A new mortality function for New Zealand radiata pine

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EXECUTIVE SUMMARY

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A new mortality function based on Reineke's 'line of self-thinning' concept has been developed for New Zealand radiata pine. The model was derived using data from nearly 5,000 permanent sample plots from throughout New Zealand using more than 24,000 measurements increments made since 1970. Versions of the model were fitted for both total mortality, and mortality excluding windthrow. Reineke's 3/2 power rule is defined on a chart of ln (Stocking) versus ln (*DBH*), and the self-thinning line is assumed to be invariant with site. However, analysis of the data showed that the self-thinning line varies with site, with more productive sites able to carry higher stockings of trees of a given *DBH* compared to lower productivity sites. Mortality levels are therefore lower for stands of similar stocking and *DBH* on high 300 Index sites. There is a reverse relationship with *SI* with mortality levels higher on high *SI* sites for stands of the same 300 Index, *DBH* and stocking. There is also a trend for the self-thinning line to be slightly concave rather than straight as defined by Reineke's rule. An increase in mortality is apparent in the year immediately following a thinning, and this effect has also been incorporated into the model. The model can be used in radiata pine stands throughout New Zealand. However, there is some evidence that it over-predicts mortality slightly in the South Island and under-predicts in the North Island, and there are other regional variations in mortality. In the implementation of the model, the user will be able to enter a percentage adjustment to account for such differences.

INTRODUCTION

Models for predicting mortality in forest stands are important components of forest growth modelling systems. For New Zealand radiata pine, an interim mortality function developed for use with the 300 Index Growth Model was presented at the May 2006 meeting of the Plantation Management Cooperative (see the Meeting Proceedings). This model has since been further developed and refined and the completed model is described in this report.

Mortality in forest plantations can be categorised into three types:

- Attritional mortality – low-level mortality not due to rare catastrophic events in stands which are not at excessively high stockings.
- Catastrophic mortality – mortality occurring as a result of rare and catastrophic events such as major storms, fires, droughts, etc.
- Competition-induced mortality – this occurs in highly-stocked stands when competition becomes intense causing the smaller, less vigorous trees to die.

There is some debate as to whether mortality functions implemented in growth modelling systems should predict the effects of all three types of mortality. Arguably, it is better to handle catastrophic mortality independently of the growth model. For example, it could be assumed that there is a certain probability of a stand being destroyed or severely damaged as a result of a major storm event during a single rotation, and this risk could be factored into the cost benefit analysis when assessing the likely returns from the forest. However, for predicting the likely stocking at the end of a rotation for a given regime, which will in turn affect the mean stem size predicted by the growth model, it is probably better not to incorporate the effects of such catastrophic events. Mortality functions in growth models should therefore predict the effects of attritional and competition-induced mortality only.

However, it can be difficult to determine whether mortality measured in sample plots is catastrophic rather than attritional or competition-induced. For example, to eliminate catastrophic mortality, Oscar Garcia removed observations from his model dataset when there were more than two tree deaths during a growth increment (Goulding, pers. com.). However, when this criterion was applied to the New Zealand radiata pine data in this study, it was apparent that growth increments with more than two tree deaths, tended to be clustered around the 'self-thinning' boundary line and were clearly often caused by competition rather than being due to catastrophic events. Therefore, it was decided not to attempt to screen out plots on the basis of excessive mortality when developing the model described in this report.

The Permanent Sample Plot (PSP) database records trees that have succumbed to 'windthrow', generally from catastrophic events such as storms, or in some cases from edge effects due to the felling of neighbouring trees. Such windthrow mortality appears not to be clustered about the self-thinning boundary but to be more randomly distributed, and is therefore more likely to be representative of genuine catastrophic mortality rather than mortality induced by competition. It therefore seems appropriate to exclude this form of mortality from the modelling. For completeness, this report describes separate analyses and models for both total mortality, and mortality excluding windthrow.

The model which predicts mortality excluding windthrow is likely to be most appropriate for general use. However, it should again be emphasised that when this model is used, some additional allowance for catastrophic mortality should be made when making long-term predictions of yield. For example, a certain percentage of forest area could be assumed to be damaged to a greater or lesser extent by extreme events such as fires or storms, and allowance made for the corresponding loss in yield and value. Note that if the model developed using the total mortality data described in this report is used, this may tend to understate true levels of catastrophic mortality as it is likely that plots in seriously damaged or destroyed stands are often been abandoned without re-measurement.

Reineke (1933) noticed that in fully-stocked plots, a graph of ln(Stocking) against ln(*DBH*) typically has a straight line with slope approximating -3/2 (the 3/2 power rule). This result was found to hold generally for a wide range of forest species in North America. In order for this relationship to hold, there must be a rise in mortality when the mean diameter of a stand approaches this self-thinning boundary. Reineke also developed a Stand Density Index (*SDI*) which classifies stands in terms of their distance from this self-thinning line. Reineke believed that each species could attain a certain maximum *SDI*, which is largely invariant to site. As will be shown, a graph of ln(Stocking) versus ln(*DBH*) for New Zealand radiata pine, clearly shows the existence of a Reineke-type relationship. It was therefore considered desirable to incorporate this concept into the new mortality model.

This report describes the model and the methodology used to develop it. A mortality model using similar methodology has been developed for New Zealand Douglas-fir by the Douglas-fir Research Cooperative.

DATA

The data used in this analysis consisted of measurements from PSPs from throughout New Zealand. Only measurements made from 1970 were used to develop the model although some additional earlier data was used to examine historic trends. Plots with less than 40 stems/ha were excluded from the analysis as were data from young stands less than 10 years old, and increments assessed over measurement increment intervals of less than 0.8 years. Mortality, expressed as an annual percentage, was calculated for each growth increment using:

[1] $$M = 100 \times \left[1 - \left(N_1/N_0\right)^{1/\Delta T}\right]$$

where N_0 and N_1 are stocking in stems/ha at the beginning and end of the increment period, and ΔT (= T_1 - T_0) is the length of the increment in years. A total of 24,139 growth increments from 4,957 PSPs were used in the analysis. The mean increment length was 1.4 years.

MODELLING METHODOLOGY

A simple model of attritional mortality which assumes a constant annual mortality rate, *M*, unaffected by stand dynamics or environmental factors, can be represented by the following equation:

[2] $$N_1 = N_0\left(1 - M/100\right)^{\Delta T}$$

where N_0 and N_1 are stocking in stems/ha at the beginning and end of the increment period, and ΔT is the length of the increment in years. To incorporate the Reineke relationship into this mortality function, the mortality rate *M* must increase for stands near the self-thinning boundary. Various functional forms could be used to achieve this objective. The earlier version of the model presented at the May 2006 meeting, used a logistic function. However, better fits have since been achieved using the following power function which is also simpler in form:

$$M = 100 \times \left(a + b \times SDI^{c}\right) \quad [3]$$
$$\text{where} \quad SDI = N \times D^{d}$$

In the above function, M is percentage annual mortality, and SDI is a Stand Density Index similar to that defined by Reineke, in terms of the stocking, N (stems/ha), and the quadratic mean DBH, D (in metres). The model parameters are a, b, c and d and each have an interpretation: a is the minimum mortality rate and can be regarded as the attritional mortality (possibly including also a component from rare catastrophic events) in stands not subject to serious competition; b can be used to define the intercept of the self-thinning boundary line; c controls the rate at which mortality increases as a stand approaches the boundary; and d is the slope of the self thinning boundary (without the minus sign) which according to Reineke should have a value of about 3/2. Note that to enable a more general form of the relationship, the parameter d was estimated from the data rather than assumed to have a value of 3/2. To use the model for predicting a change in stocking, the mortality predicted by [3] is applied in Equation [2] to predict stocking N_1 from the previous stocking N_0 over a time step length ΔT.

