Quantification and management of the risk of wind damage to New Zealand's planted forests

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Quantification and Management of the Risk of Wind Damage to New Zealand's Planted Forests

Report prepared for MAF SLMACC 2008/09 under FRST contract UOCX0809

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Executive Summary

The overall objective of this study was to quantify the risk posed by wind damage to planted forests in New Zealand and to investigate different options that owners of forests registered under the Emissions Trading Scheme (ETS) can use to manage this risk.

A chronology of wind damage events was assembled that contained 76 records of damage, totalling approximately 63 000 ha in the estates of large forests owners (i.e., those who own or manage an area of at least 10 000 ha). This included nearly 11 000 ha of damage that had occurred since 1990, much of which occurred in the storms of 2004 and 2008. The total extent of damage that occurred in a single event ranged from 3 ha up to 26 000 ha, with a median of 90 ha. In most cases, damage from a storm was confined to a single wood supply region (as defined by the Ministry of Agriculture and Forestry), with several storms causing damage to two regions that were usually adjacent to each other. The July 2008 storm was unique in this respect as it caused damage in five different wood supply regions from the Central North Island through to the West Coast of the South Island.

The relative risk of wind damage for each wood supply region was estimated by calculating the percentage of total net stocked area that has been damaged by wind. Overall across all wood supply regions, an average of 0.21% of net stocked area per annum has been damaged by wind; however, in the most affected region the average level of damage was 0.94% of net stocked area per annum, while in the least affected region it was 0.03%. The total area damaged by wind each year was modelled using a generalised Pareto distribution, which enabled the probability of different levels of annual damage to be estimated along with the level of damage associated with different return periods. Using this model, the return period for 100 ha of damage was estimated to be 2.4 years, while for 1000 ha of damage it was estimated to be 12.4 years.

Different options for managing the risk of wind damage were discussed. These included acceptance of losses, sharing of losses and risk confrontation. Acceptance of

losses can be viewed as the “do nothing” option, but may actually involve extensive contingency planning, for example around salvaging wind damaged trees. However, this option may be less viable for owners of forests registered under the ETS where losses are not limited to the opportunity cost of harvesting revenues foregone, but also include the cost of emissions units prematurely surrendered.

Sharing of losses can be undertaken through insurance schemes, or possibly by a group of forest owners forming an insurance mutual. Only 19% of the large owner forest estate currently has insurance cover against wind damage. This may reflect the cost of insurance cover as well as the maximum limit on claims that many policies have. As an alternative to insurance, individual owners may decide to spread their risk by locating their estate in several different wood supply regions, as our analysis of historical data showed that damage from a storm was generally confined to a single region.

Risk reduction can be achieved through risk avoidance and/or risk confrontation. Risk avoidance involves selecting those sites where the risk of damage is lower. Our analysis of historical data showed that certain regions have had lower levels of damage. At a more local scale, sites where the wind is accelerated or funnelled are often associated with wind damage, and could either be avoided or different silvicultural regimes could be employed on them.

Risk confrontation involves actions to alter the vulnerability of the forests to damage from a given storm. Thinning and harvesting are the two forest management practices that have been shown to affect the risk of damage. In particular, late and severe thinning increases the risk of damage, especially in the 2-3 year period immediately following removal of the trees. Using a mechanistic wind risk model, we demonstrated the effect that different thinning regimes had on the risk of damage.

We did not prescribe silvicultural regimes that would reduce the risk of wind damage for those forests registered under the Emissions Trading Scheme; the development of regimes is the responsibility of the forest owner, and wind risk is but one factor that must be considered along with many others. The extent to which wind risk influences the choice of silvicultural regime will depend on an individual forest owners’ attitude towards risk. However, it is recommended that due consideration be given to the risk of wind damage when decisions on thinning and harvesting of stands are made.

1. Introduction

To help meet its obligations under the Kyoto Protocol, the New Zealand Government established the Emissions Trading Scheme (ETS), which introduced a price for greenhouse gases in order to provide an incentive to reduce emissions and increase forest sinks (New Zealand Government, 2008). Forestry is the first sector to enter the ETS. An owner of post-1989 forest land can choose to participate in the ETS which entitles them to receive credits for the increase in carbon stocks in their forest from 1 January 2008 onwards. However, it also requires that they repay emissions units whenever the carbon stocks in their registered forest falls below a previously reported level. This could be as a result of harvesting, but could also be due to damage from biotic or abiotic agents, for example wind or fire.

Wind is a significant physical risk to planted forests in New Zealand, which is evidenced by a history of damage events that extends back more than 50 years (Thompson, 1976; Somerville, 1989; 1995). In natural forests, wind is an important disturbance agent; however, in planted forests managed primarily for wood production its effects are mostly negative (Quine and Gardiner, 1991). For example, wind damage affects wood flows by increasing short-term wood supplies (as a result of salvaging damaged trees), but can ultimately decrease the sustainable yield due to a reduction in growing stock. The costs of salvaging wind damaged trees are higher than for conventional harvesting mainly due to reduced production rates, and there can also be considerable danger to workers associated with salvaging wind damage (Childs 1966). Revenues from salvage operations are generally reduced, particularly where there are high levels of stem breakage, but also because of fungal decay.

Manley and Wakelin (1989) used an estate modelling approach to investigate the impact of different levels of wind damage (expressed as in terms of net stocked area of a forest) on the present net worth of a forest. For example, they showed that an annual level of damage of 1% could reduced the present net worth of a forest by up to 11%. These calculations only considered the impact of reduced timber revenues and increased harvesting costs; premature surrender of emissions units due to a reduction in carbon stocks was not considered.

The financial consequences of wind damage could be very significant, depending on the extent of the damage and when in the rotation it occurs. For example, damage to a mid-rotation aged stand (i.e., ~15-18 years of age) might result in substantial losses due the opportunity cost of timber revenue forgone as well as the value of the emissions units prematurely surrendered (Manley and Watt, 2008). Given the potential financial losses associated with wind damage, it is important that owners of forests registered under the ETS have a better understanding of the risks posed by wind and the options available for managing this risk.

In this report, we focus on the risk of wind damage to forests. In particular, we will catalogue historical damage events that have occurred and from this information we will calculate the risk of damage (expressed as a percentage of net stocked area lost per annum) by region. For these damage events, we will also look at how common it is for losses to occur in more than one region, as well as the more general question of how common it is for losses to occur in more than one region during a year. We will attempt to describe in more detail the damage events that occurred in 2004 and 2008, focussing on the nature of the damage, the relationship with wind speeds recorded in the area and the structure of the damaged stands. Much of the information presented here is from the analysis undertaken by Park (2009).

The second part of this report will focus on the management of wind damage risk. Here we will discuss the various options available to forest owners to manage the risk of wind damage, including sharing of losses (e.g., through insurance) and risk reduction. For the latter, we will use a mechanistic wind damage model (Moore and Somerville, 1998; Gardiner and Quine 2000) to demonstrate the effect that choice of silvicultural regime has on the risk of damage. This mechanistic model can also be used to demonstrate the potential impact of future climate change on the risk of damage, as was described in Watt et al. (2008).

2. Quantification of Wind Damage Risk

2.1. Documentation of historical damage

Until its demise in the late 1980s, much of the record keeping related to wind damage in New Zealand's planted forests was done by the New Zealand Forest Service; however, records were also kept by the major private forestry companies at the time, i.e., NZ Forest Products and Tasman Forestry (Ainsworth, 1989; Carter, 1989; New, 1989). The task of documenting wind damage in planted forests now rests with the private companies or individuals that own or manage these forests, as New Zealand, like most countries, does not have a formal wind damage reporting scheme. Much of the information that is available is contained in published papers, student dissertations (e.g., Wrathall, 1989; Whiteley, 2001; Tolan, 2005) and the grey literature (i.e., unpublished reports) (Table 1). These sources generally document the more significant events in which there is widespread severe damage to mature and semi-mature plantations. Damage to young plantations, losses arising from smaller storms (often referred to as attritional damage) and damage to the estates of small-scale owners has largely remained undocumented.

The first major occurrence of wind damage was recorded in Canterbury in 1945. On Friday July 13th, winds gusting up to 145 km/h caused damage to forest from Hanmer south to Waimate (Jolliffe, 1945). Damage was most severe at Balmoral Forest and in forests owned by the Selwyn Plantation Board. Damage at Balmoral was exacerbated by the 45 cm of snow that fell immediately following the storm (Prior, 1959). Wind damage continued to affect Canterbury forests, particularly Balmoral Forest, through the 1950s, but a lack of adequate surveys meant the true extent of these losses could not be quantified. In 1964 another major storm hit the Canterbury region. This time strong northwest winds occurring on March 13-14, 20-21, 24-25 and 26 heavily damaged approximately 3000 ha at Eyrewell Forest (Wendelken, 1966). A further 1500 ha of stands had at least 50% of their total volume damaged. The total damaged volume was approximately 1.1 million m^3. Older age classes of trees were worst affected.

Table 1. Summary of key published and unpublished studies documenting wind damage to planted forests.

Reference	Year	Location
Published papers		
Chandler (1968)	1950s	Otago/Southland
Conway (1959)	1959	Northland
Irvine (1970)	1963, 1968	Nelson
Littlejohn (1984)	1982	Central North Island
Prior (1959)	1945	Canterbury
Rasmussen (1989)	1988	Northland
Wendelken (1966)	1964	Canterbury
Wilson (1976)	1975	Canterbury
Student dissertations		
Whiteley (2001)	2000	Canterbury
Wrathall (1989)	1988	Central North Island
Tolan (2005)	2004	Nelson
Unpublished reports		
Cameron (2004)	2004	Southern North Island
Moore (1995)	1994	East Coast
Moore et al. (2002)	1974, 1979, 1982, 1988, 1996	Central North Island
Somerville (1982)	1982	Central North Island
Somerville & Maclaren (1988)	1982, 1988	Central North Island
Somerville & Maclaren (1990a)	1905, 1963, 1968, 1971, 1975, 1976, 1988	Nelson
Somerville & Maclaren (1990b)	1963, 1970, 1972, 1975, 1980, 1982, 1987	Otago

In April 1968, the "Wahine storm" caused heavy damage to forests in the Nelson region as well as some minor damage to forests in Canterbury. Damage in Nelson was confined to Golden Downs Forest where approximately 650 ha of stands were damaged. Damage was related to soil type, with shallow rooting prevalent among damaged trees (Irvine, 1970). On August 1st 1975 northwest winds gusting up to 170 km/h at Christchurch Airport caused extensive damage to approximately 25% of the exotic forest area of Canterbury (Wilson, 1976). Damage was particularly severe in Balmoral and Eyrewell Forests as well as forests owned by the Selwyn Plantation Board, Christchurch City Council and the former North Canterbury Catchment Board. Damage was most severe in the older age classes, with most of the trees of merchantable age being blown over. This had a major impact on the region's wood supply for many years to come.

Prior to the late 1970s, wind damage was generally viewed as a problem that was mainly confined to Canterbury and other parts of the South Island such as Nelson and Otago/Southland. However, this view changed as a result of storms that occurred in the central and upper North Island in 1979, 1982 and 1988. The 1979 storm caused damage to 650 ha of stands in Kaingaroa Forest. The direction of damaging winds was northwest, however for Cyclones Bernie and Bola in 1982 and 1988, respectively, wind direction was southeast. The maximum wind gusts associated with these two storms were considerably less than for the Canterbury storms, but the level of damage was just as severe. In 1982, over 5000 ha of stands were severely affected, while in 1988 over 17 000 ha were affected (New, 1989).

2.2. Analysis of historical damage data (1940-1990)

Somerville (1995) quantified the risk of catastrophic and attritional damage in 17 previously State-owned forests, which were the worst wind affected and where wind damage had been documented, using data spanning the period from 1940 to 1990. The dataset used in this analysis consisted of records documenting 30 860 ha of catastrophic wind damage in 259 950 ha of forests across the Central North Island, Nelson, Canterbury, and Otago regions. In this study, catastrophic wind damage was defined to be any continuous area of wind damage over 1 ha in size in plantations over five years of age. Information on attritional damage was obtained from the permanent growth sample plot system (Dunlop, 1995). Only stands over 14 years of age were considered as the effects in younger stands would likely be negated by final thinning, which in the case of production thinning typically occurs at around 12-14 years of age. Only data for the two main species commercial species, radiata pine (*Pinus radiata*) and Douglas-fir (*Pseudotsuga menziesii*), were considered. The level of damage was expressed as a percentage of net stocked area (NSA) lost per year.

