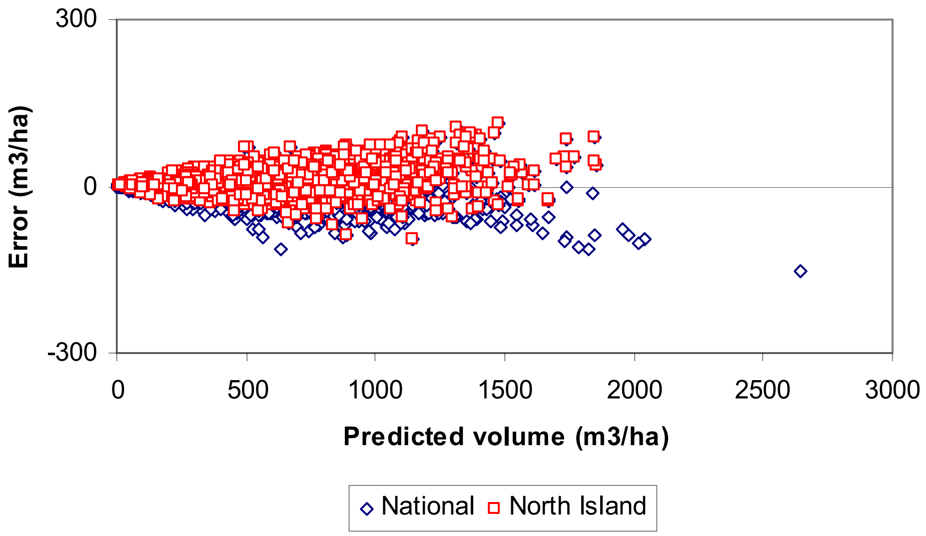


Figure 18: The residuals from the North Island compared to the national residuals for the national (model) data set. The residuals are based on volume prediction using New Formula 4.

The S36 function generated the lowest mean error in the upper South Island region (5.35%). Figure 19 shows that the residuals from the upper South Island region are predominantly on the negative side of the zero line. This illustrates that the national model is over predicting volume. The bias in this region can be observed for all the functions, despite the fact that T273 which applies to Nelson predicts almost identical aggregated stand level volumes at T274 and T275. Clearly the cause of bias is not the tree-level volume function used in Nelson. It must emanate from the particular characteristics of the mix of sample plots from Nelson used in the analysis.

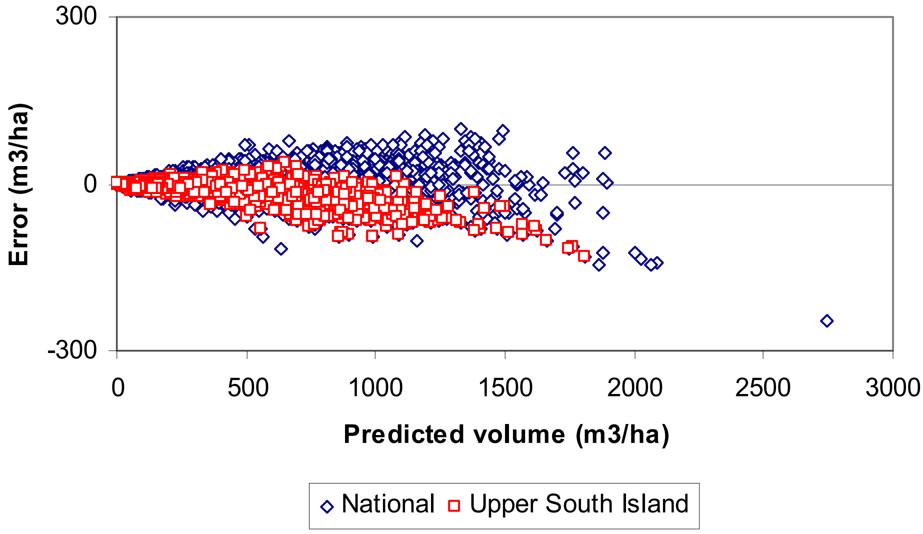


Figure 19: Residuals from the upper South Island region compared to the national residuals for the national (model) data set. The residuals are based on volume prediction using the refitted S36 function.

The Canterbury region is over predicted by each of the stand volume functions (Appendix 7). New Formula 4 was the most accurate function at predicting volume in this region (mean error 3.65%). Residual analysis in Figure 20 clearly illustrates that New Formula 4 over predicts volume in Canterbury, which is confirmed by a mean bias value of -1.5 percent.

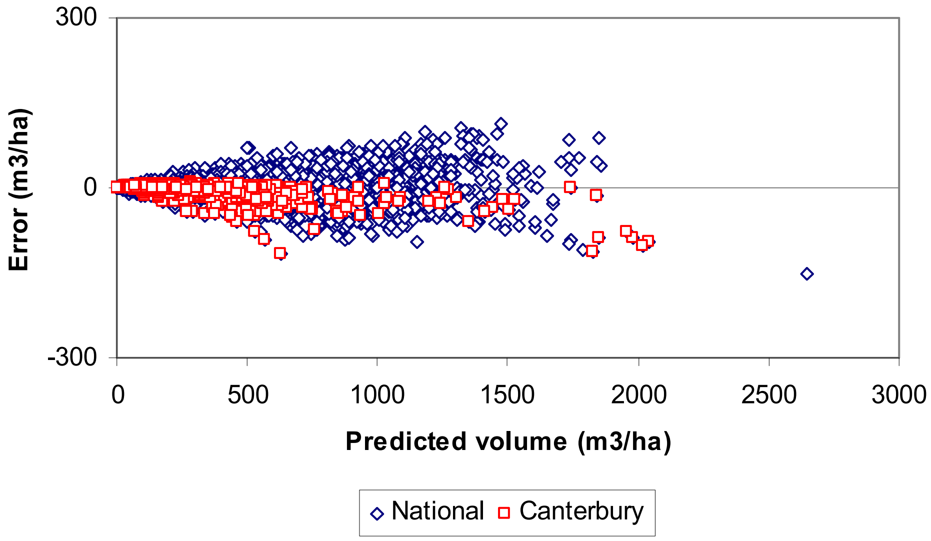


Figure 20: The residuals from the Canterbury region compared to the national residuals for the national (model) data set. The residuals are based on volume prediction using New Formula 4.

New Formula 4 is also the most accurate function at predicting stand volume in the lower South Island (mean error 3.75%). Figure 21 shows clearly that stand volume is over predicted in this region (mean bias -1.58%).