When implemented, the model will not be invariant to step length. It is necessary to take account of this when fitting the model to the data. For example, if the model is to be implemented with a step length of one year, the correct procedure would be to fit the model using the above equation, with N and D as the stocking and diameter at the beginning of the increment, only if the great majority of increments in the data were of about one year. On the other hand, if the model is to be implemented with a very short step length (e.g., 1 month or less), the terms N and D in the above equation should be replaced by $(N_0 + N_1) / 2$ and $(D_0 + D_1) / 2$, respectively when fitting the equation to the data. As the 300 Index Growth Model is implemented with a short step length, this approach was adopted.

To estimate the parameters of the combined Models [2] and [3], it was desirable to take account of the distributional form of the chosen dependent variable N_1, the number of stems in a plot at the end of each increment period. This can be assumed to follow a binomial distribution with expected value $N_0\left(1 - M/100\right)^{\Delta T}$, where N_0 is the number of stems at the beginning of the increment, and M is as defined in Equation [3]. This model was fitted using the SAS (Version 9) Nonlinear Mixed Modelling procedure NLINMIX with an allowance for over-dispersion. This method of model fitting automatically adjusts for the effects of increment length, mean mortality level, and plot size on the residual variance. All models were compared using -2(log likelihood) as the goodness of fit criteria. Generally, the model with the smallest value of this statistic has the best fit.

Several variations of Model [3] were tested. Although Reineke used the ln(N) versus ln(D) graph to establish the self-thinning boundary, other authors have suggested that tree size parameters other than D may perform better. For example, Yoda et al. (1963) used mean plant biomass. Therefore, mean top height (MTH or H in metres), and D^2H (as a surrogate for biomass), were tested in place of D in Equation [3].

Reineke believed that the self-thinning boundary was invariant to site for each species. However, other researchers had suggested that the boundary moves to the right on more productive sites, which can carry a higher stocking of trees for a given mean diameter. Two measures of site productivity were tested for inclusion in the model, namely, Site Index (SI), and the 300 Index ($I300$). These were estimated for each plot used in the analysis using an automated routine programmed in VBA. They were incorporated into the SDI term in Equation [3], for example:

$$SDI = \exp\left(f \times I300 + g \times SI + \ln N + d \ln D\right)/1{,}000 \quad [4]$$

Note that in this model, the divisor of 1,000 is included for convenience to produce *SDI* values within the range 0 to 1.

Some authors have suggested that the self-thinning boundary is non-linear. To test this, an additional quadratic term (e.g., $(\ln D)^2$) was included in Model [4]. Also, tests of different rates of mortality in different regions of New Zealand were obtained by fitting the model to regional subsets of the data with all parameters other than *b* (or, in some cases, *a*) fixed to their national estimates. The estimates of *b* obtained for each region could be converted into 'multiplier' terms suitable for each region if these were considered necessary. A similar procedure was used to test for differences in mortality rates between measurement years.

RESULTS

The average annual mortality in the complete data set was just over 0.57% per annum (Table 1). When trees identified in the database as windthrown were excluded from the calculation, the mean mortality reduced to 0.36%. Total mortality, and especially mortality excluding windthrow, was lower in the South Island than the North Island. Windthow as a percentage of total mortality was much higher in the South Island than the North Island, except in Marlborough.

Table 1. Summary of data used to develop mortality function. Data is summarised using regional authority boundaries, except for North Island coastal sand forests which are treated as a separate 'region'.

Region	Number of plots	Number of increments	Mean total mortality (%)	Mean mortality excluding windthrow (%)	Windthrow as % of Total Mortality
Northland	367	1,777	0.38	0.30	12
Auckland	269	1,200	0.39	0.37	6
N.I. Coastal Sands	233	404	0.70	0.67	4
Bay of Plenty	1,610	9,781	0.68	0.47	31
Waikato	420	1,666	0.64	0.55	14
Gisborne	193	708	1.10	0.75	32
Taranaki	23	60	0.06	0.06	0
Hawkes Bay	312	1,154	0.38	0.14	63
Wairarapa/Manawatu	265	974	0.26	0.16	28
Wellington	124	543	0.55	0.33	40
North Island	3650	18,267	0.59	0.42	29
Nelson	406	1,919	0.37	0.12	68
Marlborough	173	842	0.59	0.42	29
West Coast	118	339	1.18	0.27	77
Canterbury	277	1,258	0.43	0.12	72
Otago	195	675	0.67	0.21	69
Southland	138	839	0.40	0.11	73
South Island	1307	5,872	0.50	0.18	64
New Zealand	4957	24,139	0.57	0.36	37

Annual mortality rates were calculated from the 24,000 growth increments using Equation [1]. The statistical distribution of this mortality rate was highly skewed with most growth periods showing little or no mortality, and a few showing considerable mortality (Fig. 1). About 85% of increments showed no mortality at all, and 88% showed no mortality apart from windthrow.

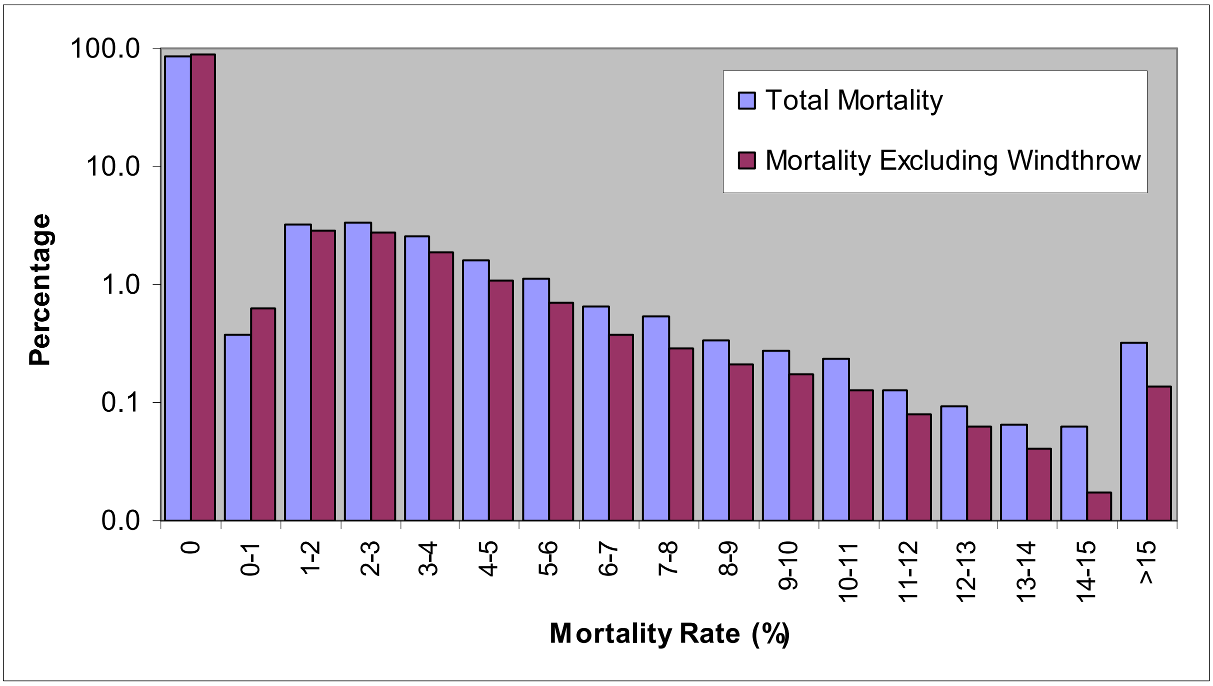

Fig. 1. Statistical distribution of mortality rate. Note that the scale is log transformed.