Somerville (1995) found that the average annual levels of catastrophic damage were similar between regions, except for Canterbury, which had been subjected to very high levels of catastrophic wind damage (Table 2). For attritional damage, Somerville (1995) found that for individual forests the level of the damage was generally higher in those forests with high levels of catastrophic damage. However, Golden Downs Forest in Nelson was found to have the highest level of attritional damage, which was in fact higher than the level of catastrophic damage. The weighted (by forest area) average level of catastrophic damage across the 17 forests was 0.38 % of net stocked area lost per year with an additional 0.25 % lost due to attritional damage. These values corresponded to an average 12 % NSA of forest damaged over a 28-year rotation. However, there was considerable variation in the overall level of damage over the course of a rotation between forests; while the estimated level of damage in the least affected forests was around 5-6%, in the worst affected Canterbury Plains forest nearly 90% of the NSA would be lost to wind over this period (Somerville, 1995).

Table 2. Levels of catastrophic and attritional wind damage in different regions as determined by Somerville (1995). Regional values are based on the average of selected forests within a region.

Region	NSA[1] in 1990 (ha)	Area damaged (ha)	Catastrophic damage (% NSA lost yr^{-1})	Attritional damage (% NSA lost yr^{-1})
Central North Island	163700	12860	0.26	0.15
Nelson	30600	1680	0.23	0.35
Canterbury	23500	14870	1.86	0.24
Otago	42150	1450	0.20	0.18
Overall[2]	259950	30860	0.38	0.25

[1] NSA is net stocked area of the selected forests within a region
[2] Values of catastrophic and attritional damage are weighted averages (weighted by net stocked area) across all 17 forests

2.3. Updated analysis

The analysis by Somerville (1995) only considered four regions and within these regions the focus was on those forests most affected by wind damage. The analysis was also limited to former State forests and did not consider privately-owned forests that suffered damage. Furthermore, there have been a number of significant wind damage events since 1990. Therefore, we attempted to update the analysis undertaken by Somerville (1995) to include additional forests and also wind damage events that occurred up to and including 2009. However, unlike Somerville (1995) we considered all ages of stands (i.e., not restricted to stands older than 5 years), but only considered radiata pine.

A database of damage events was assembled using data contained in previously published literature and unpublished reports. When species and age information for the damaged stands was unknown, it was assumed that they were semi-mature or mature radiata pine plantations. In order to obtain information on more recent events, a survey was sent to New Zealand forestry companies that own or manage over 10,000 ha of plantation; together the estates of these larger companies total approximately 900,000 ha, which is approximately 50% of national plantation estate (MAF, 2009). The names of the companies that responded to the survey and the forests they manage are given in Table 3.

Table 3. Companies that responded to the survey and the forests under their management.

Company	Forests	Region[1]
Blakely Pacific	WBOP, Matakana Island	CNI
Ernslaw One	Coromandel (Whangapoua)	Auckland
	Mangatu, Ruatoria	East Coast
	Santoft/Shannon, Waimarino, Aokautere	SNI
Hancock (HFM)	Kinleith, King Country	CNI
	Motueka Valley, Lee Valley, Richmond ranges	Nelson
	MFL estate, TPL estate	Northland
Juken New Zealand Ltd (JNL)	Wairoa	Hawke’s Bay
Nelson Forests (incl. Weyerhaeuser NZ)	Unspecified	Nelson
NZ Forest Managers	Unspecified	CNI
PF Olsen- TDC	Kingsland, Borlase, Howard, Sherry	Nelson
Rayonier (incl. Matariki Forests)	Unspecified	SNI
Timberlands	Kaingaroa	CNI
Timberland West Coast	Charleston, Granville, Hochstetter, Hohonu, Kaniere, Mahinapua, Mawhera, Mokihinui, Nemona, Omoto, Paparoa, Te Wharau, Victoria, Waimea	West Coast

[1] Wood supply region as defined in MAF (2008)

The average net stocked area of these large owners’ radiata pine estates over the record period was calculated for each wood supply region from the National Exotic Forest Description (MAF, 2009) and the regional resource descriptions produced by the New Zealand Forestry Corporation as part of the sale of State-owned forests (NZFC, 1989). The length of record varies considerably by region, with the Central North Island, Canterbury and Nelson having in excess of 50 years of record, while Auckland and the Southern North Island having fewer than 10 years (Table 4). Data from the East Coast and Hawke’s Bay regions were combined, while no records of damage were obtained for forests in Southland. Therefore, we refer to the Otago and Southland wood supply region simply as Otago. The assembled database contained records of over 50,000 ha of catastrophic wind damage for the 50-year period from 1940 to 1990. The majority of this damage is due to the events in the Central North Island and Canterbury regions that are described earlier. No pre-1990 records were found for the Auckland, East Coast/Hawke's Bay, Southern North Island, Marlborough and West Coast regions. Since 1990, there has been a total of almost 11000 ha of catastrophic damage recorded in the large forest owners' radiata pine estates (Table 4). Approximately half of this damage occurred during the storm events that affected the Southern North Island and Nelson in 2004, and Nelson in 2008. In fact, the Nelson region had a greater amount of recorded damage in the past 19 years (3110 ha) than in the 40 years prior to 1990 (2475 ha). Using these data, the risk of catastrophic wind damage was then calculated using the same approach as that taken by Somerville (1995). The total area damaged in each region was divided by the cumulative total net stocked area in that region (i.e., the product of the estimated net stocked area and the length of the recording period). The result was expressed as a percentage of net stocked area lost per annum (Table 5).

Northland and Otago had the lowest risk of catastrophic damage, with average levels of damage in both regions less than 0.1% of net stocked area per annum. In contrast, Canterbury, the Southern North Island and the West Coast had the highest levels of damage. However, caution should be exercised when interpreting these results, particularly for those areas with a short length of record. For example, the two large events that have occurred in the Southern North Island, where the length of record is only six years, may not be representative of the longer term situation in this region. The choice of the starting date for the analysis period will also have a considerable influence on the results obtained. As a result, the level of risk may be considerably overestimated in this region. In general, we recommend that values for those regions where the length of record is less than 20 years should be considered much less reliable. As noted by Quine (1995), having an accurate long-term record of damage is important for calculating average annual losses as well as making comparisons between regions, silvicultural regimes and species.

Table 4. Summary of wind damage by region for the pre-1990 and post 1990 periods. Regions where pre-1990 data do not exist are indicated with a hyphen.

Wood Supply Region	Average regional net stocked area (ha)[1]	Period for which records of damage events exist	Length of record (years)	Pre-1990 damage (ha)[2]	Post-1990 damage (ha)	Total area of damage (ha)	Average annual % damaged
Northland	138003	1988 – 2009	21	690 (1)	152 (2)	842 (3)	0.03
Auckland	7500	2002 – 2009	7	-	57 (2)	57 (2)	0.11
Central North Island	303830	1956 – 2009	53	32089 (12)	1484 (4)	33573 (16)	0.20
East Coast / Hawke's Bay	60300	1994 – 2009	15	-	993 (3)	993 (3)	0.11
Southern North Island	45280	2003 – 2009	6	-	2547 (2)	2547 (2)	0.94
Nelson	35575	1947 – 2009	62	2475 (8)	3110 (7)	5585 (15)	0.25
Marlborough	10000	1992 – 2009	17	-	188 (2)	188 (2)	0.11
Canterbury	30453	1945 – 2009	64	16650 (6)	594 (2)	17244 (8)	0.88
West Coast	20400	1998 – 2009	11	-	857 (11)	857 (11)	0.59
Otago	32780	1963 – 2009	45	760 (10)	97 (3)	857 (13)	0.06
Total	684121			52664 (37)	10536 (39)	63200 (76)	0.21

[1] This is the average net stocked area of large owners over the period for which wind damage records exist, and is therefore less than the current net stocked area

[2] Values in parentheses indicate the number of discrete wind damage events during the recording period

Of the four regions that were previously analysed by Somerville (1995), our analysis showed similar levels of annual loss for the Central North Island and Nelson regions, but a substantial decrease for the Canterbury and Otago regions (Table 5). The substantial decrease in the level of damage in Canterbury reflects the fact that there has only been 594 ha of damage recorded in this region in the 19 years since 1990, compared with the 16650 in the 46 years prior to 1990. However, it should also be noted that the analysis undertaken here only considered radiata pine stands, while Somerville (1995) considered all softwood species, but only stands older than 5 years of age.

Table 5 Comparison of catastrophic wind risk calculated as average annual % damaged between Somerville (1995) and this study.

	Average annual loss (% net stocked area lost per year)	
	Somerville(1995)	This study
Central North Island	0.26	0.20
Nelson	0.23	0.25
Canterbury	1.86	0.88
Otago	0.2	0.06

2.4. Extent of damage in each storm event

The preceding analysis determined the average annualised loss due to wind damage, rather than periodic losses due to discrete events. To better understand the extent of loss that can occur from an individual storm, further analysis of the records from the 76 individual damage events was undertaken. In these damage events, the extent of damage ranged from 2.8 ha up to 25 692 ha, but in most cases the area damaged was less than 200 ha (Figure 1). The median area damaged in an individual event was 90 ha. In eight events, the area damaged was greater than 1000 ha. Of these, the 1975, 1982 and 1988 events stand out as being particular severe, although the more recent events in 2004 and 2008 are also notable (Figure 2).

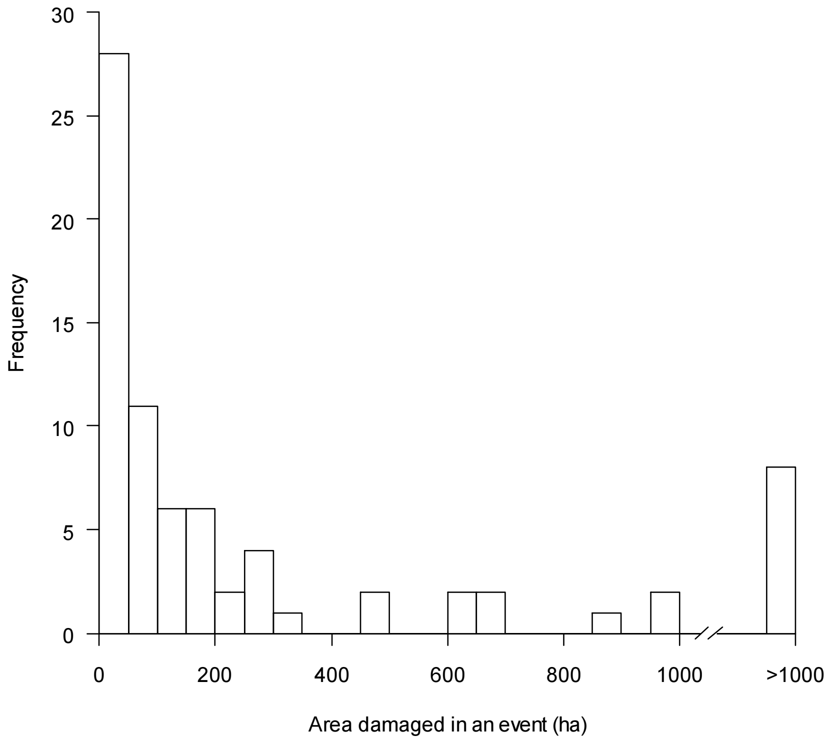

Figure 1. Histogram showing the distribution of area damaged by discrete events between 1945 and 2009.