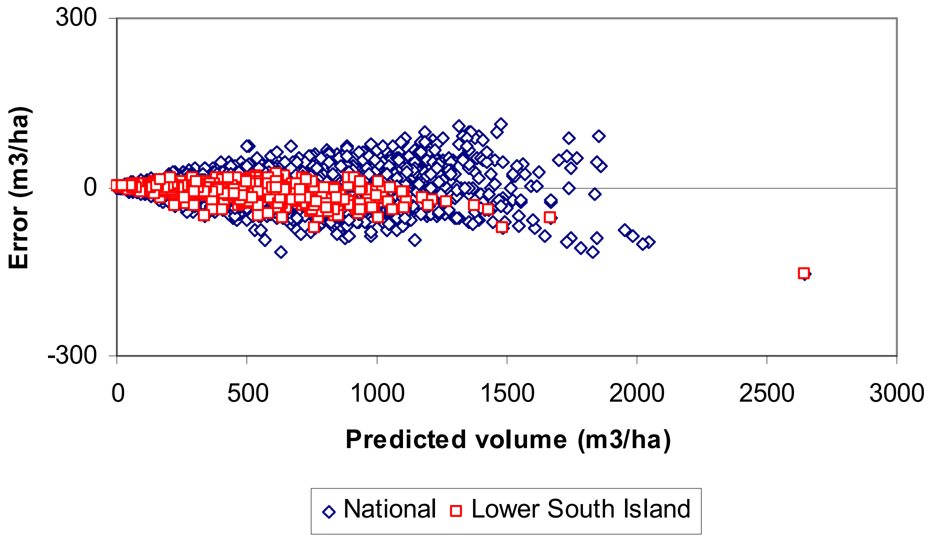


Figure 21: The residuals from the lower South Island region compared to the national residuals for the national (model) data set. The residuals are based on volume prediction using New Formula 4.

Appendix 8 details the mean error for each region in 500 m³/ha classes. It clearly shows that all functions are reasonably accurate at predicting volume below 500 m³/ha. Mean error values increases significantly at high volume levels in the southern regions. This could be attributed to the small sample sizes associated with these values. Mean error values are greater than five percent above 500 m³/ha in all regions for all of the functions. The new formulas are over-all the most accurate with consistently lower mean error values compared to the refitted functions.

The mean bias values for each region for 500 m³/ha classes are detailed in Appendix 9. It is clear that bias increases in all functions as volume level increase. The upper South Island and Canterbury regions have comparatively higher mean bias values between 500-1500 m³/ha.

Table 13 shows the top three functions for each region. The rankings are based on mean error values. The new formulas are overall more accurate with the exception of the upper South Island region. The full list of ranking is displayed in Appendix 10.

New formula 1 is ranked in the top three for all but one region. This function also has consistently low MAD values. When making a decision on which formula to choose for further analysis there is a trade off between complexity and accuracy. This formula is relatively simple compared to New Formula 4, and considering that the gain in accuracy between New Formula 1 and 4 is very small, New Formula 1 is an obvious choice for further analysis.

Table 13: Rankings for the three most accurate functions in terms of RMSR values for each region.

Region	Ranking		
	1st	2nd	3rd
North Island	New Formula 4	New Formula 1	New Formula 2
Upper South Island	S36	NZ1	New Formula 2
Canterbury	New Formula 4	New Formula 3	New Formula 1
Lower South Island	New Formula 4	New Formula 3	New Formula 1

Validation data

Regional mean error values from the new formulas were consistently low (Appendix 11). An exception was the upper South Island, which had comparatively high mean error (4.84-5.13%). These error values were consistent for both the validation and model data sets. The most accurate function in the upper South Island region was the NZ1 function. The North Island had similar mean error for both data sets and the Canterbury region had higher mean error for all functions compared to the model data set.

The mean bias values produced from the validation data set for each function revealed that over and under prediction patterns were consistent across all functions for each individual region (Appendix 11). The mean bias values in the upper and lower South Island regions decreased, compared to the values calculated from the model data set. The Canterbury region had slightly higher mean bias compared to those from the model data set.

Figure 22 illustrates that the upper South Island region is over predicted with the majority of residuals on the negative side of the zero line. The S36 function was the second most accurate model behind NZ1 (Appendix 11).

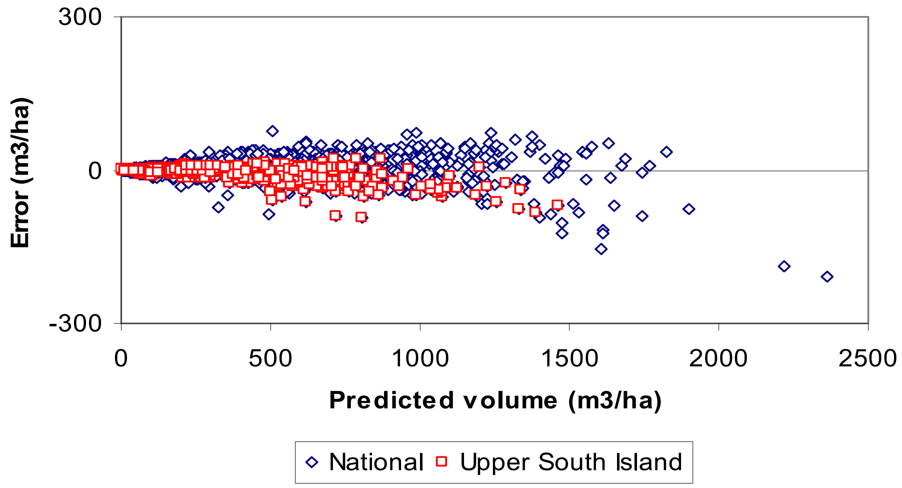


Figure 22: Residuals from the upper South Island region compared to the residuals for the national (validation) data set. The residuals are based on volume prediction using the S36 volume function.

The Canterbury region is over predicted by each of the stand volume functions (Appendix 11). New Formula 4 was the most accurate function at predicting volume in this region (mean error 3.77%). Residual analysis in Figure 23 illustrates the extent of over prediction in this region.

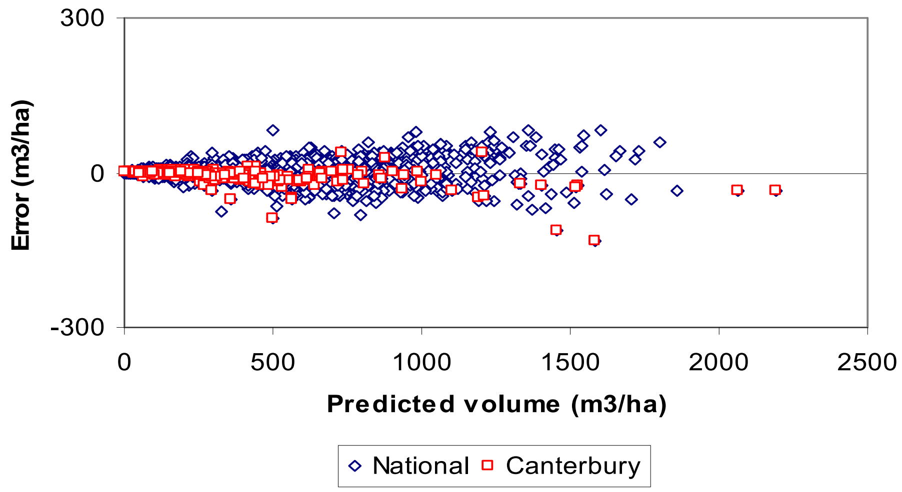


Figure 23: Residuals from the Canterbury region compared to the residuals for the national (validation) data set. The residuals are based on volume prediction using New Formula 4.