In Fig. 2, a plot of ln(Stocking) vs ln(*DBH*) is shown for the data with each point representing a measurement increment. Points are classified into three classes based on annual mortality. In this chart, the self-thinning boundary is clearly evident, and the mortality increases markedly when a stand approaches this boundary.

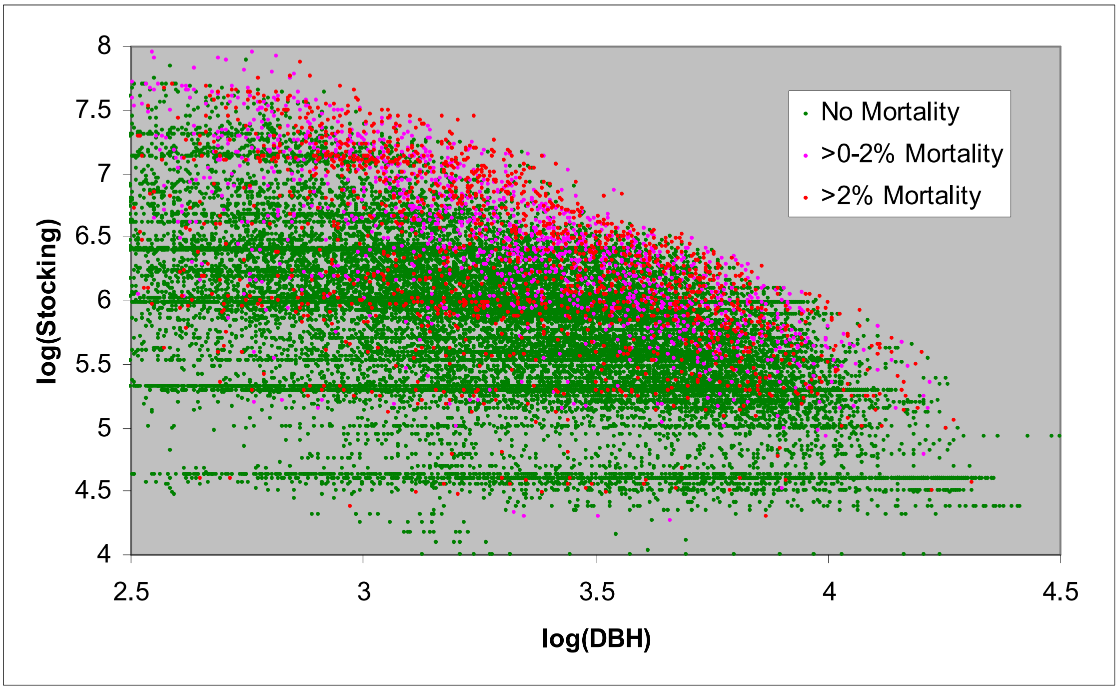

Fig. 2. Annual mortality rate plotted on the ln *N* versus ln *D* plane.

The performance of the various models tested is given in Table 2 using the -2(log likelihood) statistic. In general, the smaller this statistic, the better the model fit. In the models which did not include site productivity indices, lnD^2H was the best performing tree size variable, followed by ln$D$ and ln$H$. When the 300 Index was included in the model, there was a significant improvement in model performance demonstrating that the self-thinning boundary is not invariant with site. Site Index gave much less improvement in fit than the 300 Index, but there was considerable benefit in including both *SI* and the 300 Index in the model. When both site productivity indices were included in the model, ln$D$ was the best performing tree size variable. The relationship was improved when a quadratic term, (ln$D$)^2, was added to the model, indicating that the self-thinning boundary is slightly curved on the ln$N$ versus ln$D$ surface.

Table 2. Fit of various mortality models for predicting mortality excluding windthrow as indicated by -2(log likelihood) statistics. In general, the smaller the value, the better the fit.

	Productivity variables included in model			
Tree size variable	**None**	***300 Index***	***SI***	***300 Index & SI***
lnD	27,247	26,612	27,247	25,772
lnH	27,744	27,644	27,690	27,644
lnD^2H	27,076	26,673	27,045	26,503
$lnD + (lnD)^2$	27,136	26,359	27,133	25,624

Overall, the best model was therefore:

$$N_1 = N_0(1 - M/100)^{\Delta T}$$

[5] where $M = 100 \times (a + b \times SDI^c)$

and $SDI = \exp\left(f \times I300 + g \times SI + \ln(N) + d \times \ln(D) + h \times (\ln(D))^2\right)/1{,}000$

Parameter estimates for the model are given in Table 3, fitted separately for mortality excluding windthrow, and total mortality including windthrow. Note that D is expressed in metres in this formulation. Mortality contour threshold lines predicted by the model for sites of average 300 Index and *SI* are shown plotted against the mortality data in Fig. 3.

Table 3. Parameter estimates for Model [5].

Parameter	**Mortality excluding windthrow**		**Total mortality**	
	Estimate	**Standard error**	**Estimate**	**Standard error**
a	0.000459	0.000051	0.00216	0.00010
b	0.974	0.179	0.937	0.181
c	3.06	0.05	3.02	0.05
d	0.786	0.077	0.937	0.082
f	-0.0370	0.0010	-0.0358	0.0011
g	0.0371	0.0014	0.0404	0.0015
h	-0.320	0.029	-0.274	0.031