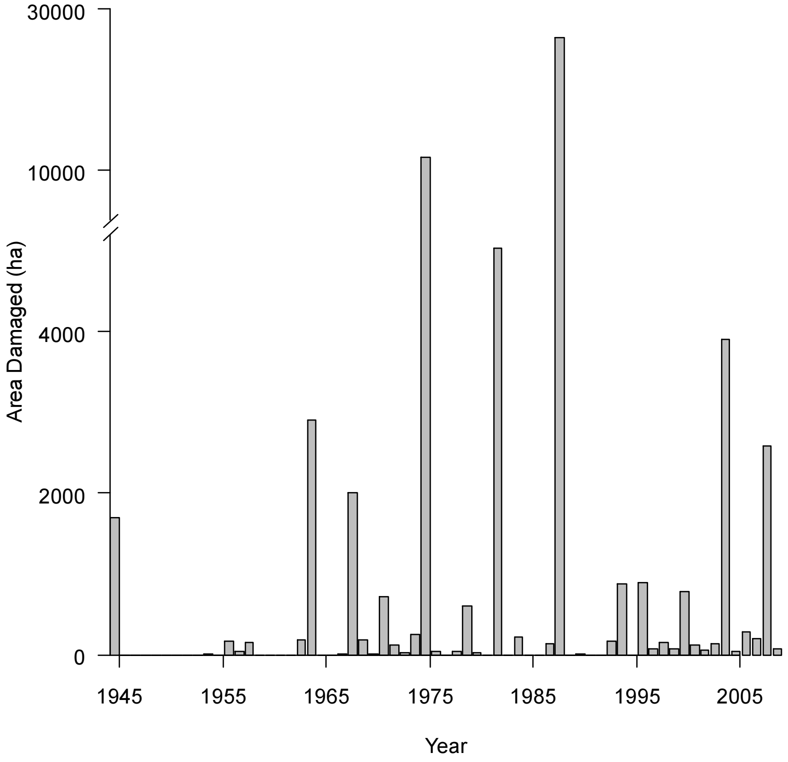

Figure 2. Area of forest damaged by wind damage per year over the past 65 years. (Note: the break in y-axis scale).

Using the time series of area damaged per year, a model was developed to predict the probability that the total area damaged in any year exceeded a certain level along with the level of damage associated with a given return period. The approach taken was to model distribution of the excesses above a certain threshold using a generalised Pareto distribution. Such an approach has also been used to model the area damaged by vegetation fires (de Zea Bermudez et al., 2009). For the generalised Pareto distribution, the probability that the area of damage that occurs in a single year (*X*) exceeds a certain level (*x*) above a threshold *u* is given by:

$$\Pr\{X > x \mid X > u\} = \left[1 + \xi\left(\frac{x-u}{\sigma}\right)\right]^{-1/\xi} \qquad [1a]$$

$$\Pr\{X > x\} = \zeta_u\left[1 + \xi\left(\frac{x-u}{\sigma}\right)\right]^{-1/\xi} \qquad [1b]$$

where σ is the scale parameter, ξ is the shape parameter and $\zeta_u = \Pr\{X > u\}$, which is normally estimated by the sample proportion of points exceeding the threshold *u*. The underlying assumptions when using this approach are discussed by Coles (2001). The first stage in fitting the model was to choose the value of the threshold *u*. The choice of threshold is a balance between variance and bias. Too low a threshold is likely to violate the asymptotic basis of the model, leading to bias; too high a threshold will generate too few excesses with which the model can be estimated, leading to high variance (Coles, 2001). To assist with selecting a value for this threshold, a mean residual life plot (also known as a mean excess plot) was produced for values of *u* starting at zero. For a given value of u, the excess is the difference between an observed value (x_i) that lies above this threshold and this threshold (i.e., $x_i - u$). The mean residual life plot shows the mean excess ($\frac{1}{n_u}\sum_{i=1}^{n_u}(x_i - u)$) plotted against different values of *u*. The generalized Pareto distribution is an appropriate model for the region where the mean excess function is linear (Coles, 2001).

For the dataset containing the area of forest damaged by wind, only those records after 1953 were considered; the period from 1946 until 1953 did not contain any records of damage, which was thought to be highly unlikely. Data from the remaining 56 years were analysed using the functions contained in the `ismev` library of the R statistical software program (R Project Core Team, 2009). The mean residual life plot

(Figure 3) indicated that a suitable threshold value is zero. The dramatic "saw-tooth" pattern above a threshold of 5000 ha reflects the fact that there are only three years where annual damage exceeded this level.

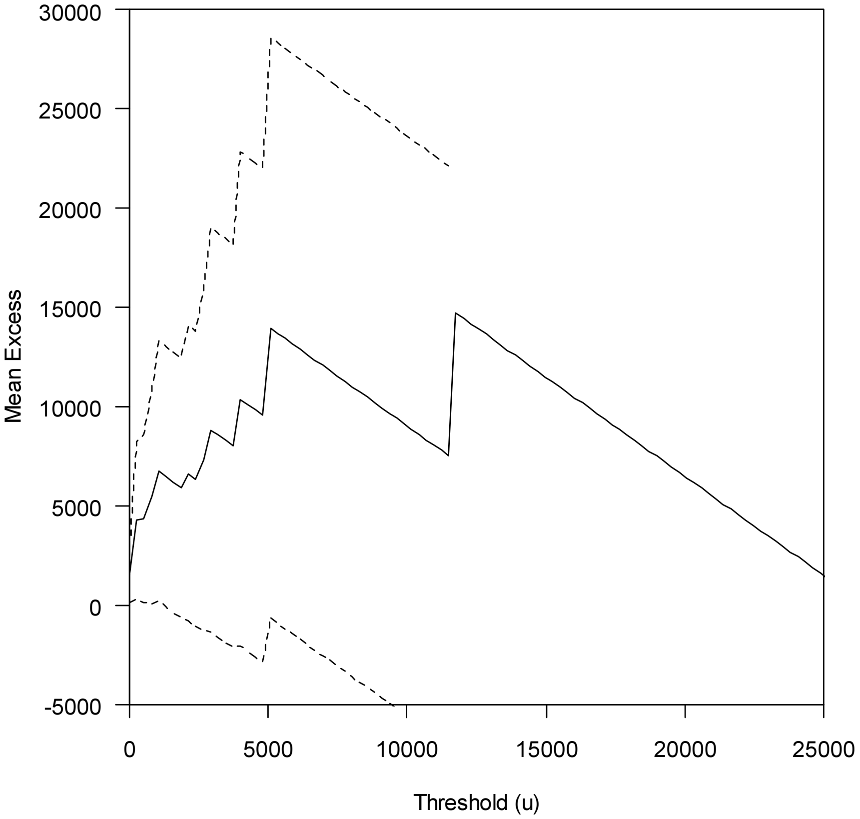

Figure 3. Mean residual life plot for annual wind damage data. The dotted lines indicate the 95% confidence limits.

Setting the threshold to 0 leads to 40 exceedances in the 56 years of records, so that $\hat{\zeta}_u = 40/55 = 0.73$. The maximum likelihood estimates of σ and ξ were 158 and 1.38, respectively. Because $\xi > 1$ it is not possible to estimate the expected value for the time series of annual damage areas as this expected value is given by $\frac{\sigma}{1-\xi}$. In addition, a quantile plot indicated considerable lack of fit for large exceedances (Figure 4) Therefore, the model was refitted with those years in which the total area of damage exceeded 5000 ha omitted. This dataset contained 53 observations and again the mean residual life plot (Figure 5) indicated that a suitable threshold was zero.

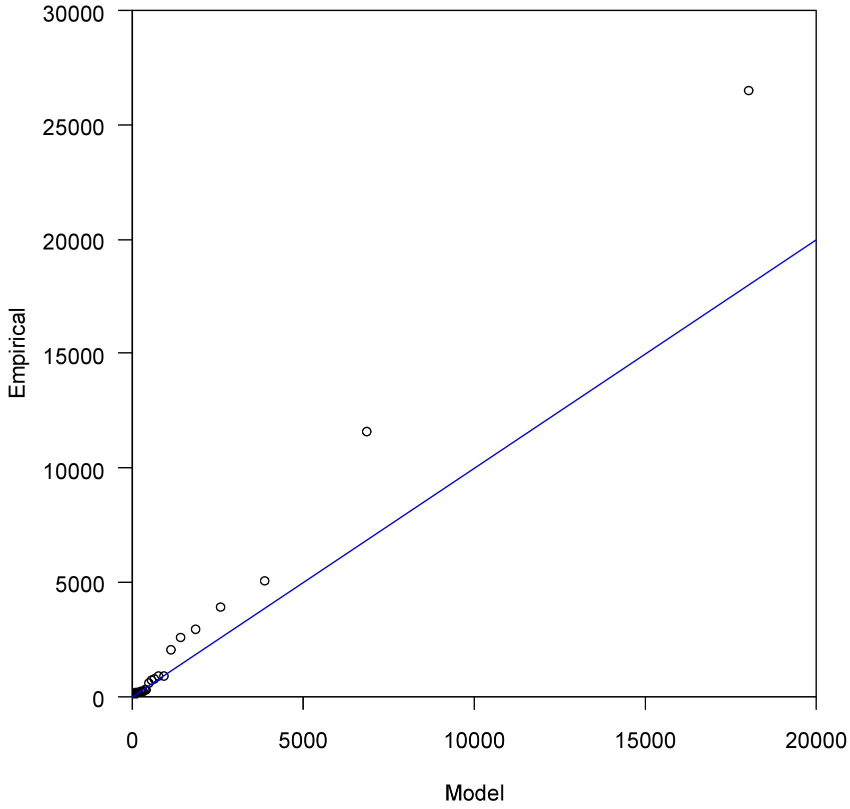

Figure 4. Comparison of the quantiles from the distribution of observed damage with those from a Pareto distribution with σ =158 and ξ =1.38. The blue line indicated a 1:1 relationship.

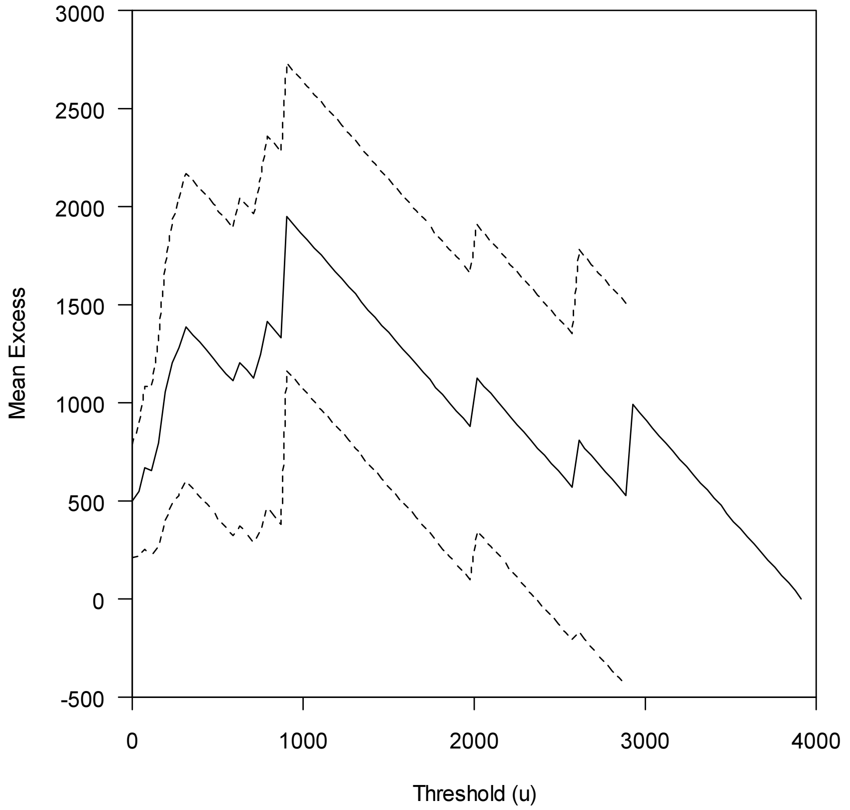

Figure 5. Mean residual life plot for annual wind damage data excluding those years when damage exceeded 5000 ha. The dotted lines indicate the 95% confidence limits.

Setting the threshold to 0 resulted in 37 exceedances in the 53 years of records, so that $\hat{\zeta}_u = 37/53 = 0.70$. The maximum likelihood estimates of σ and ξ were 152 and 0.88, respectively. This model provided a better fit to the dataset, but there was still evidence of lack of fit from the comparison of empirical and model quantiles (Figure 6). While the model fit could be further improved by removing those years in which damage exceeded 1000 ha, this would result in a model that would underestimate the probability of exceedance for larger areas of damage and the return level associated with longer time intervals.