New Formula 4 is also the most accurate function at predicting stand volume in the lower South Island (mean error 2.84%). However New Formula 1 is close behind (mean error 2.97%). Figure 24 shows that stand volume is only slightly over predicted in the region, which is confirmed by a mean bias of only -1.1 percent for both these formulas.

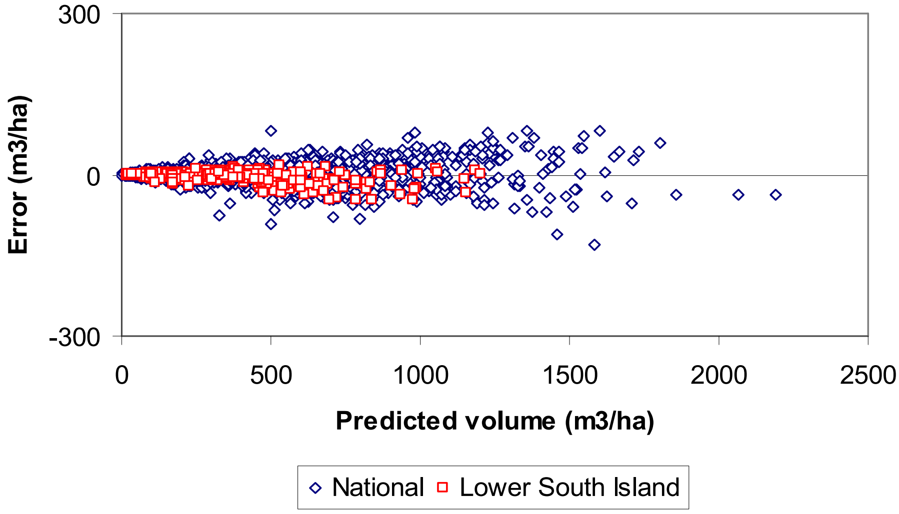


Figure 24: Residuals from the lower South Island region compared to the residuals for the national (validation) data set. The residuals are based on volume prediction using new formula 4.

Appendix 12 and 13 detail the mean error and mean bias for each region respectively. The validation data confirms that mean error values are greater than five percent for all of the southern regions, with the North Island values less at 4.6 percent for New Formula 4. The data also confirms that bias increases with the volume level across all regions. The Canterbury region had an unusually high mean error for volumes above 1000 m³/ha, explaining the exaggerated mean error for the 1000-1500 m³/ha volume class in Appendix 5.

Table 14 shows the top three functions for each region. Overall, the new formulas are more accurate than the refitted Beekhuis, S36 and NZ1, with the exception of the upper South Island region. The first and second ranked functions swapped position in relation to the model data set rankings for the North Island and upper South Island regions. The Beekhuis and S36 volume functions moved up in the ranking for the lower South Island. The full list of rankings is detailed in Appendix 14.

Table 14: Rankings of the most accurate functions in terms of mean error for each region, for the validation data set.

Region	Ranking		
	1st	2nd	3rd
North Island	New Formula 1	New Formula 4	New Formula 2
Upper South Island	NZ1	S36	New Formula 2
Canterbury	New Formula 4	New Formula 3	New Formula 1
Lower South Island	New Formula 4	Beekhuis	S36

Regionally refitted coefficients for New Formula 1

Model data

The coefficients of New Formula 1 were optimised for each individual region using the 'Solver' function in EXCEL®. Table 15 shows a reduction in mean error indicating that there are increases in accuracy across all regions with the introduction of refitted regional coefficients as against a single national model. The accuracy of predicting stand volume in the upper South Island region has increased significantly. The North Island mean error changed by the smallest amount, indicating that the national coefficients predict volume in this region reasonably well.

Table 15: Comparison of mean error for New Formula 1 between the national and regional refitted coefficients.

Region	Mean error (%)	
	Regional coefficients	National coefficients
North Island	3.62	4.48
Upper South Island	3.13	5.43
Canterbury	2.46	3.77
Lower South Island	2.39	3.9

The mean bias values for the regional refitted coefficients in Table 16 all have values that are very close to zero. These values represent an improvement on the mean bias produced by the national refitted coefficients, with the largest benefit evident against the Upper South Island data set.

Table 16: Comparison of mean bias for New Formula 1 between the national and regional refitted coefficients.

Region	Mean bias (%)	
	Regional coefficients	National coefficients
North Island	0.05	1.90
Upper South Island	-0.01	-3.12
Canterbury	-0.01	-1.54
Lower South Island	-0.13	-1.52

Figure 25 shows how accurately observed volume is being predicted in the upper South Island. This is a vast improvement on the national coefficients which were significantly over predicting stand volume in this region (Figure 25). The relationship below illustrates the trend for the other three regions.

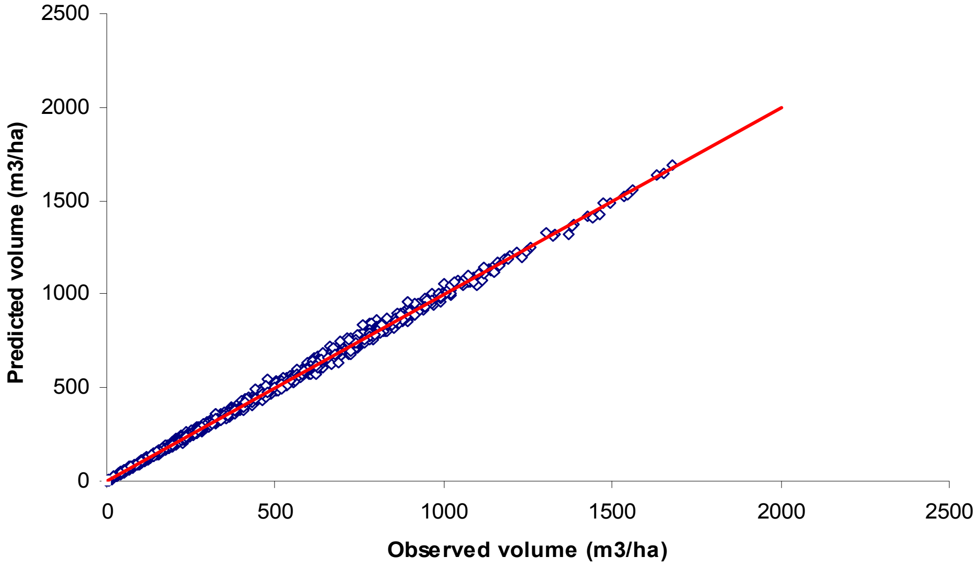


Figure 25: Observed vs. predicted volume for the upper South Island region, for the model data set. Predicted volume was calculated using New Formula 1 with regionally refitted coefficients.