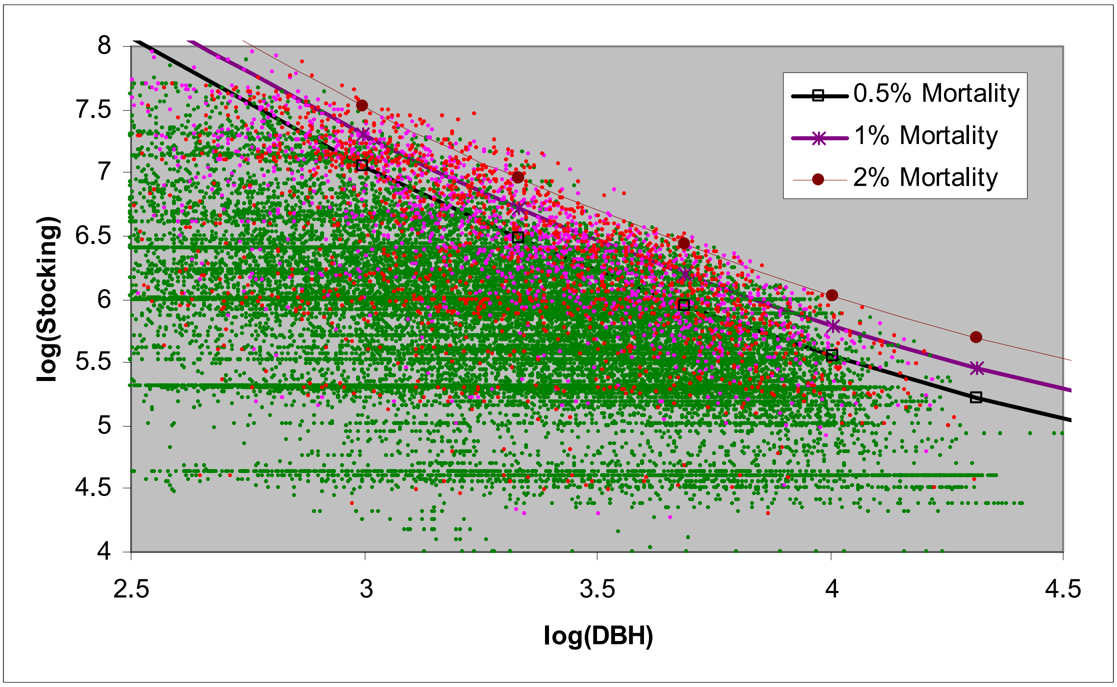

Fig. 3. Annual mortality rate plotted on the ln *N* versus ln *D* surface with 0.5%, 1% and 2% mortality thresholds as predicted using Equation [5].

Stand density indices for three simpler versions of the model are given for completeness:

[6] $SDI = \exp(\ln(N) + d \times \ln(D))/1{,}000$

[7] $SDI = \exp\left(\ln(N) + d \times \ln(D) + h \times (\ln(D))^2\right)/1{,}000$

[8] $SDI = \exp(f \times I300 + g \times SI + \ln(N) + d \times \ln(D))/1{,}000$

Parameters estimates for these models are given in Table 4. For Model [6], the self-thinning boundary slope, *d*, was 1.3, slightly lower than Reineke's theoretical value of 1.5. However, when the 300 Index and *SI* were included (Model [8]), the slope was estimated to be 1.6, slightly greater than the theoretical value.

Table 4. Parameter estimates for Models [6], [7], and [8].

Model	Parameter	Mortality excluding windthrow		Total mortality	
		Estimate	Standard error	Estimate	Standard error
[6]	*a*	0.00015	0.00004	0.00143	0.00010
	b	1.32	0.12	1.26	0.13
	c	2.51	0.03	2.36	0.04
	d	1.30	0.02	1.35	0.02
[7]	*a*	0.00017	0.00004	0.00150	0.00009
	b	0.371	0.053	0.404	0.058
	c	2.52	0.03	2.38	0.03
	d	0.460	0.079	0.538	0.085
	h	-0.325	0.030	-0.317	0.032

[8]	*a*	0.00042	0.00005	0.00208	0.00009
	b	3.129	0.45	2.465	0.37
	c	3.01	0.05	2.97	0.05
	d	1.60	0.01	1.63	0.02
	f	-0.0368	0.0010	-0.0355	0.0011
	g	0.0399	0.0014	0.0426	0.0015

The benefit of including a site productivity index in the model is demonstrated in Fig. 4 where mortality is plotted against *SDI* based on Model [7], with the data split into three 300 Index productivity classes. For the same *SDI*, mortality is lower on more productive sites and higher on less productive sites. This implies that higher productivity sites can sustain a higher stocking of trees for a given mean *DBH* than lower productivity sites, or equivalently, they can sustain the same stocking of larger diameter trees. However, when both the 300 Index and *SI* are included in the model (i.e., as in Model [5]), the *SI* coefficient is negative. This means that stands with faster height growth can sustain a lower stocking of trees for a given mean *DBH*. This may reflect the fact that on high *SI* sites, trees with the same *DBH* will generally be taller, more slender, have greater stem volume, and therefore be less stable compared with lower *SI* sites. Examples of self-thinning boundaries where 1% per annum mortality is predicted by Model [5] are shown in Fig. 5.

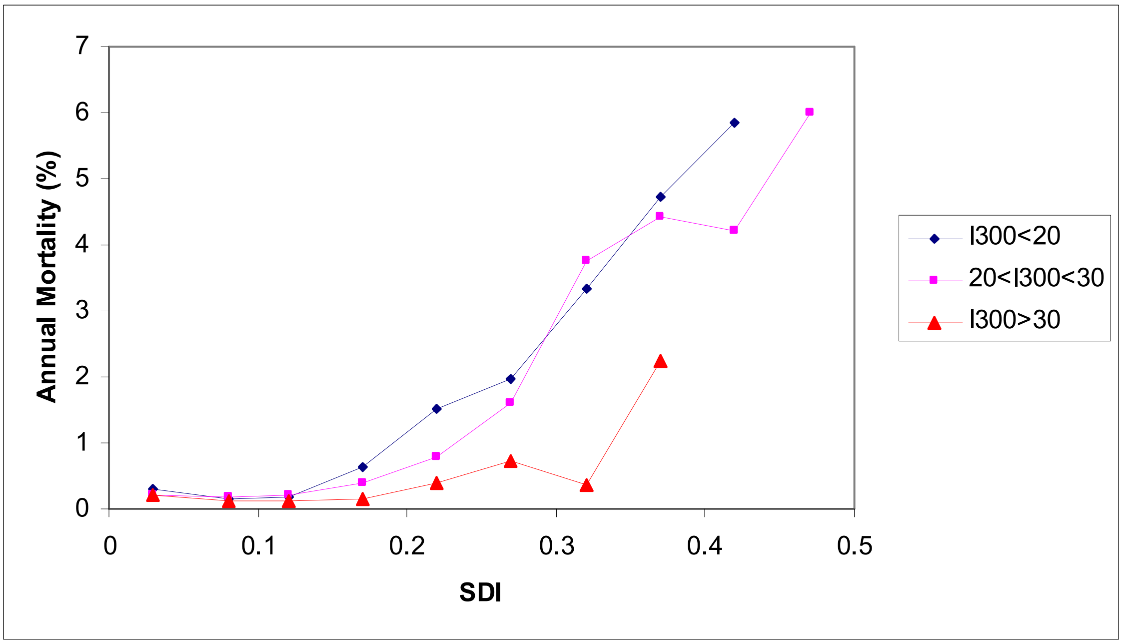

Fig. 4. Mean mortality in plots classified into *SDI* classes and into three site productivity classes on the basis of the 300 Index. In this graph, a simplified version of *SDI* (Model [7]) was used.