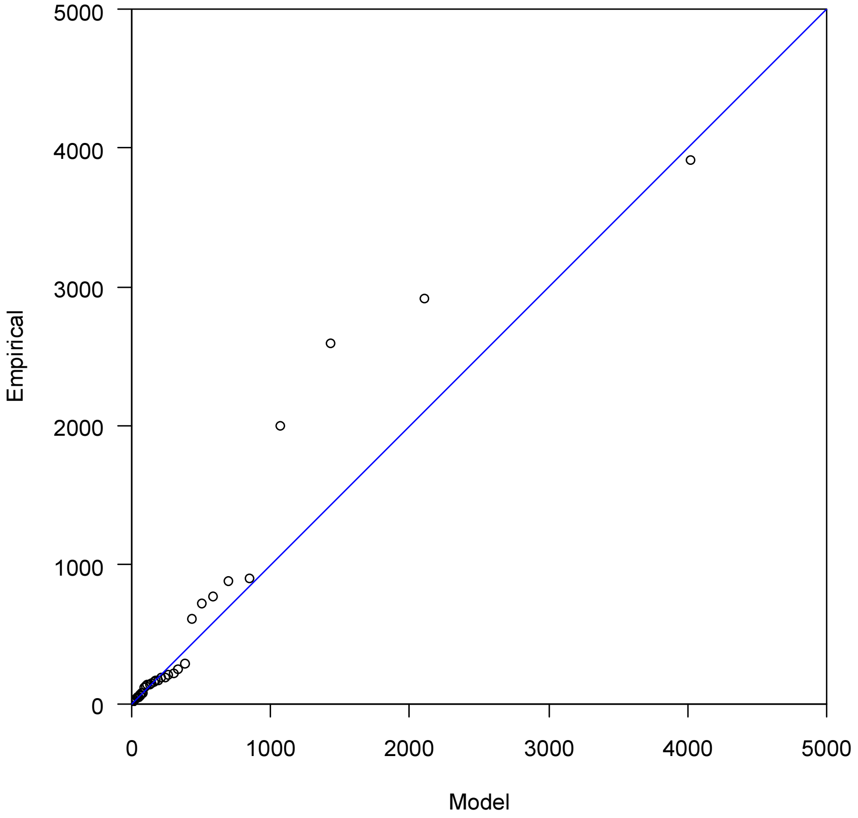

Figure 6. Comparison of the quantiles from the distribution of observed damage (excluding those years where damage exceeded 5000 ha) with those from a Pareto distribution with σ =152 and ξ =0.88. The blue line indicated a 1:1 relationship.

Using this model, the probability that the threshold level was exceeded by different amounts (i.e., different levels of annual damage) was estimated using equation [1b]. In addition, the area of damage x_m that occurs every m years (the return level) was estimated using the following equation:

$$x_m = u + \frac{\sigma}{\xi}\left[(m\zeta_u)^{\xi} - 1\right] \qquad [2]$$

The model predicted that the probability of 50 ha of damage in a year was 0.53, decreasing to 0.29 for 200 ha of damage and to 0.15 for 500 ha (Figure 7). These equate to return intervals of 1.9, 3.4 and 6.6 years, respectively (Figure 8). The estimated probably of occurrence and return interval for 500 ha of damage were 0.02 and 67 years, respectively.

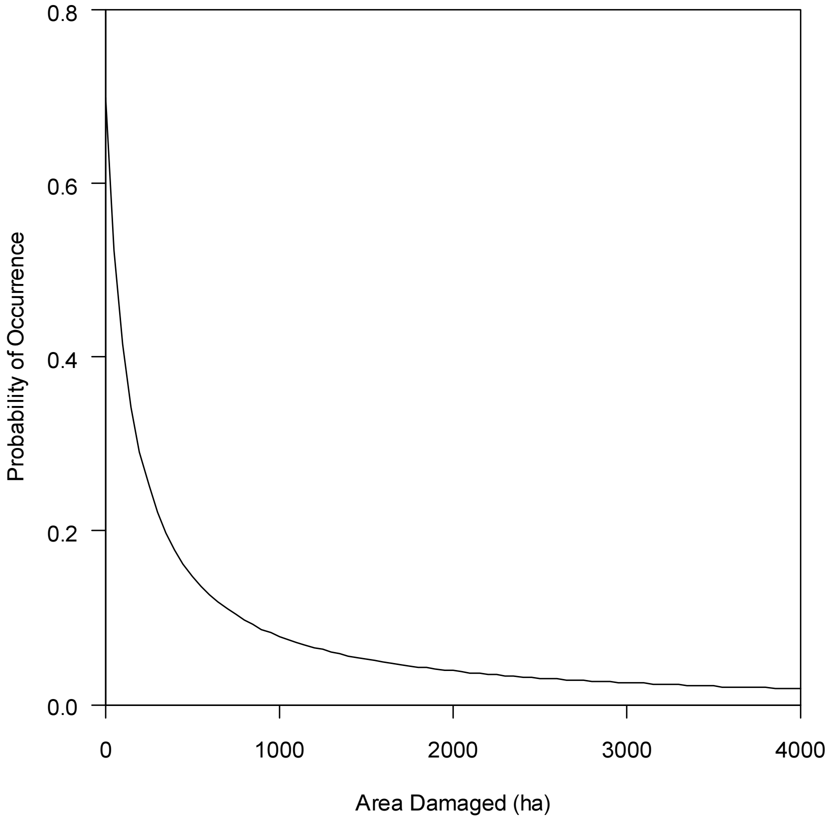

Figure 7. Estimated probability of occurrence for different levels of total annual wind damage.

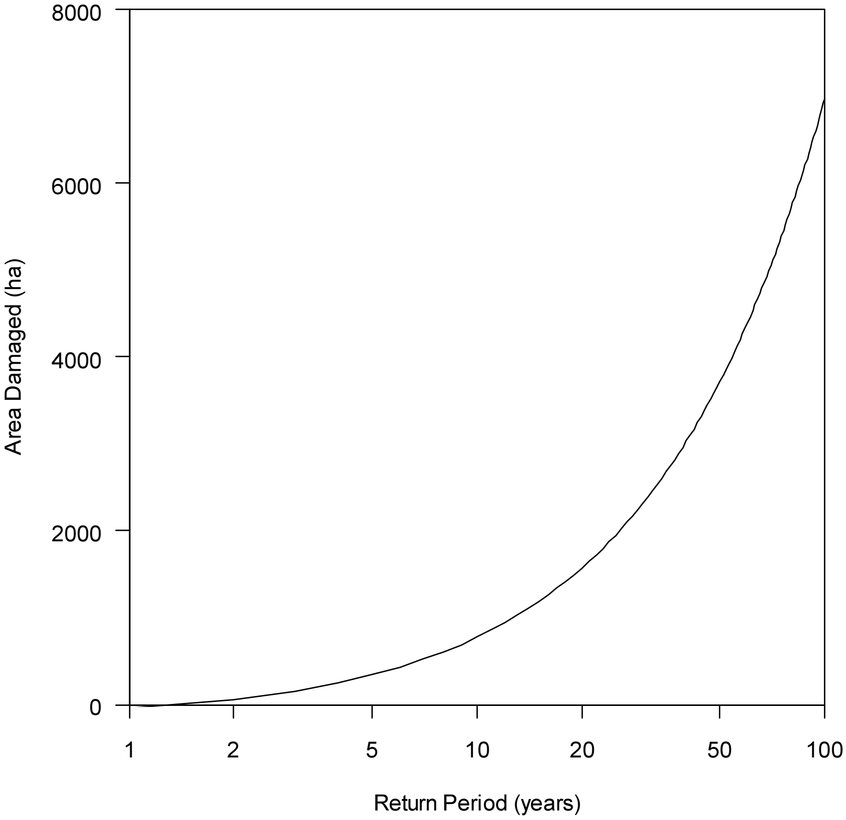

Figure 8. Estimated level of damage associated with different return periods. Note that the x-axis scale is logarithmic.

2.5. Occurrence of loss in multiple regions from a single event

In addition to quantifying the extent of damage that has occurred over time, the spatial extent of damage was investigated by determining the number of events that caused damage in multiple wood supply regions. Of the 76 records of damage, there were only 62 discrete storm events. Eleven of these storm events caused damage in more than one wood supply region (Table 6). Not unexpectedly, these events were generally the more severe events to have occurred since records began to be kept, although it is unlikely that the damage recorded in the Central North Island and Otago in 1969 and 1987 were from the same storm given the degree of spatial separation of the regions and the lack of recorded damage in other regions. Of the nine remaining wind events that caused damage in multiple regions, all except one (the July 2008 storm) caused damage to forests in two wood supply regions. In many cases, damage occurred in adjacent wood supply regions; however, the July 2008 event was particularly notable as it resulted in damage to forests in five wood supply regions. It was also one of the most severe storm events to hit New Zealand since Cyclone Bola in 1988.

Table 6 Summary of storm events that caused damage to multiple wood supply regions.

Date of event	Wood supply regions damaged[1]	Total area damaged (ha)	Notes
10-May-1957	Nelson (8), Canterbury (29)	37	Southerly gale force with rain
19-Apr-1968	Nelson (963), Canterbury (1000)	1963	Tropical storm/cyclone (Wahine)
1969	CNI (39.7), Otago (150)	189.7	Unlikely to be the same event
31-Jul-1975	Canterbury (11000), Otago (78)	11078	NW in Otago
1987	CNI (40), Otago (95)	135	Unlikely to be the same event
7-Mar-1988	Northland (690), CNI (25692)	26382	SE Tropical cyclone (Bola)
9-Nov-1994	East Coast (613), Hawke's Bay (270)	884	Westerly storm
16-Feb-2004	SNI (2463), West Coast (185)	2648	SW Storm
14-Oct-2004	Nelson (1138), Marlborough (75)	1213	SW Storm
10 & 11 July 2007	Northland (102), Auckland (51)	153	NE Storm
30 July 2008 (28th for CNI)	CNI (281), SNI (84), Nelson (1625), Marlborough (113), West Coast (489)	2592	E Storm in CNI, SNI, NE Cyclonic in Nelson/Marl
Total		46949	

[1] Numbers in parentheses refer to the area damaged in each region

2.6. Limitations of this type of approach

While the estimates of the average annual losses and probabilities associated with different levels of damage presented here are based on actual data, this approach does have limitations. In particular, the estimates are specific to the characteristics of the underlying population for which they were derived. Strictly speaking, these estimates are not valid when there have been changes in this underlying population, such as the distribution of forests, species composition, age class structure, management practices and the general wind climate. For example, the total area of planted forests in New Zealand has increased from 356 000 ha in 1950 to 1.8 million ha in 2009, while the rotation length for stands has decreased from over 30 years (and in many cases over 40 years) to less than 25 years in some instances.

This approach also requires a substantial time series of dependable data on the occurrence of wind damage. As noted previously, for those regions were there are fewer than 20 years worth of records (and particularly those where there are fewer than 10 years), the estimates of average annual loss should be treated with extreme caution. Nevertheless, provided that accurate records of wind damage events are maintained and if the underlying population remains relatively constant (i.e., there is no radical shift in silvicultural regimes or the location of forests), this approach should give useful information on the relative risk of damage between regions.

3. Description of the 2004 and 2008 Events

As noted previously, one of the key requirements in order to better understand and quantify the risk posed by wind damage is high quality information on events that have occurred and the damage resulting from them. For most of the major storms that have occurred in New Zealand (e.g., 1964 and 1975 storms in Canterbury, Cyclones Bernie and Bola in the Central North Island), descriptions of the storm event and the resulting damage are contained in published papers (see Table 1). After these events, the storms that occurred in 2004 and 2008 caused the most extensive damage to forests since records began (Figure 2); however, unlike these other events no published information exists describing the damage that occurred. The events that occurred in the Southern North Island and Nelson in 2004 were documented in unpublished reports (Cameron, 2004; Tolan, 2005), but damage resulting from the 2008 storm is still undocumented. Further efforts should be made to ensure that it is. We have highlighted some of the key information contained in the reports of Cameron (2004) and Tolan (2005), who describe the damage in the Southern North Island and Nelson, respectively, that occurred as a result of the 2004 storms and have provided information on the wind speeds recorded during the 2008 storm.