Appendix 15 details the mean error and mean bias for each region for the 500 m³/ha classes. The North Island, upper and lower South Island have mean error values less than five percent up to 1000 m³/ha. The upper and lower South Island have low mean error through all volume levels. The Canterbury region has a mean error of 5.9 percent at the 501-1000 m³/ha volume level; the mean error for this region continues to increase as volume increases. There is very little bias in all regions and at all volume levels, with the exception of the Canterbury region at 1001-1500 m³/ha, which has a mean bias value of 6.2 percent. There are small sample sizes for all regions when volume is above 1500 m³/ha.

Validation data

The refitted regional coefficients in the New Formula 1 were tested against the validation data set. Table 17 illustrates that overall, the results remain the same as for the model data sets, with the upper and lower South Island and North Island regions have mean error values that are very similar for both data sets. The exception was the Canterbury region which had a slightly higher mean error value for the validation data set.

Table 17: Comparison of mean error for New Formula 1 between the model and validation data sets. Values are based on regionally refitted coefficients.

Region	Mean error (%)	
	Model data set	Validation data set
North Island	3.57	3.62
Upper South Island	3.08	3.17
Canterbury	2.43	2.77
Lower South Island	2.36	2.33

The mean bias values for the validation data set are slightly higher compared to the model data set for the North Island, upper South Island and Canterbury regions (Table 18). The validation data produced a mean bias value lower than the model data set for the lower South Island. The mean bias values from the validation data set are all less than ± 0.25%, indicating that there is no significant bias in any region.

Table 18: Comparison of mean bias for New Formula 1 between the model and validation data sets. Values are based on regionally refitted coefficients.

Region	Mean bias (%)	
	Model data set	Validation data set
North Island	0.05	-0.17
Upper South Island	-0.01	0.19
Canterbury	0.00	0.22
Lower South Island	-0.13	0.03

Appendix 16 details the mean error and mean bias for each region for 500 m^3/ha classes for the validation data. As with the model data the North Island, upper and lower South Island have mean error values less than five percent up to 1000 m^3/ha. The upper but not lower South Island has low mean error through all volume levels. The Canterbury region also had similar values to the model daevident in all regions at volume levels below 1000 m^3/ha. The Southern regions above 1000 m^3/ha have very small sample sizes, consequently mean bias and mean error values could be affected by just a few sample plots.

DISCUSSION

Current national functions

The Beekhuis volume function with its current coefficients is a simple formula that uses height and basal area to predict volume at the stand level. It does not incorporate stocking. The predictions by this function were reasonably accurate with a good fit and only a small amount of bias being present. The accuracy of the formula can be attributed to the recent refitting of the coefficients (Knowles, 2005). The precision of the function illustrates that it is sufficient as an interim national stand volume predictor. Analysing the model's accuracy for volume classes of 500 m^3/ha intervals revealed that the model produces significant amounts of error at volume levels above 1500 m^3/ha. At a practical level this trend may be irrelevant as few Douglas-fir stands have volumes over 1500 m^3/ha.

The S36 function has one more coefficient than the Beekhuis function, as it uses stocking in addition to height and basal area to predict stand volume. Even though the coefficients used in this function have been developed to predict stand volume for Douglas-fir, considerable bias in the form of over prediction was recorded at a national level. This confirms previous observations. This bias makes S36 with its current coefficients an unsuitable function for the national prediction of volume for Douglas-fir at the stand level, and indicates that there is a need for the refitting of the coefficients.

The NZ 1 function has one more coefficient than the S36 function making it slightly more complex. This model also uses stocking, height and basal area to predict volume at stand level. NZ 1 severely under predicted stand volume, demonstrating that with its current coefficients it is inappropriate for predicting stand volume for Douglas-fir.

The accuracy of each function was based on mean error. The Beekhuis function was considered the best of these current functions to predict stand volume at a national level. The S36 and NZ 1 models were ranked second and third respectively. Approximately 1000 sample plots from across the country were used to evaluate these formulas, providing confidence in the accuracy of the findings.

Some 500 additional sample plots were also used to validate the volume prediction trends of the Beekhuis, S36 and NZ 1 functions with their current coefficients. The findings were generally the same as for the model data set. The Beekhuis function was reasonably accurate while the S36 and NZ 1 functions had much more bias in their predictions.

Regional effects of current national functions

The data was split into four regions based on the tree level volume functions used to predict observed volume, North Island, upper South island, Canterbury and the lower South Island. Stand volume was predicted in each region by the three current national functions. The Beekhuis model predicted volume in the North island region with no significant bias. However, in the other three regions, the upper South Island, Canterbury and the lower South Island, this function over-predicted volume.

The S36 function over-predicted volume in all four regions continuing the national trend. The function was however reasonably accurate in the North Island region with only a small amounts of bias. The consistent bias across all regions illustrates that the coefficients for this model need refitting. The NZ 1 function also continued its national trend, under-predicting in all regions. This function was extremely inaccurate for the North Island, with the error in the South Island regions being much less severe. The trends identified for each function in each region were similar when tested against the validation data set.

A noticeable trend across all three functions was the inaccuracy in terms of mean error in the upper South Island region. This region produced large error values for volumes above 500 m^3/ha. The first part of this study shows that this is not due to the under-lying tree level volume function T273. It more likely arises as an artefact of the particular characteristics of the PSP data set for Nelson.

Refitted national coefficients

The coefficients were refitted for the current national functions, resulting in an increase in accuracy and a decrease in bias. The NZ 1 function had the best fit followed by the S36 and Beekhuis models respectively. These rankings were directly correlated to the complexity of the functions. NZ 1 is the most complex function with four coefficients followed by S36 with three and Beekhuis with two.

The difference in the accuracy of each model was very small. This illustrates that the basal area and height terms in the Beekhuis model provide an adequate means for predicting volume at the stand level. The inclusion of new parameters in the S36 and NZ 1 functions add only small amounts of accuracy.

The refitted coefficients for each function were used to predict volume for the validation data. The Beekhuis function was the most accurate followed by the S36 and NZ 1 functions respectively, reversing the rankings from the model data. The result reinforce that there is very little difference between the accuracy of these three functions. The validation results further illustrate how powerful the two parameters- basal area and height- are in terms of stand volume prediction.

Regional effects of refitted national coefficients

In the North Island the Beekhuis function with refitted coefficients decreased in accuracy compared to the current coefficients. This supports the conclusion that the original coefficients may have been tailored to predominantly North Island data. The accuracy of the Beekhuis model with refitted coefficients in all of the South Island regions increased compared to the current coefficients at the expense of a small reduction in accuracy in the North.

The bias in the southern regions for all functions was in the form of over prediction. The upper South Island region was the least accurate for each function. This follows the trend from the original coefficients.

Mean error increased significantly in all regions for each function at volumes greater than 500 m^3/ha. There was also at least a small amount of bias across all of the regions for each function, indicating that there is always going to be a certain level of bias in each region, if a national function is used to predict stand volume.