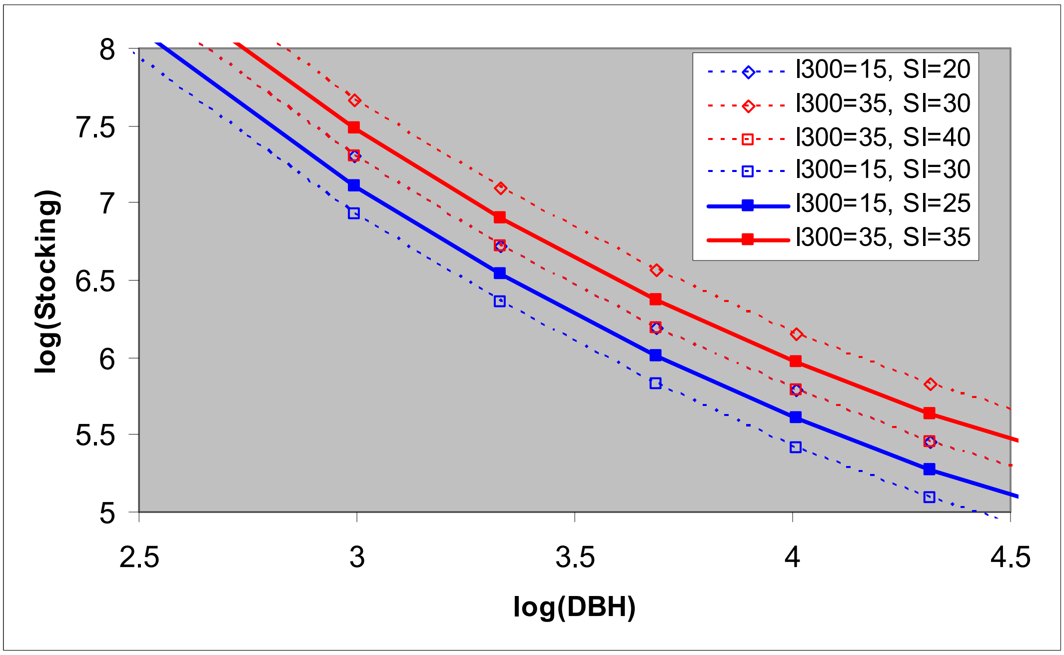

Fig. 5. Self-thinning boundaries where 1% per annum mortality is predicted using Model [5] for various site types.

An examination of the frequency distribution of *SDI* (from Model [5]) within the dataset showed that it had a maximum of about 0.5, but that the 99th percentile was 0.3 (Fig. 6) which may be taken as a more practical upper limit for the species. The maximum *SDI* in well managed stands will generally be lower than this.

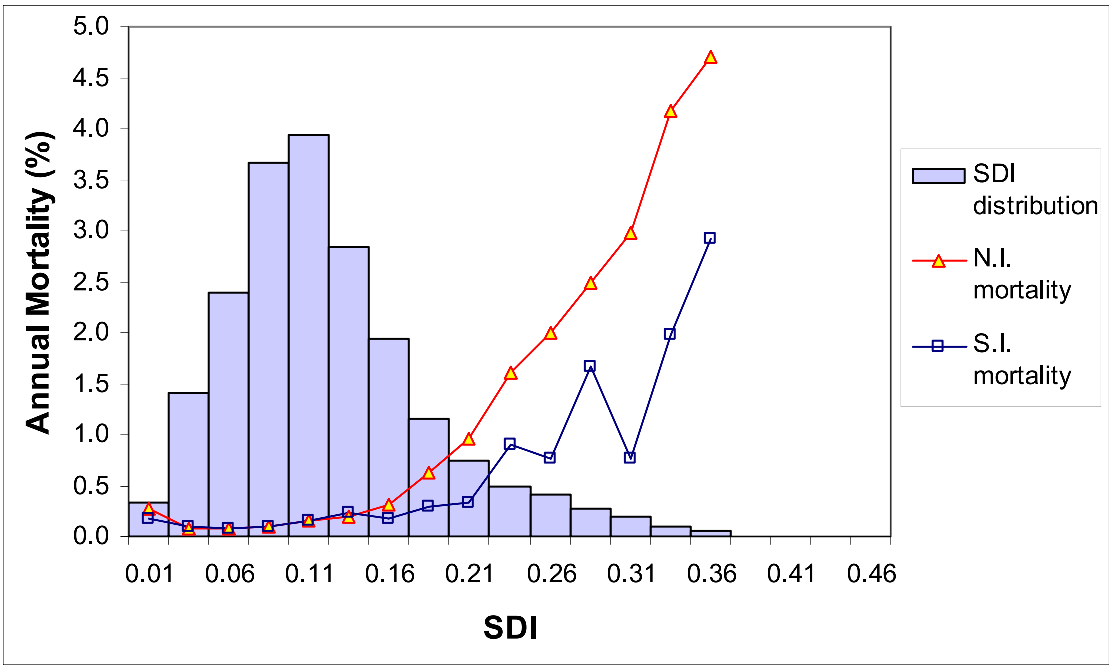

Fig. 6. National frequency distribution of *SDI* (from Model [5]), and mean mortality in 0.025 *SDI* steps for North Island and South Island.

Figure 6 also shows the mean mortality of the data in 0.025 *SDI* steps for both the North and the South Islands. As predicted by the model, mortality generally increases with increasing *SDI*. It appears that North Island stands may generally have higher levels of mortality than South Island stands of equivalent *SDI*. Although the upper limit for *SDI* in radiata pine is about 0.3, Fig. 6 shows that mortality begins to increase at much lower *SDI* values. In fact, the mortality begins to rise appreciably when the *SDI* is at a half to two-thirds of its maximum. This is in agreement with Long & Daniel (1990), who state that competition begins at 35% maximum *SDI*, and self-thinning begins at 60% maximum *SDI*. Fig. 6 suggests that 'self-thinning' is a much more gradual process than is often believed and does not have a sharp threshold.

To explore the issue of regional variation in mortality, an additional multiplier term was added to the second term in Model [5] so that it became:

[6] $M = 100 \times R \times \left(a + b \times SDI^{c}\right)$

The *R* parameter allows this model to predict higher or lower levels of mortality than the standard model. A value of *R* = 1 gives no adjustment while a value of *R* = 2 will double the mortality and a value of *R* = 0 will reduce the mortality to zero. The other parameters in the model retain their estimated values as given in Table 3. This model was fitted to subsets of the data and parameter estimates of *R* obtained for each subset. Fig. 7 shows estimates of *R* for the major geographical regions represented in the database.

In the North Island, the Bay of Plenty, Waikato and Gisborne have had above average mortality in the period since 1970, while in the South Island, the West Coast and Otago have had above average mortality. The dominance of Bay of Plenty in the data means that overall, the North Island had a higher level of mortality than the South Island. However, mortality has varied considerably over time. For example, a comparison of Fig. 8 (post-1990 data) with Fig. 9 (1970-1990 data), shows that Waikato had above average mortality in 1970-1990, but below average mortality since 1990. The West Coast had consistently higher than average mortality in both periods, as to a lesser extend did the Bay of Plenty, and Gisborne. Auckland, Wanganui/Manawatu, Marlborough, Nelson and Canterbury all had below average mortality. There was insufficient data from Hawkes Bay, Taranaki, Otago and Southland in 1970-1990 to establish clearly the levels of these regions during this period. The values shown in these Figures are tabulated in Table 5.