3.1. Damage in the Southern North Island – 2004

On Sunday February 15th, 2004 a low-pressure centre deepened east of the North Island directing a strong southeast airstream over the southern North Island and drawing in moist air from the tropics (Figure 9). This resulted in rain and strong gales in the Wellington region throughout the day. Overnight a small but intense low moved in close to the Wairarapa coast and accentuated the wind and rain, with the heaviest rain occurring between midnight and 6 am on February 16th (Watts and Gordon, 2004). The storm was also characterised by a long period of sustained rainfall rather than short intense rainfall. The maximum hourly (10-minute average) wind speed recorded at Wellington Airport was 87 km/h at 0500 on February 16th (Figure 10); wind direction at the time of this peak wind speed was 200° (i.e., SSW). The maximum 3-second gust recorded at Wellington Airport during this storm was 113 km/h (Figure 10). Higher wind speeds were recorded at other more exposed weather stations in the Wellington and Wairarapa regions.

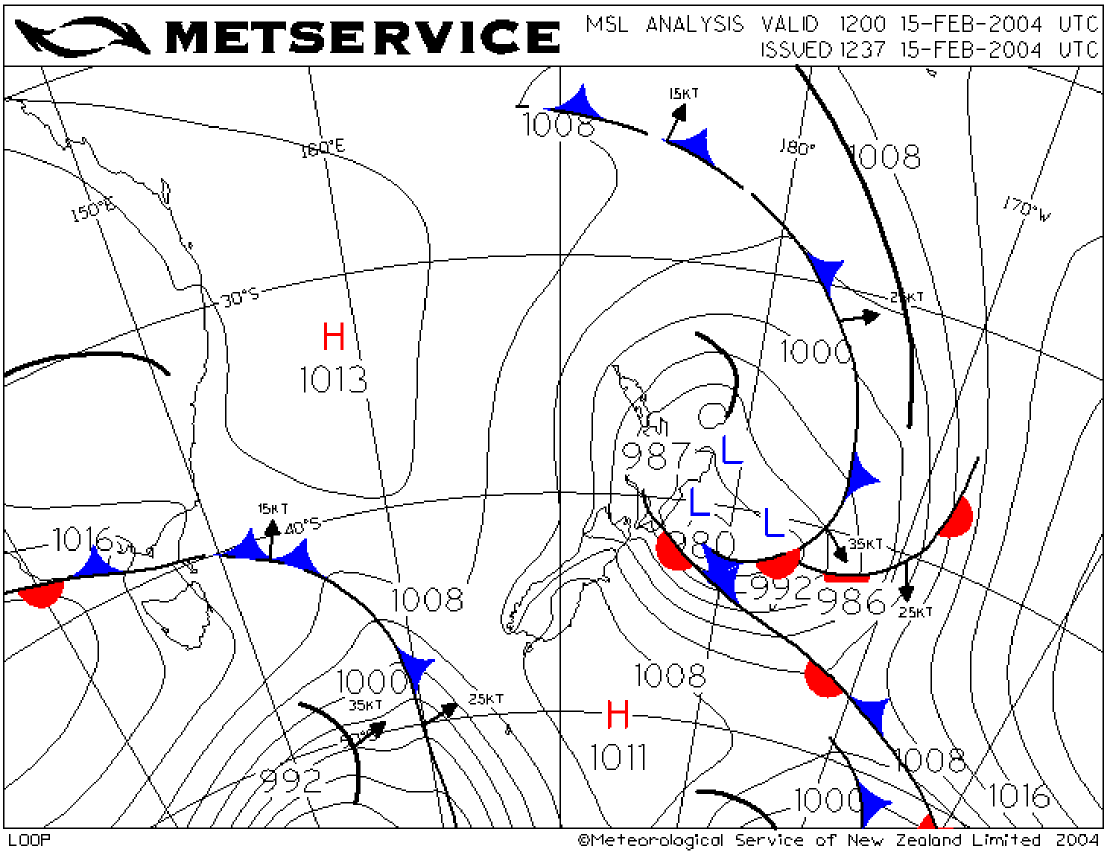

Figure 9. Synoptic weather chart for 1200 hours NZST on 15 February 2004.

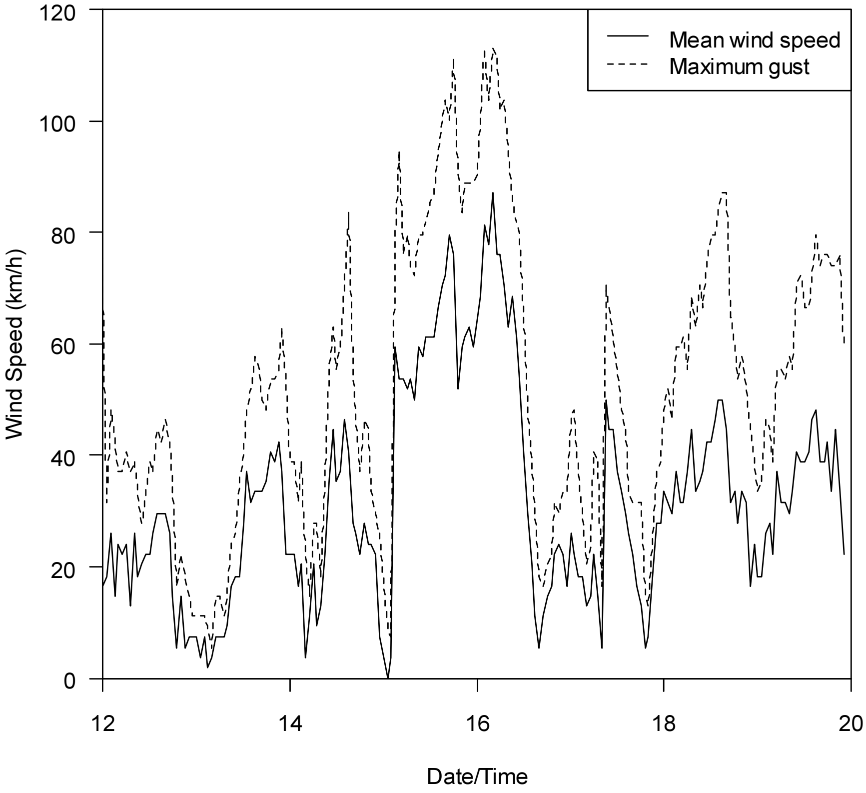

Figure 10. Hourly mean wind speeds and maximum gusts recorded at Wellington Airport between February 12th and 20th, 2004.

Some of the impacts of this storm were described by Cameron (2004), who estimated that between 1000 and 2500 ha of forest were damaged by both wind and flooding. Follow-up with forest owners and managers as part of this current project confirmed that the actual level of damage was at the upper end of the estimate produced by Cameron (2004). In 2004, survey forms were sent out to a number of forest managers to try to obtain more information on the characteristics of the damaged stands. While only a small number of returns were received, mostly from farm foresters, these highlighted the effect of thinning on the risk of damage. Many of the damaged stands were 10 to 11 years old and had been recently thinned (in one case in the month before the storm). Unfortunately, more detailed information on the location of damage and the characteristics of those stands that were damaged in larger estates was not able to be collated. It is recommended that, if possible, that these data should be collated and analysed.

3.2. Damage in Nelson and Marlborough – 2004

On October 14th 2004 strong southwest winds arising from a low pressure system to the west of New Zealand (Figure 11) caused severe damage to forests in the Nelson region. The damage caused by this storm was described in detail by Tolan (2005) and is summarised in the following section. The maximum hourly wind speed recorded at Big Pokoraro was 76 km/h on the morning of October 14th (Figure 12); wind speeds recorded at two other stations (New Dovedale and Takaka) were considerably lower.

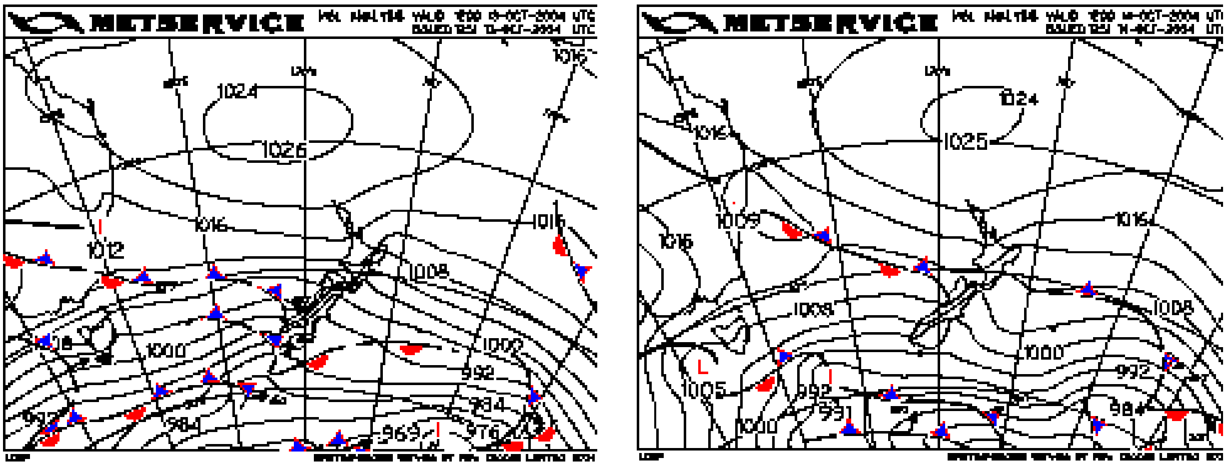

Figure 11: Synoptic weather charts for New Zealand on 13th (left) and 14th (right) October 2004.

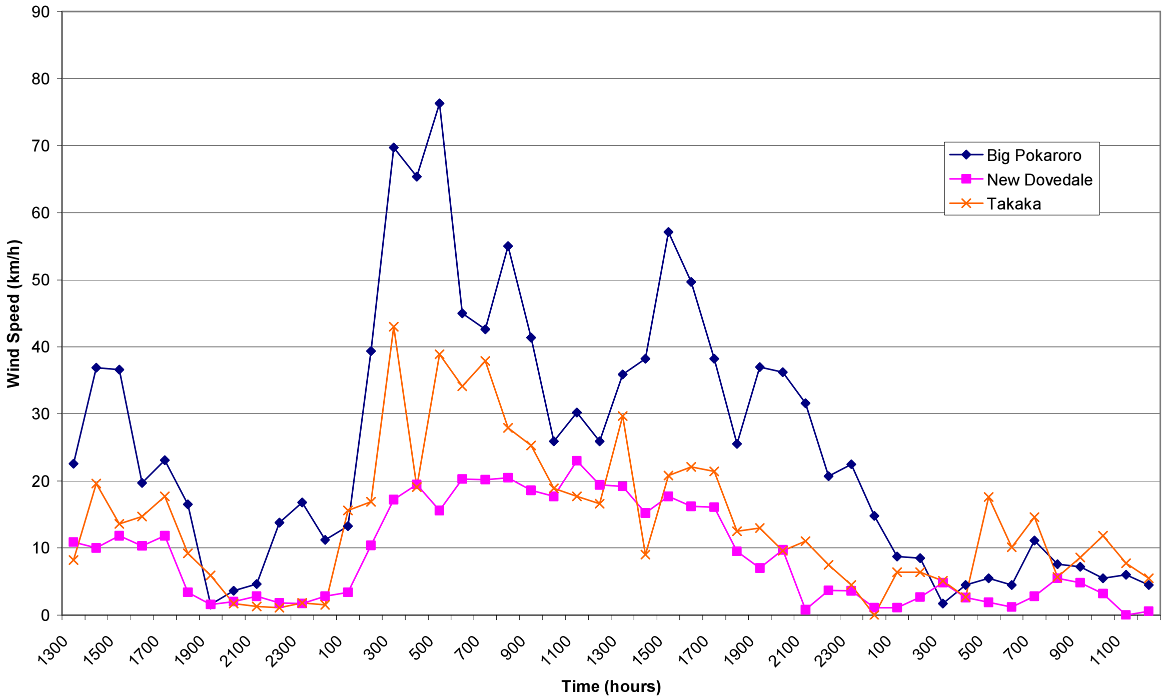

Figure 12: Hourly wind speeds from each weather station between 1300 13th October 2004 and 1200 15th October 2004.