Results from the validation data confirm most of the regional observations, with the exception of the Canterbury region. The accuracy of the Canterbury region for each refitted model was significantly reduced. This could simply be a combination of outliers and a small sample size.

Improved functional forms

The new formulas generally predicted stand volume with more accuracy and consistently less bias than the refitted Beekhuis, DF NAT and NZ 1 functions. The new formulas especially had a better fit and bias at high volume levels. Nationally these formulas had extremely small mean bias values. Accuracy was directly related to the complexity of the formulas. The most complex, New Formula 4 had the smallest error, however the increase in accuracy from New Formula 1 to 4 was very small. Testing the same functions against the validation data generally confirmed these results.

Regional effects of improved functional forms

The new formulas followed similar regional trends as the refitted Beekhuis, DF NAT and NZ 1 models, under-predicting the North Island and over-predicting the southern regions. The difference was that these new formulas were slightly more accurate and slightly less biased. The new formulas also had highest error in the upper South Island region.

The validation data confirmed the trends from the model data. The exception was a decrease in accuracy in the Canterbury region and as previously stated this could be due to the small number of sample plots used.

The mean error values of the new formulas were higher at volume levels above 1000 m^3/ha. This trend has been consistent through both the current and refitted models and the new formulas, suggesting that coefficients may need to be refitted regionally to reduce error at higher volumes.

Regionally refitted coefficients for New Formula 1

New Formula 1 was chosen for further analysis because it had a good overall national and regional fit with very little bias, and was not overly complex. Coefficients were refitted for New Formula 1 for each region. This was done to improve the fit and remove the bias that occurred from predicting stand volume using a set of national coefficients. The result was an overall increase in accuracy and significant decreases in bias in all four regions, especially the upper South Island. The error in the 1001-1500 m^3/ha volume level was reduced for all regions compared to the national coefficients.

The new coefficients for the North Island were generated from a very large data set giving the results credibility. The other three sets of coefficients were produced from much smaller data sets casting a little more doubt on their accuracy. However when the coefficients were tested against the validation data set very similar results were generated.

The error in the 1001-1500 m^3/ha volume class for the validation data was much higher than the model data in Canterbury and the lower South Island. However the validation sample size for each of these regions was small, putting less confidence in these results.

LIMITATIONS

- Trends observed from regional effects, especially the southern regions, were produced from small samples. The validation sample sizes for these regions were even smaller. This has resulted in less confidence being placed in the results for these regions.

- The stand-level analysis will need to be repeated once the new tree level volume function ‘3P’ project is completed.

CONCLUSIONS

Significant bias was confirmed in the S36 model, suggesting that it is not suitable as a national stand volume function with existing coefficients in the Douglas-fir calculator. The Beekhuis interim model is more suitable as a national stand volume predictor in the calculator.

The refitting of the existing coefficients increased the accuracy of the Beekhuis, S36 and NZ1 models when applied nationally. However, there was still considerable error and bias in the prediction of volumes above 1000 m^3/ha. This trend was also evident in the four new functional forms that were tested, but to a lesser extent.

New Formula 1 was considered the best function in terms of the trade off between complexity and accuracy. Consequently, it is recommended as the best option for a national function in the Douglas-fir calculator. New Formula 1 is relatively simple with only three coefficients, but consistently predicted volume with less error in comparison to the majority of functions analysed. This function however, still showed increasing error in predicted volumes above 1000 m^3/ha, and for application in the upper South Island region suggesting that regionally refitted coefficients may be an option.

Coefficients were refitted to each region for New Formula 1 resulting in an overall increase in accuracy and decrease in bias in all four regions, especially the upper South Island. The error in the 1001-1500 m^3/ha volume level was markedly reduced for all regions. The use of four regional formulas in the Douglas-fir calculator offers more accuracy but increases the intricacy of the system. It is recommended that New Formula 1, with its national coefficients, is used in the present calculator. The practicality of incorporating four regional functions into the calculator using New Formula 1 should also be assessed.

There was consistently significant error and bias in the upper South Island region when national functions were applied.. This seems unlikely to e due to the underlying tree-level volume function, and could be the result of older, more densely stocked stands being present in the mix of PSPs used in the analysis. It will be necessary to refit new stand-level formula 1 once the new '3P' tree-level volume function is available.

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APPENDICES

Appendix 1

Existing stand-level volume functions: national coefficients, national refitted coefficients, new functional forms and regionally refitted coefficients for New Formula 1.

Existing coefficients		
Function	**Coefficients**	
Beekhuis	**a**	0.928
	b	0.3208
DF NAT	**a**	0.8502
	b	0.33337
	c	4.73E-05
NZ1	**a**	0.5814
	b	0.30625
	c	0
	d	0.000324

Existing refitted coefficients		
Function	**Coefficients**	
Beekhuis	**a**	0.971434
	b	0.316786
DF NAT	**a**	1.065932
	b	0.315211
	c	-0.00014
NZ1	**a**	1.045469
	b	0.307508
	c	0.151785
	d	3.62E-05

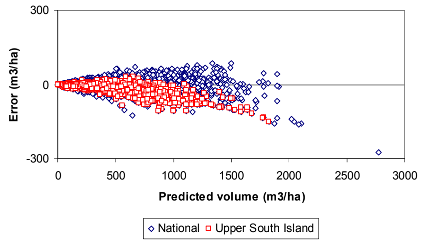
New functional forms		
Function	**Coefficients**	
New Form 1	a	-0.6388
	b	0.9758
	c	0.9092
New Form 2	a	-0.62308
	b	0.977855
	c	0.905634
	d	-0.00188
New Form 3	a	-0.7792
	b	1.009197
	c	0.845497
	d	0.0591
	e	-0.00397
	f	0.009045
	g	-0.00474
New Form 4	a	-1.27661
	b	1.110042
	c	0.794216
	d	0.171614
	e	0.015687
	f	0.06542
	g	-0.01316
	h	-0.07886

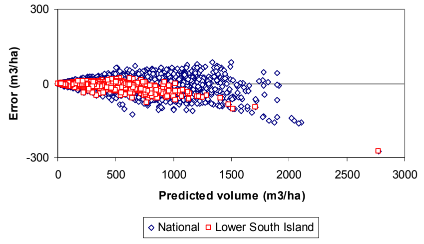
New Formula 1 (regional coefficients)		
North Island	a	-0.68688
	b	0.973756
	c	0.930887
Upper South Island	a	-0.55675
	b	0.981322
	c	0.86952
Lower South Island	a	-0.51635
	b	90.44826
	c	9.510429
Canterbury	a	-0.55352
	b	0.981041
	c	0.868736

Appendix 2

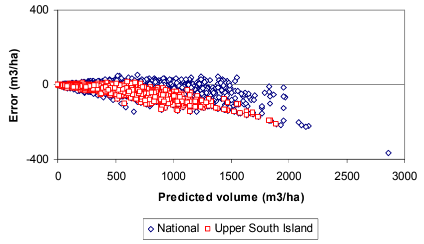
Appendix 2 illustrates the spread of the residuals of each region in relation to the entire national data set. This comparison is based on the predicted volume residuals from the Beekhuis, S36 and NZ1 functions using original coefficients.