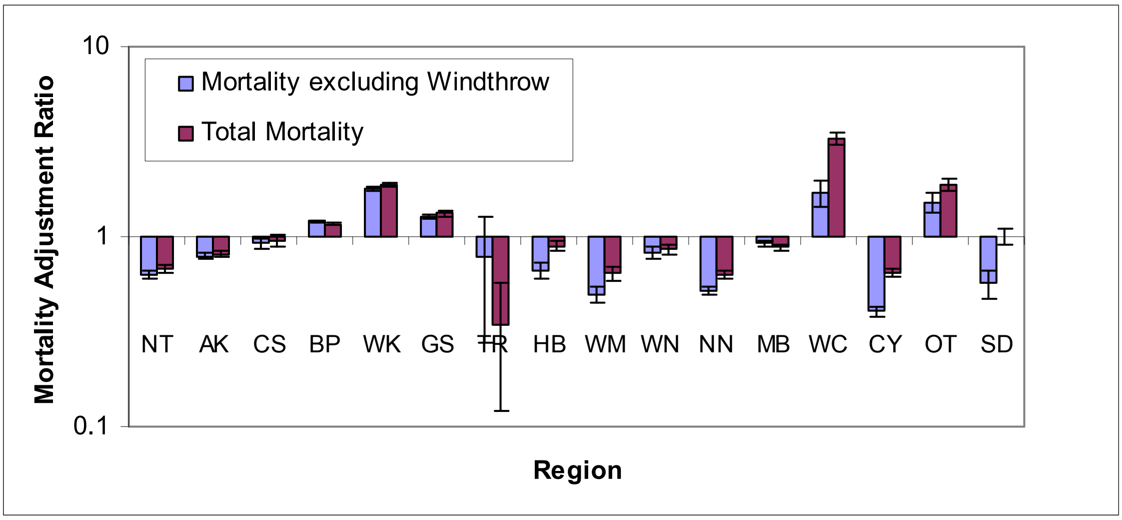

Fig. 7. Mortality adjustment ratios *R* estimated for each region calculated using all post-1970 data. Error bars indicate standard errors.

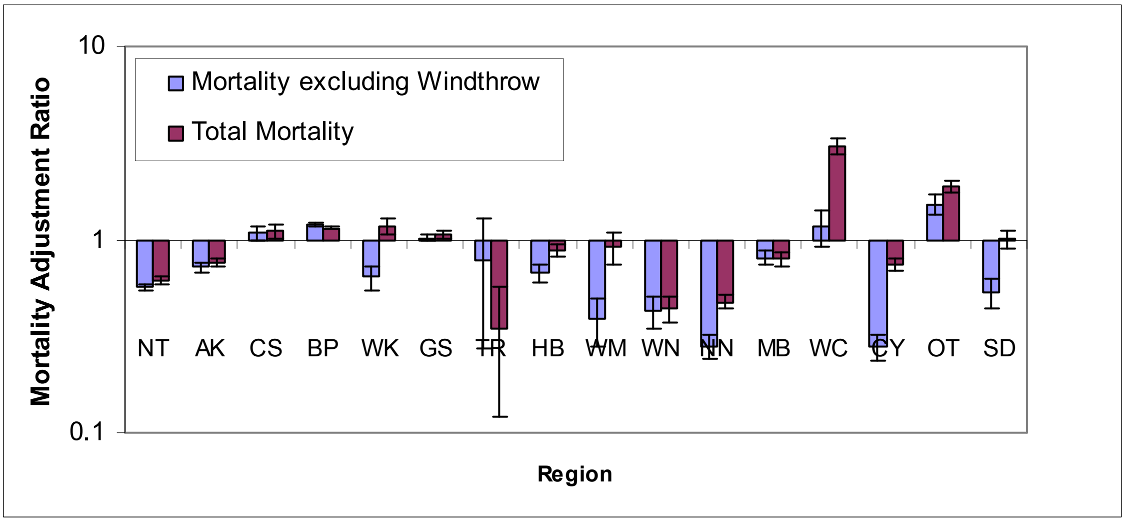

Fig. 8. Mortality adjustment ratios *R* estimated for each region calculated using post-1990 data. Error bars indicate standard errors.

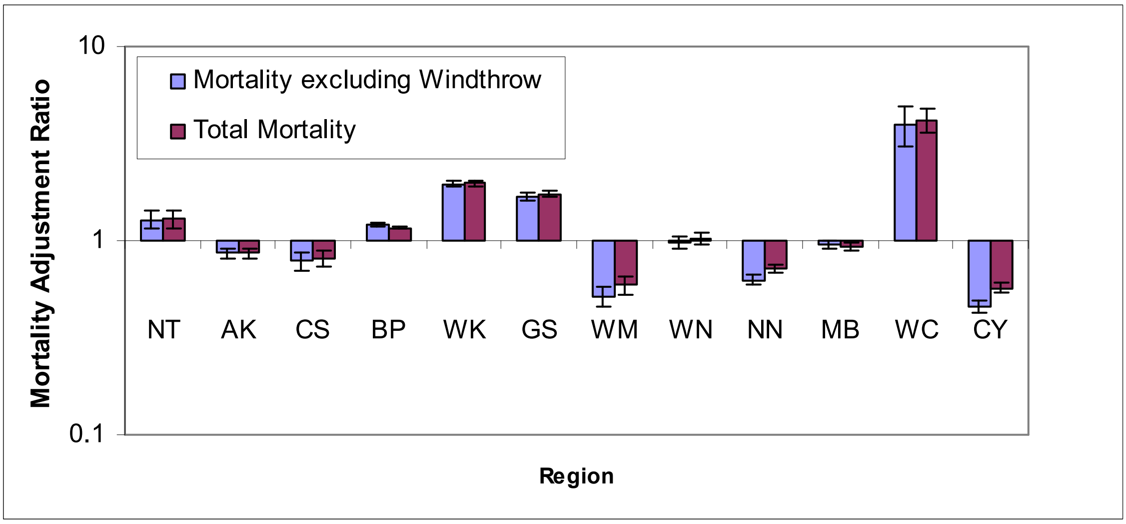

Fig. 9. Mortality adjustment ratios *R* estimated for each region calculated using 1970-1990 data. Several regions had insufficient data to provide useful estimates. Error bars indicate standard errors.

Table 5. Mean mortality adjustment ratios *R* by region.

Region	1970-2006		1970-1990		1990-2006	
	Excluding Windthrow	Total	Excluding Windthrow	Total	Excluding Windthrow	Total
Northland	0.63	0.68	1.28	1.29	0.57	0.62
Auckland	0.79	0.81	0.86	0.86	0.72	0.76
N.I. Coastal Sands	0.92	0.95	0.78	0.81	1.08	1.11
Bay of Plenty	1.20	1.16	1.20	1.16	1.20	1.15
Waikato	1.78	1.87	1.96	1.98	0.64	1.18
Gisborne	1.28	1.32	1.70	1.75	1.02	1.06
Taranaki	0.78	0.34			0.78	0.34
Hawkes Bay	0.67	0.89			0.67	0.88
Wanganui/Manawatu	0.50	0.64	0.52	0.59	0.39	0.92
Wellington	0.83	0.86	0.98	1.03	0.43	0.44

Nelson	0.52	0.63	0.63	0.71	0.28	0.48
Marlborough	0.93	0.89	0.96	0.93	0.81	0.79
West Coast	1.71	3.30	3.98	4.18	1.17	3.05
Canterbury	0.40	0.64	0.46	0.57	0.28	0.75
Otago	1.52	1.88			1.52	1.88
Southland	0.57	1.00			0.53	1.00

These regional variations in mortality are further explored in Figs. 10-12 which show the *R* parameter calculated for each region in five-year bands since 1970. For the North Island, these Figures show that, at least since the mid-1980's, mortality in the Bay of Plenty and Gisborne regions have been consistently above the average, Auckland, Waikato and Hawkes Bay have been below average, and Wellington and Wanganui/Manawatu well below average. Other North Island regions (Northland, Coastal Sands, Taranaki) have been inconsistent, or have too little data to provide good estimates. In the South Island, the West Coast has had above average mortality, while Nelson, Marlborough, Canterbury and Southland have had below average. Results from Otago have been inconsistent.