Overall, there was 1112 ha of catastrophic wind damage in radiata pine stands in the estates of CHH Forests Ltd and Weyerhaeuser NZ Inc (managers of these forests at the time of the storm). The affected forest stands were scattered over a large area that stretched from Golden Downs and the Motueka Valley, over to the Wairau Valley. However, most damage occurred in and around the Golden Downs and Motueka Valley (Figure 13). The majority of the area that contained the wind-affected stands was established on Moutere gravels and the Separation Point granite soils in the Motueka river valley. Irvine (1970) commented that forests established on Moutere gravels exhibit shallow rooting, which could contribute to tree stability issues if soil moisture is high and wind is strong.

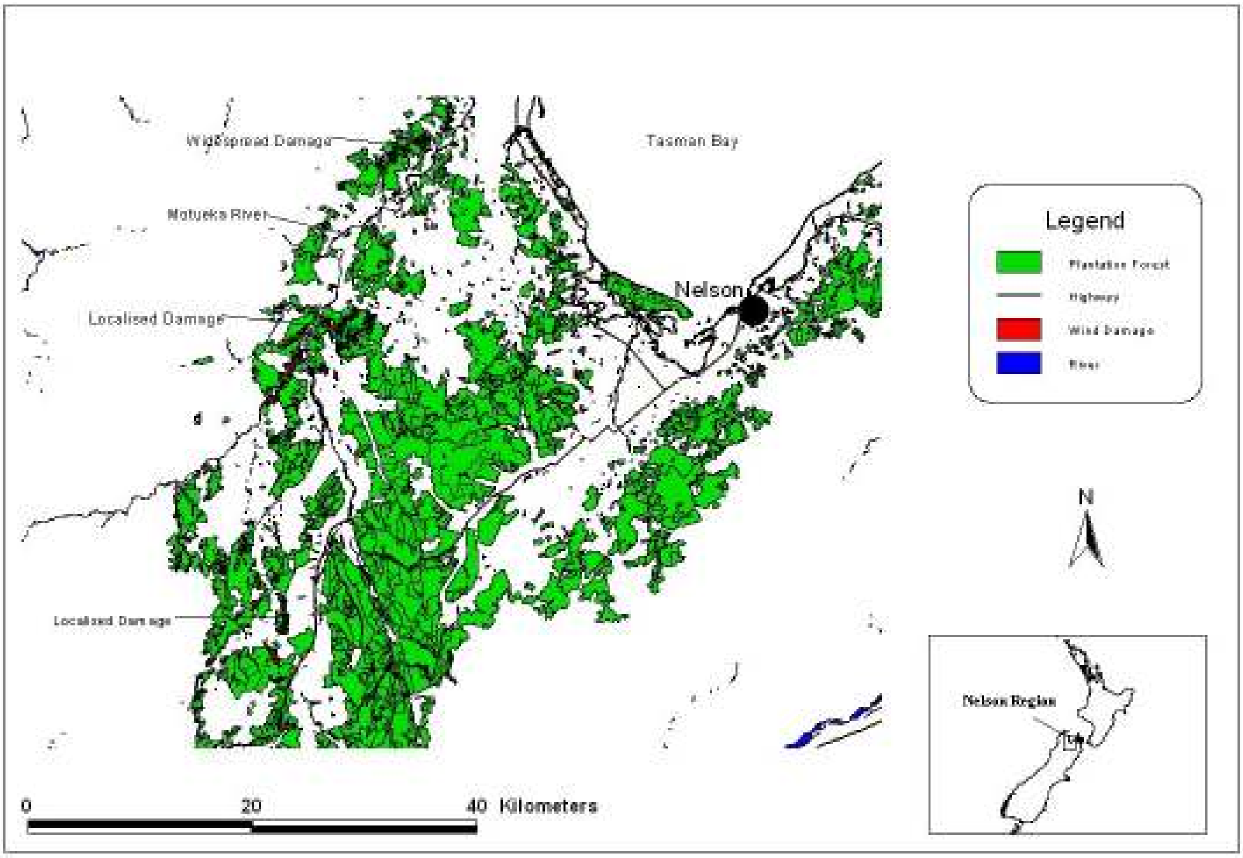

Figure 13: A map of the Nelson planted forest estate showing the location of damage from the wind storm (Planted forest polygons were obtained from Landcover Database 2).

Damage occurred in stands ranging in age from 18 up to 36 years (Figure 14). The average age of damaged stands was 25 years. Most damage occurred (both in terms of total area and proportion) in 27 and 32-year-old stands. This was related to the fact that these age classes corresponded to the rotation ages for the sawlog and clearwood regimes. Therefore, a large area of the forest estate contained stands of these ages that were awaiting harvesting. No stands under18 years old were damaged since there was only a relatively small area of the estate in the location affected by wind in these younger age classes. The risk of damage did not appear to be affected by thinning, primarily because the most recent thinning operations in those stands located near the main area of severe damage had been carried out nine years prior to the event, meaning the forests would have had enough time to close their canopies and achieve adequate diameter growth. In addition, the thinning regimes applied in stands around the Nelson estate involve an early thinning, between the ages of seven to eleven years, which would encourage stand stability from a young age.

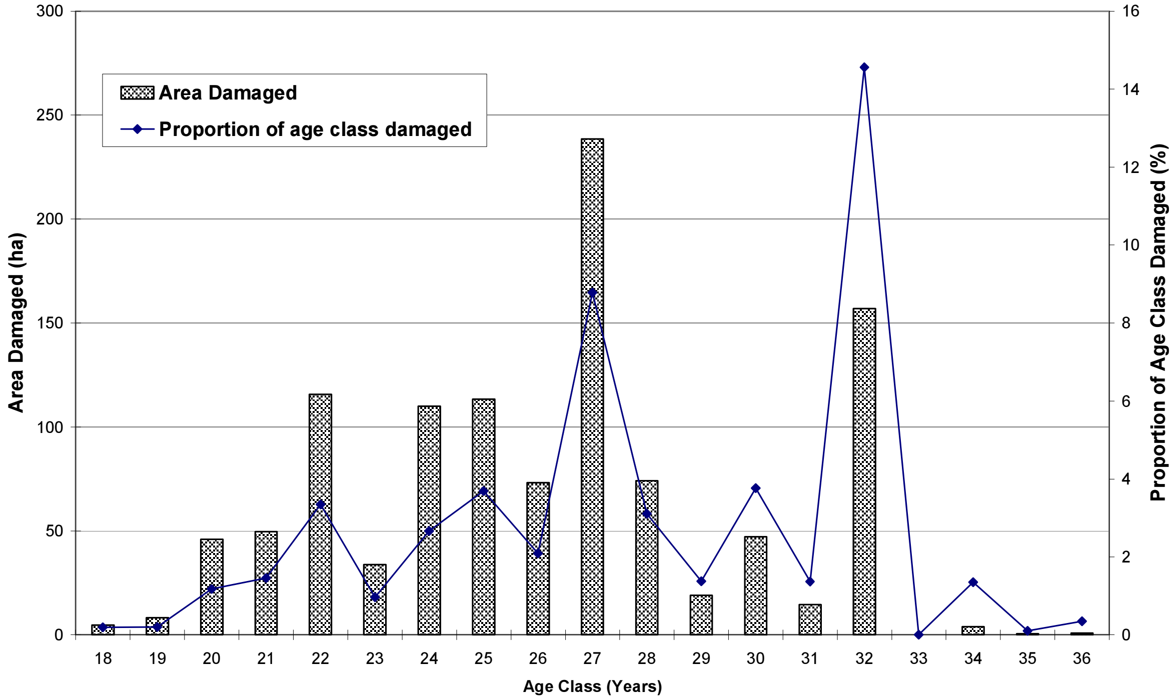

Figure 14: Area damaged by age class and the proportion of damaged area in each estate age class by the October wind storm event in the Nelson region.

3.3. Damage from the 2008 storm

Two storm events occurred in late July, 2008. The first has been described as “no ordinary storm” (McDavitt, 2008) due to the rate of decrease in air pressure as the low deepened. The centre of this storm travelled across the upper North Island from

Northland across to the Bay of Plenty and East Cape on July 26th and 27th (Figure 15). While winds along the coast gusted between 130 and 160 km/h between Cape Reinga and White Island, most of the damage to forests was caused by a much larger winter low that followed this storm and which took four days to travel from west of Northland to east of Southland. This storm is unique in terms of the distribution of damage throughout the country. Damage from previous storms has been confined to a single wood supply region, or occasionally to two adjacent regions; however, this storm caused damage in five different wood supply regions extending from the Central North Island to the West Coast of the South Island. Wind speed data from stations located in each damage region are shown in Figure 15.

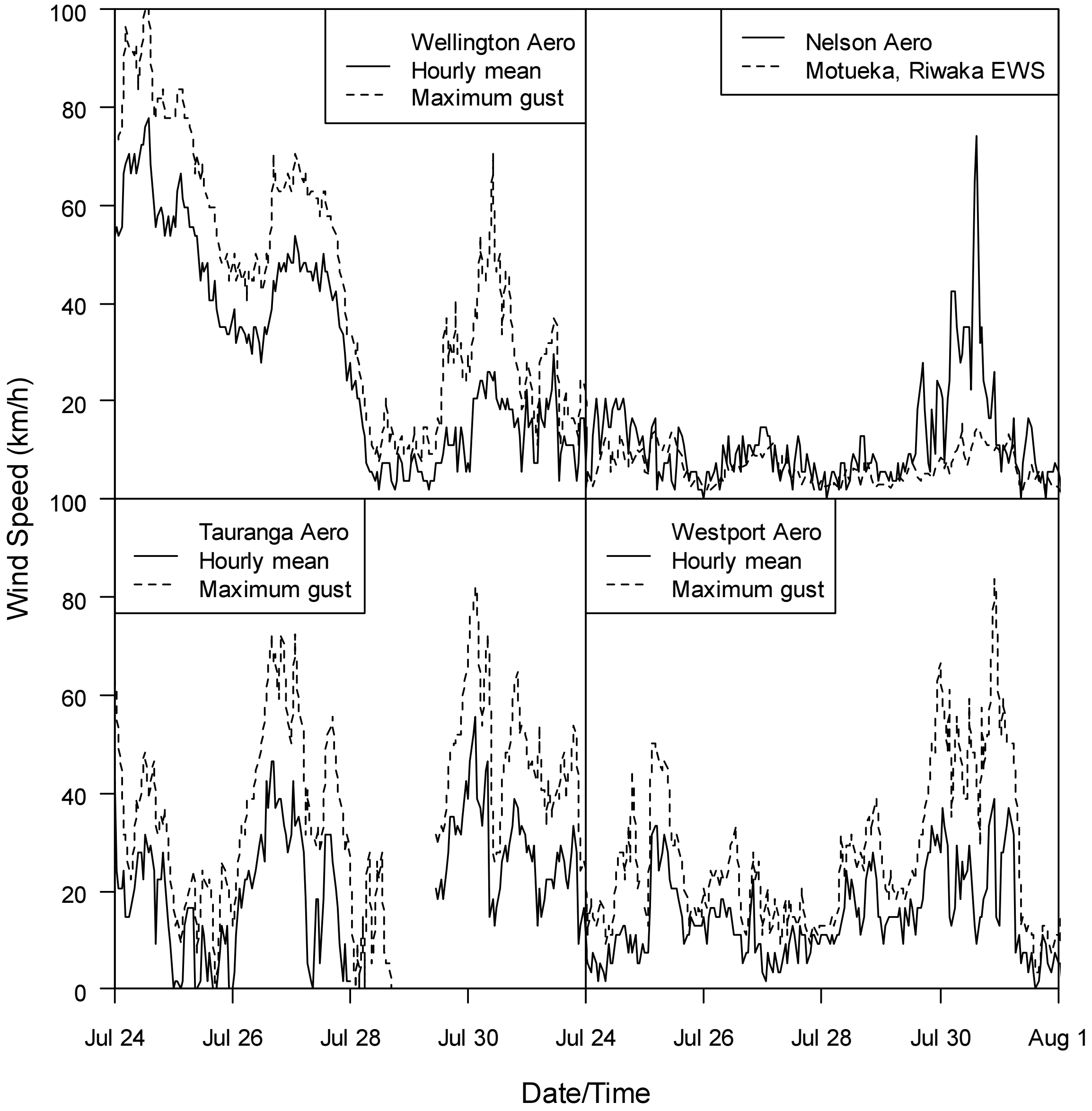

Figure 15. Wind speeds recorded in four regions where wind damage occurred in July 2008.