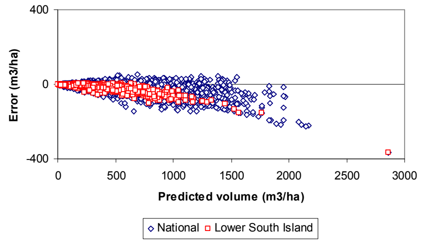
Beekhuis

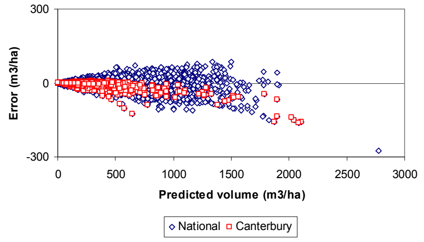




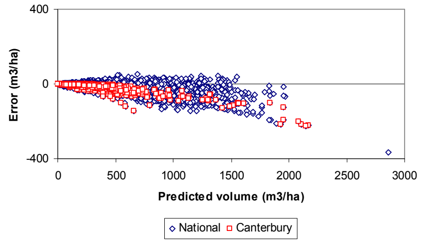
DF NAT





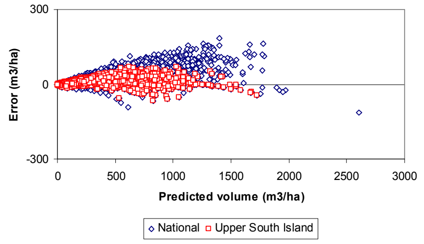


300
0
-300
Error (m3/ha)
0
500
1000
1500
2000
2500
3000
Predicted volume (m3/ha)
National
Canterbury

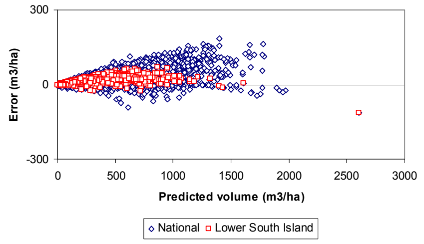


400
0
-400
Error (m3/ha)
0
500
1000
1500
2000
2500
3000
Predicted volume (m3/ha)
National
Canterbury

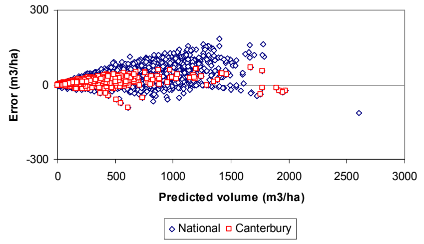
NZ1



300
0
-300
Error (m3/ha)
0
500
1000
1500
2000
2500
3000
Predicted volume (m3/ha)
National
Upper South Island



300
0
-300
Error (m3/ha)
0
500
1000
1500
2000
2500
3000
Predicted volume (m3/ha)
National
Lower South Island



300
0
-300
Error (m3/ha)
0
500
1000
1500
2000
2500
3000
Predicted volume (m3/ha)
National
Canterbury

Appendix 3

The mean error and mean bias for each of the existing functions, in each region, for the model data set, at 500 m³/ha volume intervals.

Region	Volume interval (m3/ha)	Mean error (fit) (%)		
		Beekhuis	DF NAT	NZ1
North Island	0-500	2.7	3.4	5.0
	501-1000	4.7	4.9	12.2
	1001-1500	6.9	7.4	16.7
	1501+	4.9	6.5	8.7
Upper South Island	0-500	2.5	3.9	3.6
	501-1000	8.3	13.1	6.5
	1001-1500	16.4	26.0	6.3
	1501+	37.1	54.3	8.5
Canterbury	0-500	3.6	5.5	5.2
	501-1000	10.2	16.5	10.1
	1001-1500	19.6	34.5	15.0
	1501+	52.7	76.4	15.8
Lower South Island	0-500	6.6	10.6	6.9
	501-1000	7.7	13.4	8.8
	1001-1500	17.1	28.7	8.6

Region	Volume interval (m3/ha)	Mean bias (%)		
		Beekhuis	DF NAT	NZ1
North Island	0-500	0.8	-0.5	4.2
	501-1000	2.3	-2.5	12.4
	1001-1500	2.3	-6.0	19.2
	1501+	-1.1	-12.8	23.6
Upper South Island	0-500	-1.2	-2.7	2.5
	501-1000	-6.4	-11.7	4.4
	1001-1500	-15.0	-24.6	3.1
	1501+	-29.9	-44.0	-5.8
Canterbury	0-500	-1.5	-3.4	3.7
	501-1000	-7.7	-14.7	7.8
	1001-1500	-16.8	-31.1	12.7
	1501+	-43.4	-64.8	1.1
Lower South Island	0-500	-3.6	-7.5	5.7
	501-1000	-5.7	-11.9	7.5
	1001-1500	-14.5	-25.6	6.2

Appendix 4

The mean error and mean bias for each of the existing functions, in each region, for the validation data set, at 500 m^3/ha volume intervals.

Region	Volume interval (m3/ha)	Mean error (fit) (%)		
		Beekhuis	DF NAT	NZ1
North Island	0-500	2.1	2.0	5.1
	501-1000	4.4	4.7	12.5
	1001-1500	8.0	11.3	19.1
	1501+	11.1	19.9	22.9
Upper South Island	0-500	2.7	4.2	3.7
	501-1000	7.6	12.3	7.5
	1001-1500	15.4	25.3	7.2
	1501+			
Canterbury	0-500	2.3	3.8	5.0
	501-1000	7.5	13.2	9.3
	1001-1500	10.4	22.8	17.5
Lower South Island	0-500	3.0	4.7	5.0
	501-1000	7.9	14.3	12.5
	1001-1500	39.7	55.6	17.3

Region	Volume interval (m3/ha)	Mean bias (%)		
		Beekhuis	DF NAT	NZ1
North Island	0-500	0.8	-0.6	4.1
	501-1000	2.1	-2.6	11.9
	1001-1500	0.9	-7.5	17.6
	1501+	-3.6	-15.5	19.4
Upper South Island	0-500	-1.2	-2.7	2.3
	501-1000	-5.6	-10.8	5.2
	1001-1500	-13.4	-23.0	4.8
Canterbury	0-500	-1.1	-2.9	3.7
	501-1000	-5.5	-12.7	10.4
	1001-1500	-30.6	-45.7	-1.4
Lower South Island	0-500	-1.1	-2.8	3.7
	501-1000	-5.5	-11.7	7.9
	1001-1500	-7.4	-18.1	13.9

Appendix 5

The mean error and mean bias for the refitted existing and new functions for the model data set at 500 m³/ha volume intervals.