The reasons for these regional differences in mortality, whether due to disease or insect attack, climatic factors, differences in soil or typography, are beyond the scope of this report. However, the high levels of mortality in the West Coast of the South Island, and especially of windthrow mortality, is likely to be due to waterlogged soil leading to instability (Ross Jackson, pers. com.). In the implementation of the model, the user will be able to enter a percentage adjustment to account for such differences. There will also be a facility to add a constant annual mortality rate to the predicted value. For example, based on Table 1, if an allowance for windthrow is required to be added to the windthrow-excluded model, adding an additional annual mortality rate of about 0.2% would be appropriate.

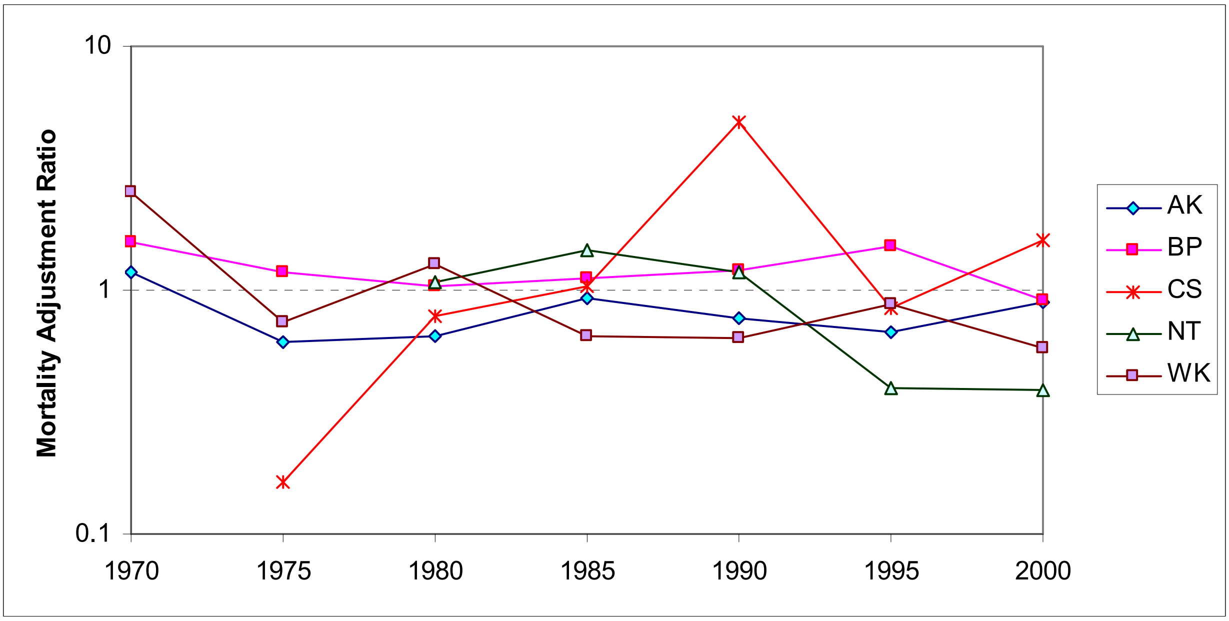

Fig. 10. Adjustment ratios for mortality excluding windthrow for northern and central North Island regions summarised in five-year bands. Ratios were only calculated for data points with more than 20 observations.

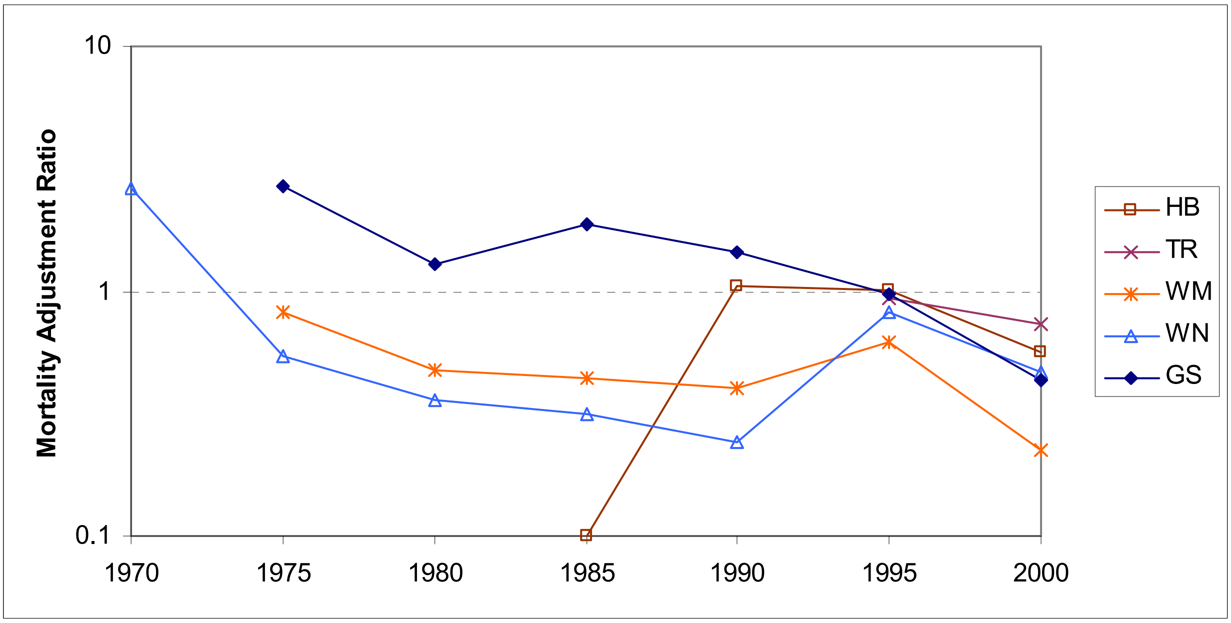

Fig. 11. Adjustment ratios for mortality excluding windthrow for northern and southern North Island regions summarised in 5-year bands. Ratios were only calculated for data points with more than 20 observations.