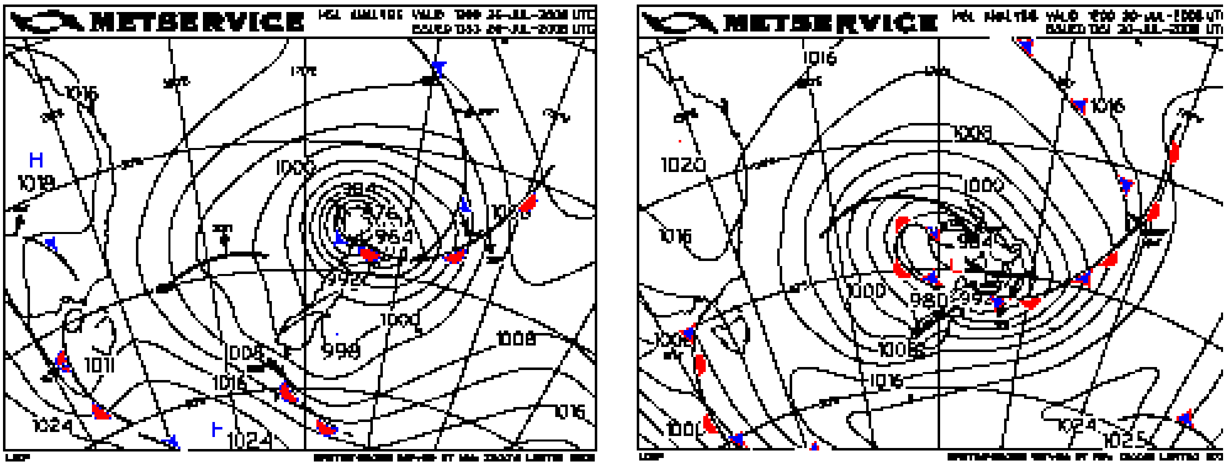

Figure 16: Synoptic weather charts for New Zealand on 26th (left) and 30th (right) July 2004.

At each station, maximum gusts of approximately 80 km/h were recorded on July 31st. High wind speeds were also recorded at Tauranga Aero on July 27th, and at Wellington Aero on July 24th and 27th. Gust information was not available for Nelson Aero, but a very high mean wind speed was recorded at 1500 and 1600 hours on July 30th. These mean hourly wind speeds were more than twice those recorded in the preceding and subsequent hours; it is not clear whether there were any recording issues at the time. This storm was also accompanied by heavy rain, which in addition to causing widespread flooding is likely to have created saturated soil conditions.

Some very general information about the location and extent of damage was obtained via the survey sent out to large forest owners. However, more specific information such as the age and structure of damaged stands, and the type of damage has not been collated. As with the 2004 event in the Southern Island, these data should be collated and analysed so that a robust time series of loss information is available.

4. Management of Wind Damage Risk

The preceding sections of this report have focussed on the quantification of risk; however, this is only one aspect of the process of risk management, which consists of:

- analysis of risk
- assessment of alternative courses of action

- choice of response to risk

In their review of risk management in forestry, Manley and Watt (2008) noted that risk analysis has received considerably more attention in the scientific literature than the other aspects. This is also true for the risk of wind damage. Manley and Watt (2008) also noted the inconsistency in the use of the term "risk" by those who study wind damage and those who work in the broader field of risk management. Von Gadow (2001) defines risk as "the expected loss due to a particular hazard for a given area and reference period", whereas the wind damage community frequently refers to risk as the probability that the hazard (i.e., wind of a particular magnitude will occur) will occur (Gardiner et al., 2008). This distinction is important when discussing risk management; while the hazard presented by wind cannot be controlled, the impact of this hazard on forest and thus the resulting expected loss can be managed.

In this section, we discuss the three broad strategies that can be adopted in managing the risk of wind damage, which are:

- acceptance of loss
- sharing of loss
- reduction of loss

We also briefly discuss the factors that influence the response of forest managers to the risk of wind damage, which include the level of calculated risk, their attitude to risk (often influenced by past experience of wind damage) and the context which is a function of factors including the objectives of management, and the scale of the enterprise.

4.1. Acceptance of losses

Because of the high proportion of damage caused by large magnitude, low frequency storms, many forest managers choose to accept the losses (Gardiner and Quine, 2000). Such a strategy does not necessarily imply a "do nothing" approach. In fact, it may involve extensive contingency planning to cope with an event once it occurs, for example, ensuring that there are sufficient personnel qualified to work in wind damage salvage (e.g., Childs, 1966; Grayson, 1989). However, for the owners of forests registered under the Emissions Trading Scheme, the losses are no longer limited to the opportunity cost of the potential revenue that was not realised, but also include the value of emissions units that may have to be repaid (see Section 3.2 in Manley and Watt (2008)). Therefore, the potential cost of adopting this strategy may mean that this is no longer a viable option, particularly for small to medium sized owners who could suffer losses to a significant proportion of their estate in a single storm. These owners may choose a more proactive approach to managing this risk of wind damage.

4.2. Sharing of losses

There are a number of mechanisms for sharing of losses and these are discussed in more detail by Manley and Watt (2008). Large corporate forest owners are often able to use their size to effectively "self-insure". Smaller companies and individual private owners lack the size to self-insure, particularly against catastrophic losses, and so must either purchase insurance or form an insurance mutual with other forest owners. A number of insurance products are available for the forestry sector and all but one of these offers cover for wind damage (see Table 4.1 in Manley and Watt (2008)). A survey of forest companies that own or manage more than 10,000 ha of plantation by Manley and Watt (2008) found that only 19% of the total area falling under such ownership (1,053,00 ha) was insured against wind damage. (Note: most of the post-1990 ("Kyoto") forests would not be included here because they are part of the estates of smaller private owners. Some of these forests are likely to be insured). Manley and Watt (2008) suggested that possible reasons why the level of insurance against wind damage wasn't higher include: (1) cost of premiums; (2) exclusion of young stands, i.e., toppling is not covered; and (3) there is often a limit on individual claims. This last point means that there could be a significant proportion of the "at-risk" value of an owner's estate that would not be covered in the event of wind damage. For example, Manley and Watt (2008) calculated that in a mature 50 ha plantation only approximately 45% its at-risk value (i.e., the net claim value of the trees plus carbon credits) would be insured if the limit on claims was $500,000. Therefore, in events such as the 2004 and 2008 storms it is likely that the levels of damage meant that the losses of some individual owners exceeded the limit on claims. Manley and Watt (2008) discussed other options for risk sharing including insurance mutuals or a national scheme coordinated by the government to cover the premature surrender of carbon credits in catastrophic events.

4.3. Reduction of losses

Another option available to forest owners is to try to reduce the risk of wind damage, either through risk avoidance or risk confrontation (Gardiner and Quine, 2000). Because the wind climate at a particular site cannot readily (if at all) be manipulated, risk avoidance is generally achieved though the choice of sites on which to practise forestry. There is considerable variation in the extreme wind climate of New Zealand (de Lisle, 1965; Reid, 1981) and this is reflected in the regional variation in the levels of wind damage that have occurred (Table 4). Therefore, one strategy for reducing the risk of wind damage would be for an owner to locate some or all of their estate in those regions that historically have been shown to have lower risk. Site selection can also apply at a more local scale; wind speeds are strongly influenced by terrain. Locations such as the tops of hills and valleys where the wind is channelled and accelerated could be avoided in favour of sites where local wind speeds are lower.

Risk confrontation involves the application of treatments to make trees, stands and forests less vulnerable to wind damage. At the individual tree level, options can include choice of species, quality of tree stocks, soil cultivation, and planting quality. At the stand level, options for risk reduction can include choice of initial spacing, timing and intensity of thinning, and rotation length. Finally, at the whole forest scale options can include manipulation of forest structure, distribution of age classes, timing of harvesting and location of harvesting units (Somerville, 1980; Quine et al., 1995). Two well-known and documented examples of risk confrontation occurred on the Canterbury Plains, due to the past history of wind damage in this region. In the first example, the structure of Eyrewell Forest was drastically changed by the then New Zealand Forest Service following the storm of 1964 (Swale and Inglis, 1984). The second example was the Selwyn Plantation Board's use of a silvicultural regime that aimed to reduce the risk of wind damage by promoting mutual sheltering of the trees, but which also aimed to reduce salvage costs and losses by minimising the amount of stem breakage (Studholme, 1995). In other regions of New Zealand, past experience of wind damage has generally resulted in a move away from late and severe thinning treatments as these have often been associated with increased risk (Somerville, 1980; 1995).

4.3.1. Investigating risk reduction strategies

Many risk reduction treatments are based on trial and error or from observations made following damaging storms. This is one reason why it is important to document and analyse data from storm events. However, even with good data it is often not straightforward to determine those factors that are associated with wind damage as there are often a number of confounding factors (Quine, 1995). For this reason, there has been considerable focus on the development of mechanistic models that predict the probability of the onset of damage, but not the magnitude of losses (Gardiner et al., 2008). Two of the most widely-used models are GALES and HWIND (Gardiner et al., 2000), which predict the critical wind speed required to damage a stand of trees based on an understanding of the underlying mechanisms causing tree failure, and then use some assessment of the local wind climatology to calculate the probability of such a wind speed occurring at point where the stand is located.

The GALES model has been applied to New Zealand forests (Moore and Somerville, 1998) and has been used to quantify the effects of different factors on the risk of damage. The structure of the model is shown in Figure 17. This model calculates the minimum wind speed at which the onset of damage occurs from information on the stand structure and the root anchorage strength obtained from tree pulling tests (e.g., Moore, 2000). An airflow model is then used to adjust this threshold wind speed for the effects of topography, and the average return period for this wind speed is then predicted using recurrence functions fitted to a time series of extreme values.

This model can be used to explore a number of different risk reduction strategies, such as choice of species, site, thinning schedules and rotation length. The model can be linked to a growth and yield simulator to enable wind risk to be considered when developing silvicultural regimes. It can also be used to investigate the potential impacts of future climate change on the risk of damage (e.g., Quine and Gardiner, 2002; Olofsson, 2006; Watt et al. 2008). As an illustrative example, we compared four different thinning scenarios that range from no thinning through to a late and severe thinning (Table 7).

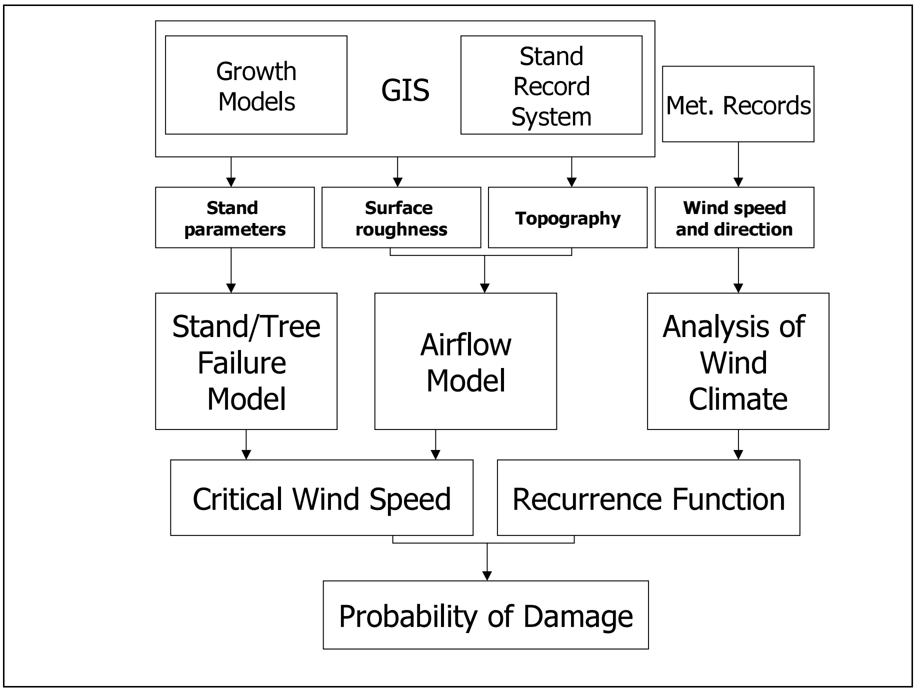

Figure 17. Schematic diagram of the deterministic/probabilistic wind risk analysis model.