Volume interval (m3/ha)	Mean error (%)						
	Beekhuis	DF NAT	NZ1	New formula 1	New formula 2	New formula 3	New formula 4
0-500	2.3	2.3	2.3	2.3	2.3	2.3	2.3
501-1000	6.5	6.5	6.4	6.3	6.3	6.3	6.2
1001-1500	10.5	10.5	10.7	10.6	10.6	10.4	10.4
1501+	21	20.9	20	17.2	17.1	17.3	16.9

Volume interval (m3/ha)	Mean bias (%)						
	Beekhuis	DF NAT	NZ1	New formula 1	New formula 2	New formula 3	New formula 4
0-500	0.2	0.2	-0.1	-0.1	-0.1	-0.1	-0.1
501-1000	0.5	0.5	0.4	-0.1	-0.1	-0.1	-0.2
1001-1500	0.8	0.8	1.5	3	3	2.9	3.1
1501+	-9.6	-9.8	-7.7	-2.5	-2.6	-2.2	-2.6

Appendix 6

The mean error and mean bias for the refitted existing and new functions for the validation data set at 500 m³/ha volume intervals.

Volume interval (m3/ha)	Mean error (%)						
	Beekhuis	DF NAT	NZ1	New formula 1	New formula 2	New formula 3	New formula 4
0-500	2.33	2.31	2.28	2.22	2.23	2.23	2.21
501-1000	5.72	5.72	5.55	5.49	5.5	5.53	5.44
1001-1500	40.09	40.25	42.45	38.45	38.75	37.88	35.85
1501+	19.64	19.69	23.87	16.41	16.86	15.21	11.43

Volume interval (m3/ha)	Mean bias (%)						
	Beekhuis	DF NAT	NZ1	New formula 1	New formula 2	New formula 3	New formula 4
0-500	0.3	0.3	0	0	0	0	0
501-1000	1.3	1.3	1.1	0.7	0.7	0.7	0.7
1001-1500	-1.1	-1	-0.5	1.2	1.2	1.4	2.1
1501+	-6.2	-6	-5.9	1	0.8	1.7	4.4

Appendix 7

The mean error and mean bias calculated from the model data set for each region. Volume is predicted using the refitted coefficients and the new formulas.

Region	Mean error (%)						
	Beekhuis	DF NAT	NZ1	New formula 1	New formula 2	New formula 3	New formula 4
North Island	4.61	4.66	4.59	4.48	4.49	4.49	4.45
Upper South Island	5.46	5.35	5.37	5.43	5.39	5.41	5.43
Canterbury	4.07	4.06	3.91	3.77	3.77	3.67	3.65
Lower South Island	4.26	4.24	4.34	3.90	3.91	3.87	3.72

Region	Mean bias (%)						
	Beekhuis	DF NAT	NZ1	New formula 1	New formula 2	New formula 3	New formula 4
North Island	2.26	2.26	2.07	1.90	1.89	1.89	1.94
Upper South Island	-2.77	-2.71	-2.87	-3.12	-3.10	-3.08	-3.07
Canterbury	-1.52	-1.61	-1.73	-1.55	-1.57	-1.58	-1.50
Lower South Island	-1.79	-1.84	-2.04	-1.52	-1.54	-1.53	-1.58

Appendix 8

The mean error and mean bias for each of the refitted existing and new functions, in each region, for the model data set, at 500 m³/ha volume intervals.

Region	Volume interval (m3/ha)	Mean error (fit) (%)						
		Beekhuis	DF NAT	NZ1	New formula 1	New formula 2	New formula 3	New formula 4
North Island	0-500	2.6	2.6	2.5	2.2	2.2	2.2	2.1
	501-1000	5.4	5.4	5.3	5.0	5.0	5.0	4.8
	1001-1500	7.7	7.8	8.1	8.5	8.5	8.4	8.5
	1501+	5.0	5.0	5.1	5.7	5.7	5.6	5.7
Upper South Island	0-500	2.2	2.2	2.3	2.7	2.7	2.6	2.8
	501-1000	7.2	7.0	6.9	7.4	7.3	7.4	7.4
	1001-1500	13.9	13.7	13.9	11.5	11.4	11.2	10.7
	1501+	32.3	31.5	30.6	24.1	23.7	25.5	26.2
Canterbury	0-500	3.3	3.2	3.4	3.7	3.7	3.7	3.6
	501-1000	8.8	8.8	8.8	9.2	9.2	9.1	8.8
	1001-1500	15.9	15.9	13.6	11.4	11.4	11.2	10.9
	1501+	46.6	47.0	42.0	33.0	33.2	30.9	32.1
Lower South Island	0-500	5.8	5.7	5.9	5.3	5.3	5.2	5.0
	501-1000	6.5	6.5	7.0	6.8	6.8	6.7	6.6
	1001-1500	14.2	13.7	12.6	11.4	11.2	10.9	9.7

Appendix 9

The mean error and mean bias for each of the refitted existing and new functions, in each region, for the validation data set, at 500 m³/ha volume intervals.

Region	Volume interval (m3/ha)	Mean bias (%)						
		Beekhuis	DF NAT	NZ1	New formula 1	New formula 2	New formula 3	New formula 4
North Island	0-500	1.1	1.1	0.8	0.7	0.7	0.7	0.8
	501-1000	3.6	3.6	3.4	2.9	2.9	2.9	2.8
	1001-1500	4.5	4.4	5.1	6.3	6.3	6.2	6.2
	1501+	1.9	1.5	3.4	7.6	7.3	7.9	7.4
Upper South Island	0-500	-0.8	-0.8	-1.1	-1.3	-1.3	-1.3	-1.3
	501-1000	-5.1	-5.0	-4.9	-5.5	-5.5	-5.5	-5.5
	1001-1500	-12.5	-12.2	-12.0	-10.0	-9.9	-9.8	-9.3
	1501+	-26.0	-25.4	-24.5	-19.3	-19.0	-20.5	-21.0
Canterbury	0-500	-1.2	-1.3	-1.6	-1.4	-1.4	-1.4	-1.3
	501-1000	-6.1	-6.2	-6.3	-6.7	-6.7	-6.7	-6.5
	1001-1500	-13.1	-13.1	-10.8	-8.7	-8.6	-8.3	-8.4
	1501+	-37.8	-38.1	-33.3	-25.1	-25.3	-22.8	-24.2
Lower South Island	0-500	-2.8	-2.9	-3.2	-2.4	-2.4	-2.4	-2.5
	501-1000	-4.2	-4.3	-4.6	-4.5	-4.5	-4.3	-4.3
	1001-1500	-11.7	-11.2	-9.9	-9.1	-8.9	-8.3	-7.1

Appendix 10

The ranking of each of the refitted existing and new functions for the national (model) data is based on mean error values for each region.

Region	Function						
	Beekhuis	DF NAT	NZ1	New formula 1	New formula 2	New formula 3	New formula 4
North Island	6th	7th	5th	2nd	3rd	4th	1st
Upper South Island	7th	1st	2nd	6th	3rd	4th	5th
Canterbury	7th	6th	5th	3rd	4th	2nd	1st
Lower South Island	6th	5th	7th	3rd	4th	2nd	1st

Appendix 11

The mean error and mean bias calculated from the validation data set. Volume is predicted using the refitted coefficients and the new formulas.