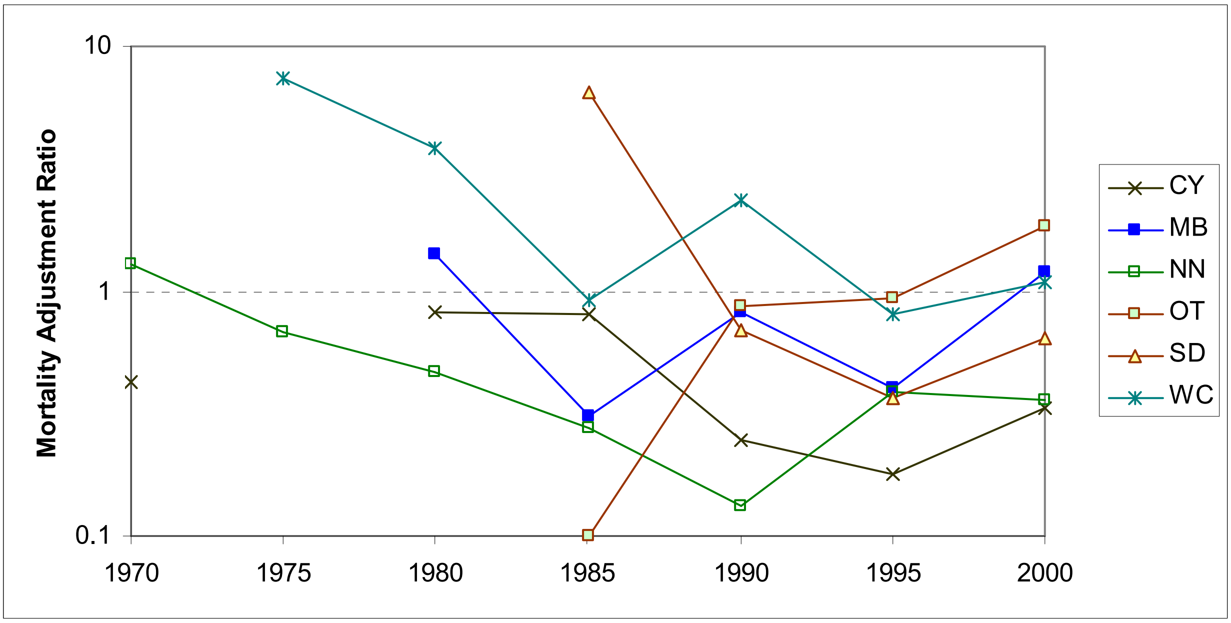

Fig. 12. Adjustment ratios for mortality excluding windthrow for South Island regions summarised in 5-year bands. Ratios were only calculated for data points with more than 20 observations.

This PSP data included measurements obtained as early as the 1950's in addition to the post-1970 data used to develop the model. Estimates of *R* were obtained for each measurement year and used to estimate mortality for stands at a constant representative stocking and *DBH* using the model (Fig. 13). Mortality varied considerably between years, with North Island levels generally higher than South Island levels. Mortality in the 1950's, especially in the North Island was considerably higher than in more recent decades due, presumably to the impact of the *Sirex noctilio* epidemic.

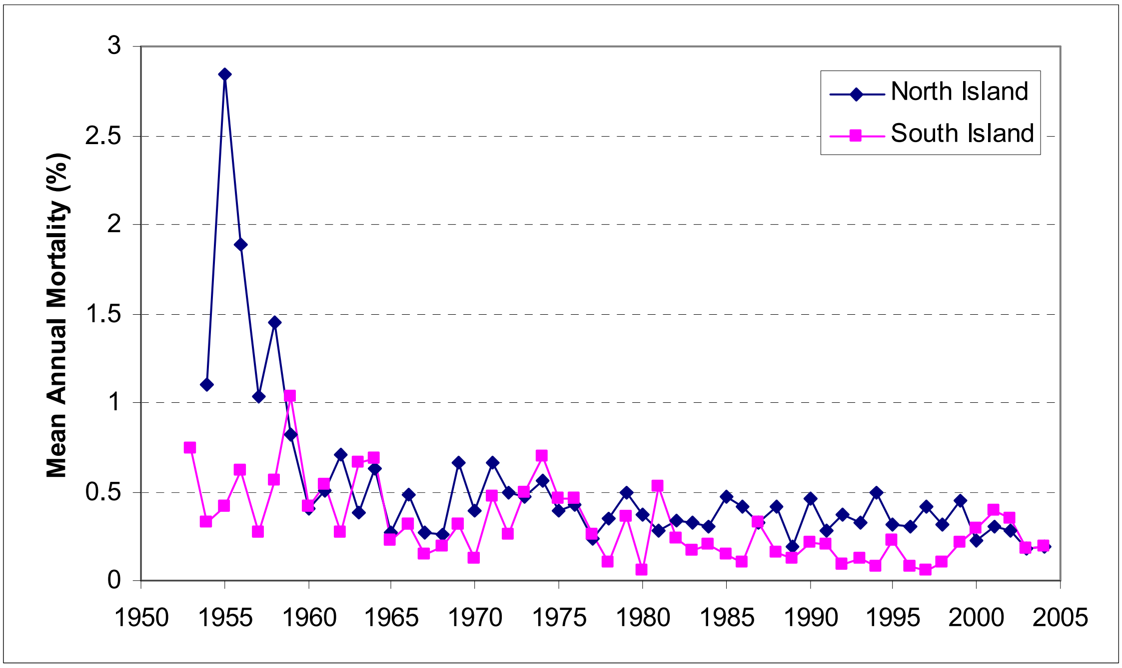

Fig. 13. Mean mortality excluding windthrow, adjusted to common stand parameters, and estimated for each measurement year since 1954 for the North and South Islands.

The data contained 4,127 thinning events from 3,135 PSPs, and these provided strong evidence of an increase in mortality immediately following thinning. For example, when Equation [6] was fitted to the mortality data in the measurement increment immediately following thinning, the parameter *R* was estimated to be 2.74 (i.e., in the year following thinning, the mortality was elevated by an average of 174%). However, in the second measurement increment following a thinning, mortality rates returned to normal with R estimated at 0.98, not differing significantly from one. A method was therefore developed to incorporate this thinning effect into the model.

The thinning-induced increase in mortality was found to be related to the severity and timing of the thinning. If M_1 is the mortality rate predicted using Model [5] from the stocking and mean *DBH* immediately before thinning, and M_2 is the predicted mortality rate from the stocking and mean *DBH* immediately following thinning, then the difference in these values, $M_{diff} = M_2 - M_1$, provides a measure of the severity and timing of the thinning. M_{diff} will be greatest in late and heavily thinned, or highly stocked stands, and least in early, lightly thinned or under-stocked stands. This variable was incorporated into the model using the following equation to predict mortality rate during the year following the thinning:

[10] $$M = 100 \times \left(1 + r \times \sqrt{M_{diff}}\right) \times \left(a + b \times SDI^{c}\right)$$

where *r* was estimated from the data to be 1.43 with standard error 0.24, and *SDI* and the *a*, *b* and *c* parameter values are as given in Model [5]. This effect should only be applied during the year immediately following thinning, with reversion to the standard Model [5] in subsequent years.

CONCLUSIONS

A new mortality function based on Reineke's line of self-thinning concept has been developed for New Zealand radiata pine. Versions of the model were fitted for both total mortality, and mortality excluding windthrow. The model predicts mortality as a function of ln(Stocking) and ln(*DBH*). The level of mortality is influenced by site productivity, with more productive sites able to carry higher stockings of trees of a given size compared to lower productivity sites. This effect is incorporated into the model using the 300 Index and *SI*. Mortality levels are lower for stands of similar stocking and *DBH* on high 300 Index sites. There is a reverse relationship with *SI* with mortality levels higher on high *SI* sites for stands of the same 300 Index, *DBH* and stocking. There is also a trend for the self-thinning line to be slightly concave rather than straight as defined by Reineke's rule. An increase in mortality occurs in the year immediately following thinning, and this effect has also been incorporated into the model. The model can be used for predicting mortality in radiata pine stands throughout New Zealand. However, there is some evidence that it over-predicts mortality slightly in the South Island and under-predicts in the North Island, and there are a number of other regional differences in mortality. When implemented, the user will be able to enter a percentage adjustment to account for such regional differences.

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