Table 7. Description of scenarios used to illustrate the effect of thinning on the risk of wind damage

Operation	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Initial spacing	1250 trees/ha	1250 trees/ha	1250 trees/ha	1250 trees/ha
Thinning 1	600 trees/ha (Age 7)	600 trees/ha (Age 7)	250 (Age 13)	-
Thinning 2	-	250 trees/ha (Age 12)		-
Rotation length	32 years	32 years	32 years	32 years

The model shows that under all four scenarios the critical wind speed required to cause damage declines with increasing stand age beyond about 10 years (Figure 18). Therefore, the probability that this critical wind speed is exceeded will increase with age, which is consistent with empirical evidence indicating that older age classes generally suffer more damage in storm events. Comparison of the different thinning scenarios indicates that the critical wind speeds are considerably lower in the two scenarios where the stands were thinned to a residual density of 250 trees/ha. The timing of thinning also affected the critical wind speeds, with the stand thinned from 1250 trees/ha to 250 trees/ha in a single operation having a lower critical wind speed than the stand that was thinned to the same density, but in two operations. The model also shows the large decrease in critical wind speed following thinning which takes 3-4 years to recover. Again, this result is consistent with empirical observations that indicate a higher risk of damage immediately following a thinning operation (Somerville, 1989). The stand that was thinned to 600 trees/ha at age 7 years had a very similar critical wind speed to the unthinned stand. This scenario is similar to the regime employed by the Selwyn Plantation Board in their Canterbury Plains forests in order to reduce the risk of wind damage (Studholme, 1995).

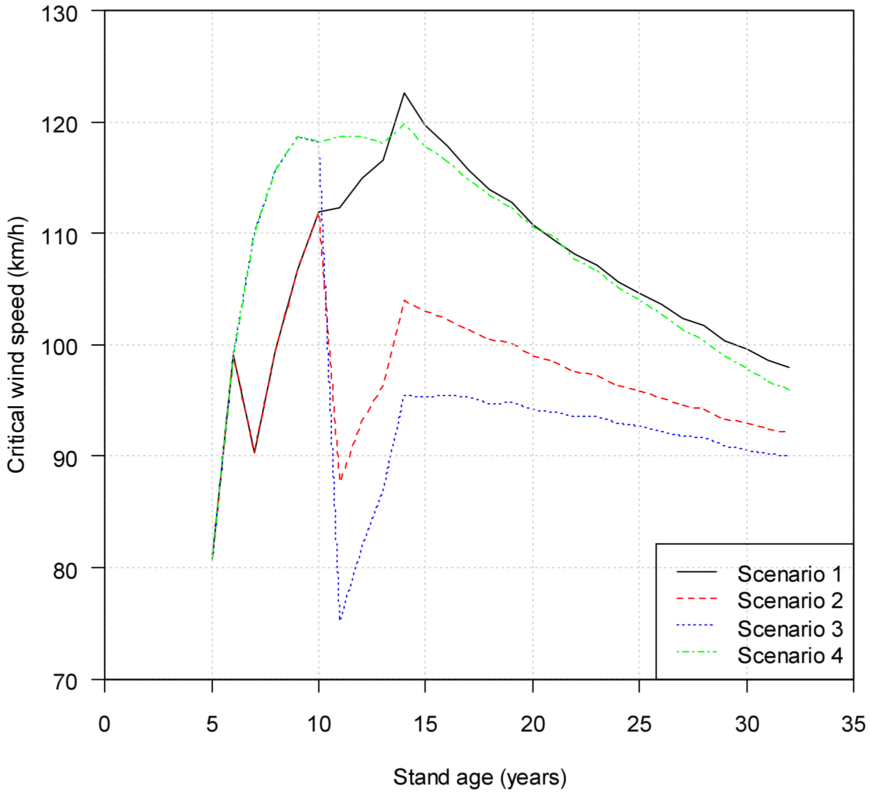

Figure 18. Comparison of critical wind speeds between four different thinning scenarios (see Table 7 for details of the scenarios).

4.4. Risk management in practice

So far, this section has focussed on how the risk of wind damage can be managed. Some insight into actual risk management practices in New Zealand was gained through a survey that was conducted of members of the New Zealand Forest Owners Association in 2003. The majority of respondents (59%) reported that their silvicultural practices explicitly focus on minimising or reducing the risk of wind damage. Of those respondents whose silvicultural practices focus on reducing the risk, the most common method employed for reducing the risk of damage was to manipulate the timing and intensity of thinning (92% of respondents). Choice of species, final crop stocking level and location of clearcut boundaries were also identified as common approaches for reducing the risk of damage (41%, 51% and 41% of respondents, respectively). Only one respondent indicated that they reduced rotation length in order to reduce the risk of wind damage. A number of other approaches for reducing the risk of damage were also suggested. These included: planting method, soil cultivation (i.e., deep ripping), direction of planting lines, increased initial stocking, and sail pruning. Many of these approaches are designed to reduce the risk of toppling in young stands, rather than focusing explicitly on older stands. Of those respondents whose silvicultural regimes did not explicitly focus on reducing the risk of wind damage, twenty-four offered reasons why. The most common reason was that the level of risk did not warrant it (18 out of 24 respondents), followed by the belief that these methods are not effective at reducing the risk (13 out of 24 respondents). This may reflect the fact that in the most severe storms, stands are damaged because they are located where the strongest wind occurred and that it is unlikely that any risk reduction actions would have been effective. Approximately one-third of respondents (9 out of 24) believed that risk reduction methods were not cost-effective.

5. Discussion and Conclusions

The dataset assembled here represents the most comprehensive time series of the area of planted forests lost to wind damage. Records documenting approximately 11 000 ha of damage that has occurred since 1990 have been added to the earlier dataset assembled by Somerville (1995). While the average annual area of wind damage is approximately 1000 ha, the distribution of area damaged is highly skewed with less than 200 ha of forest damaged in most years. High levels of damage occurred during three major events (the 1975 storm in Canterbury, Cyclone Bernie in 1982 and Cyclone Bola in 1988) which between them account for nearly two-thirds of all recorded damage. In contrast to previous studies that have calculated average annual levels of damage, we attempted to model the probability of occurrence of different amounts of annual damage. The generalised Pareto model that was initially developed exhibited considerable lack of fit due to the large amount of damage that occurred in 1975 and1988, and therefore years where the area damaged exceeded 5000 ha had to be removed in order to improve the model fit. The resulting model still exhibited some lack of fit, but a trade-off had to be made between this lack of fit and the model utility. Removing those years where the annual level of damage exceeded a certain threshold had very little effect on the predicted probabilities of occurrence for annual levels of damage below 1000 ha, but did have a considerable effect on the predicted probabilities for higher levels damage.

In modelling extreme events, it is difficult to predict the probabilities of occurrence for the largest events for which the average return period is similar to, or exceeds, the length of record available. Our analysis indicated that this appears to be the case for the levels of damage that occurred in 1975 and 1988. Despite problems with estimating the probability of occurrence of the most extreme events, the model does provide a useful tool for quantifying the risk of wind damage for the levels of annual damage that typically occur; for the analysis period considered there were only eight years when the area damaged exceeded 1000 ha and five years when it exceeded 2000 ha. The key outcome from the model is that is shows how the probability of damage declines exponentially, e.g., the probability that a total of 50 ha is damaged in a year is approximately 0.5, while the probability that 1000 ha is damaged is less than 0.1.

In addition to the temporal variation in the risk of damage, this study has also highlighted the spatial variation. In this analysis, risk was expressed as the percentage of net stocked area damaged by wind in each of the wood supply regions. Levels of damage in the most affected wood supply regions were 15 to 20 times greater than those in the least affected regions. We also obtained similar results to those of Somerville (1995) for the regions common to both studies, with the exception of Canterbury where the risk had decreased considerably due to a relative absence of wind damage since 1975. Regions such as the Southern North Island, West Coast and Nelson have incurred significant damage since 1990 (mainly since 2000) and are notable for their relatively high level of risk. In fact, the Southern North Island has a higher level of risk (expressed as the average annual percentage of net stocked area damaged) than Canterbury, which was formerly the region with the highest level of risk. However, only a comparatively short time series of records is available for the Southern North Island and therefore this result should be treated with caution. In particular, the decision to choose 2003 as the start of the analysis period has a large effect on the estimated annual level of loss. Had we chosen 1990 as the start date and made the assumption that any large damage event would have been recorded, the average annual level of damage would be reduced from 0.94% of net stocked area to 0.30%. A similar situation exists in those other regions where there is only a short length of record.

In addition to the average catastrophic damage that we have calculated here, there will be further losses resulting from damage to individual trees (or small groups of trees). Some of these losses will be accounted for in the mortality functions contained in growth and yield models, but any losses over and above this level will reduce the increment in carbon stocks in a forest. The magnitude of these attrition losses was not determined here, but they could be estimated using data contained within the Permanent Sample Plot system following the approach taken by Somerville (1995).

The spatial extent of damage in individual events suggests that one risk management option for small to medium sized forest owners would be to spread their risk by locating their estate in multiple wood supply regions, as historical data show that damage is generally confined to a single region, or at most to two adjacent regions. This could be achieved by individual owners purchasing forests in several different wood supply regions, or possibly through groups of owners joining together to form an insurance mutual as discussed by Manley and Watt (2008). Insurance cover is also available, but in the case of larger events damage to the estates of individual owners may exceed the limit on single claims. From our modelling, storms that cause the extent of damage recorded in the 2004 storm in the southern North Island (i.e., ~ 2500 ha) have an average return period of approximately 25 years.

The other main risk management option available to forest managers is risk reduction. This can be achieved through risk avoidance, which involves choosing locations that have a lower risk of damage. Site selection can be done at the regional level, i.e., selecting those regions that historically have a lower incidence of wind damage, as well as at the more local scale with respect to topography. Clearly, a number of other factors such as land availability, growth rates, access, distance to markets, etc. will be the main inputs to decisions about site selection, but the degree of wind damage risk could have a considerable bearing, particularly for more risk averse forest owners. An example of the inclusion of risk into site selection decisions is the awareness of site factors on the risk of wind damage to young trees (i.e., toppling) (Moore et al., 2008).

The other main risk reduction option we have focussed on is risk confrontation. Two of the key factors associated with previous damage events have been the creation of new abrupt edges and thinning, particularly when it is carried out late in the life of the stand and the reduction in stand density is high (Somerville, 1980; 1989). In addition, choice of species, initial spacing and rotation length can also affect the risk of damage. Therefore, there is considerable opportunity to influence the risk through forest management practices; depending on the decisions made the risk can be reduced, but conversely can even be increased.

In this report we provided an illustrative example of how a mechanistic risk model can be used to develop and test various silvicultural strategies for reducing the risk of damage. The model shows, as intuitively expected, that the risk of damage increases substantially when thinning is carried out later in the life of a stand and the reduction in density is severe. It also highlighted the period of high risk immediately following thinning, when the wind is able to penetrate deeper into the stand and the wind loading acting on each individual tree is much greater; over time the trees will acclimate to their new environment and the stability of the stand will increase.

We have deliberately avoided attempting to prescribe silvicultural regimes that would reduce the risk of wind damage for those forests registered under the Emissions Trading Scheme; the development of regimes is the responsibility of the forest owner, and wind risk is but one factor that must be considered along with many others. The extent to which wind risk influences the choice of silvicultural regime will depend on an individual forest owners' attitude towards risk. However, we do recommend that consideration be given to the risk of wind damage when decisions on thinning and harvesting of stands are made. This does not necessarily mean evaluating potential regimes using a mechanistic risk model; past experiences of wind damage and common sense may be sufficient. The earlier survey of members of the New Zealand Forest Owner's Association suggests that forest managers are already giving some consideration to the risk of wind damage in their silvicultural decision making.

As a final point, and also repeating one that we have made several times in this report, we cannot overemphasise the need to document actual wind damage events. Not only is information about the large events in 2004 and 2008 required, but we also need to capture information from smaller events as these are by far the most common. Our knowledge about the influence of site and stand characteristics on the risk of damage is largely developed through the analysis of data collected from actual events. Without long-term accurate records of the extent of wind damage it is not possible to quantify the risk of wind damage. This information is also used by insurance companies to calculate risk and therefore to calculate premiums for wind damage insurance. In the absence of complete information, insurance companies are likely to adopt a conservative approach which will most likely result in increased cost of insurance for forest owners.

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