Region	Mean error (%)						
	Beekhuis	DF NAT	NZ1	New formula 1	New formula 2	New formula 3	New formula 4
North Island	4.49	4.54	4.42	4.28	4.31	4.34	4.29
Upper South Island	5.13	4.95	4.84	5.17	5.11	5.11	5.11
Canterbury	6.07	6.08	7.18	5.20	5.31	4.85	3.77
Lower South Island	2.94	2.92	3.06	2.97	2.99	2.96	2.84

Region	Mean bias (%)						
	Beekhuis	DF NAT	NZ1	New formula 1	New formula 2	New formula 3	New formula 4
North Island	2.05	2.05	1.85	1.74	1.74	1.75	1.79
Upper South Island	-2.30	-2.16	-2.23	-2.51	-2.47	-2.43	-2.44
Canterbury	-1.66	-1.76	-2.11	-1.77	-1.82	-1.69	-1.28
Lower South Island	-1.24	-1.29	-1.46	-1.14	-1.16	-1.16	-1.11

Appendix 12

The mean error and mean bias for each of the refitted existing functions and new formulas, in each region, for the model data set, at 500 m³/ha volume intervals.

Region	Volume interval (m3/ha)	Mean error (fit) (%)						
		Beekhuis	DF NAT	NZ1	New formula 1	New formula 2	New formula 3	New formula 4
North Island	0-500	2.3	2.3	2.1	1.9	1.9	2.0	2.0
	501-1000	5.1	5.2	4.9	4.6	4.6	4.7	4.6
	1001-1500	8.4	8.6	8.9	9.1	9.2	9.1	9.2
	1501+	10.3	10.5	10.9	11.5	11.6	11.7	11.3
Upper South Island	0-500	2.5	2.4	2.5	2.8	2.7	2.7	2.8
	501-1000	6.6	6.4	6.4	7.0	6.9	6.9	7.0
	1001-1500	13.0	12.6	11.3	10.8	10.6	10.6	10.1
	1501+							
Canterbury	0-500	2.7	2.7	2.9	3.2	3.2	3.2	3.1
	501-1000	6.7	6.8	7.5	7.4	7.5	7.6	6.8
	1001-1500	35.4	35.4	40.5	30.0	30.5	28.3	22.7
Lower South Island	0-500	2.2	2.2	2.4	2.2	2.2	2.1	2.0
	501-1000	6.3	6.3	6.6	6.7	6.7	6.7	6.4
	1001-1500	7.6	7.4	6.3	5.6	5.6	5.7	5.5

Appendix 13

The mean error and mean bias for each of the refitted existing functions and new formulas, in each region, for the validation data set, at 500 m³/ha volume intervals.

Region	Volume interval (m3/ha)	Mean bias (%)						
		Beekhuis	DF NAT	NZ1	New formula 1	New formula 2	New formula 3	New formula 4
North Island	0-500	1	1	0.8	0.6	0.6	0.6	0.7
	501-1000	3.3	3.3	3	2.7	2.7	2.7	2.6
	1001-1500	3.1	3.1	3.7	5.1	5.1	5	5.2
	1501+	-0.4	-0.2	1.4	5.2	5.2	5.2	5.6
Upper South Island	0-500	-0.9	-0.8	-1.1	-1.2	-1.2	-1.1	-1.2
	501-1000	-4.3	-4.1	-3.9	-4.7	-4.6	-4.6	-4.6
	1001-1500	-11	-10.6	-9.2	-8.7	-8.6	-8.3	-7.7
Canterbury	0-500	-0.8	-0.9	-1.2	-1.2	-1.3	-1.2	-1.1
	501-1000	-3.8	-3.9	-3.9	-3.9	-4	-3.8	-3.4
	1001-1500	-26.6	-26.6	-29.6	-21.6	-22	-20	-13.7
Lower South Island	0-500	-0.8	-0.8	-1.1	-0.6	-0.6	-0.6	-0.6
	501-1000	-4	-4.1	-4.2	-4.4	-4.4	-4.3	-4.1
	1001-1500	-4.7	-4.4	-2.7	-2.2	-2	-1.5	-0.9

Appendix 14

The ranking of each function for the national (validation) data is based on mean error values for each region. The rankings are based on the nationally refitted coefficients and the new formulas.

Region	Function						
	Beekhuis	DF NAT	NZ1	New formula 1	New formula 2	New formula 3	New formula 4
North Island	6th	7th	5th	1st	3rd	4th	2nd
Upper South Island	6th	2nd	1st	7th	3rd	4th	5th
Canterbury	5th	6th	7th	3rd	4th	2nd	1st
Lower South Island	2nd	3rd	7th	5th	6th	4th	1st

Appendix 15

The mean error and mean bias for regionally refitted New Formula 1, in each region, for the model data set, at 500 m^3/ha volume intervals.

Region	Volume interval (m3/ha)	Mean error (%)
North Island	0-500	1.7
	501-1000	4.2
	1001-1500	7.3
	1501+	8.9
Upper South Island	0-500	1.9
	501-1000	4.3
	1001-1500	5.1
	1501+	2.9
Canterbury	0-500	2.7
	501-1000	5.9
	1001-1500	8.6
	1500+	15.1
Lower South Island	0-500	3.2
	501-1000	4.2
	1001-1500	4.1

Region	Volume interval (m3/ha)	Mean bias (%)
North Island	0-500	0.1
	501-1000	-0.2
	1001-1500	0.9
	1501+	0.4
Upper South Island	0-500	-0.1
	501-1000	-0.1
	1001-1500	1.4
	1501+	0.3
Canterbury	0-500	-0.1
	501-1000	0.1
	1001-1500	6.2
	1500+	-3.3
Lower South Island	0-500	-0.2
	501-1000	0.6
	1001-1500	1.2

Appendix 16

The mean error and mean bias for regionally refitted New Formula 1, in each region, for the validation data set, at 500 m^3/ha volume intervals.

Region	Volume interval (m3/ha)	Mean error (%)
North Island	0-500	1.8
	501-1000	3.6
	1001-1500	7.7
	1501+	11.0
Upper South Island	0-500	2.1
	501-1000	4.8
	1001-1500	4.5
Canterbury	0-500	2.4
	501-1000	6.7
	1001-1500	13.6
Lower South Island	0-500	2.0
	501-1000	4.4
	1001-1500	9.3

Region	Volume interval (m3/ha)	Mean bias (%)
North Island	0-500	0.0
	501-1000	-0.3
	1001-1500	-0.5
	1501+	-3.1
Upper South Island	0-500	0.0
	501-1000	0.5
	1001-1500	1.4
Canterbury	0-500	0.1
	501-1000	3.1
	1001-1500	-2.6
Lower South Island	0-500	-0.2
	501-1000	0.5
	1001-1500	6.8