provided through the Logging Industry Research Organisation Ltd by the Foundation for Research Science and Technology.

REFERENCES

Clerk, R.L and J.W. Worley. (1994): "Accuracy of DGPS Position Information from Land Based Moving vehicles with a C/A Code GPS Receiver". Presented at the 1994 ASAE meeting. Paper No. 94-3545, ASAE, 2950 Niles Road, St Joseph, MI 49085-9659, USA.

D'Eon, S.P. (1995): "Accuracy and Signal Reception of a Hand-held Global Positioning System (GPS) Receiver". The Forestry Chronicle 71(2):192-196.

Firth, J. and R. Brownlie. (1994): "Accuracy of GPS for Updating Forest Maps: The Marlborough Sounds Experience". LIRO report Vol. 19, No. 13.

Flaherty, M. and G. Rowe. (1997): "The Use of New Technology for Surveying and Mapping in the Forestry Sector". NZ Institute of Surveyor's Journal, 287, April 1997.

Jalinier, C, and J. Courteau. (1993): "Forest Road Surveys with GPS". Forest Engineering Institute of Canada, Technical Note TN-196, 6 p.

Jasumback, T. (1995): "Trimble CENTURION GPS Receivers". Engineering Tech Tips, February 1995, USDA Forest Service Technology and Development Program.

Jasumback, T, (1996): "GPS Evaluation: West Coast Test Site". Operational GPS Support Tech Tips, September 1996, USDA Forest Service Technology & Development Program.

Lachapelle, G. and J. Henriksen. (1995): "GPS Under Cover: The Effect of Foliage on Vehicular Navigation". GPS World, March 1995: 26-35.

Lawrence, M., J. Firth, and R. Brownlie. (1995): "Three Forestry Applications of the Global Positioning System (GPS) in New Zealand". NZ Forestry, 40(2): 21-22.

Marshall, G, (1996): "Characterizing Accuracy of Trimble Pathfinder Mapping Receivers". Proceedings of the 2nd Trimble Surveying and Mapping User Conference & Exposition, San Jose, USA.

New Zealand Forest Research Institute, (1992): "Satellite Navigation in Forestry". What's New In Forest Research, No. 222, 4 p.

Petersen, C., (1990): "Into the Woods with GPS". GPS World, Nov./Dec. 1990: 31-36.

Rempel, R.S., A. R. Rodgers, and K. F. Abraham. (1995). "Performance of a GPS Animal Location System under Boreal Forest Canopy". J. Wildlife Management, 59(3): 543-551.

Trimble. (1992): "General Reference for the GPS Pathfinder™ System". Document No. 18470-00, Trimble Navigation, Ltd., Sunnyvale, CA 94088-3642, USA.

Trimble. (1994): "An Introduction to GPS Mapping and Data Capture for GIS Applications". Trimble brochure Lit ID# 1-611-0280-6/1994. Trimble Navigation, Ltd., Sunnyvale, CA 94088-3642, USA.

ARTICLES

Assessing the risk of wind damage to plantation forests in New Zealand

John Moore and Alan Somerville[1]

Abstract

Current techniques for assessing the risk of wind damage to plantation forests attempt to rank different sites and/or silvicultural treatments, but cannot successfully assign a probability value to the occurrence of damage. Probability values derived from historical records of wind damage events are only applicable to stands with the same structure and location as those from which the historical records were obtained. Since 1994 research at the New Zealand Forest Research Institute and the British Forestry Commission Northern Research Station has focused on the development of a fundamentally-based system designed to predict both site wind speed at which a stand is likely to fail and the probability of occurrence of wind speeds in excess of this threshold value. This approach will allow evaluation of the effects of geographic location and changes in species selection, silviculture and rotation age on the risk of wind damage.

Introduction

A number of classification systems have been devised to assess the risk of wind damage to forests. Many of these rank the relative risk of different sites and/or silvicultural treatments, but do not assign a probability to the likelihood of damage. One such system is the British Windthrow Hazard Classification (Booth 1977, Miller 1985, Quine and White 1993) which combines an assessment of geographical locations in which damage is likely to occur with an estimate of when in the life of the crop it may take place.

Quantitative assessments of risk require magnitude and frequency data on the occurrence of wind damage. The probability of wind damage can be derived from a time series of wind damage records. In New Zealand records date back to the 1940s. Many of the main events are documented in published accounts (Wendelken 1955; Prior 1959; Wendelken 1966; Chandler 1968; Irvine 1970; Wilson 1976; Somerville 1989) and unpublished records, inventories and aerial photographs. During the 50-year period to 1990, New Zealand's plantation estate has suffered over 50,000 ha of catastrophic wind damage, defined as continuous damage covering more than one hectare (Somerville 1995). Damage in many of the worst wind storm events has been aggravated by orographic lee waves and wind channelling associated with mountainous topography. These effects are most prevalent in the Canterbury Plains, due to the Southern Alps, and in the central North Island, due to the eastern chain of mountains (Littlejohn 1984). A large proportion of the damage was directly associated with management activities, particularly recent clearfelling, late thinning and the creation of new non-windfirm stand boundaries. Documentation of damage to young plantations, and attritional losses in stands from smaller storm events is rare. However, stand condition and wind damage in plantation

[1] *Scientists, New Zealand Forest Research Institute, Private Bag 3020, Rotorua.*

Wind damage at Balmoral Forest resulting from 1975 storm. Damage is a mixture of storm breakage and uproot. Photo: Alan Papesch

Stem breakage at Kaingaroa Forest caused by Cyclone Bola in 1988. (Copyright Forest Research.)

Tree winched over at Maramarua Forest which has failed by stem fracture. Photo: John Moore

forests have been monitored in permanent sample plots (Dunlop 1995) and these records offer some information about attritional loss.

Somerville (1995) quantified the risk of catastrophic and attritional wind damage to radiata pine and Douglas-fir stands in the State-owned forests (259,950 ha) most seriously affected by wind from 1940 through to 1990. Risk was quantified as the average percentage of net stocked area (NSA) lost per annum to either catastrophic or attritional damage during this period. Catastrophic type damage ranged from 0.02% to 3.65% of forest NSA lost per year and an overall weighted average (based on area in 1990) of 0.38% was determined. Corresponding levels of attritional damage losses ranged from 0.08 to 0.34% (for forests with sufficient observations) and a weighted average loss of 0.25% NSA per annum. Over the course of a 28-year rotation a plantation could, on average, be expected to lose 12.2% NSA due to wind damage. In this paper, problems associated with use of this approach in risk assessment are discussed and the current stage of development of a new system designed to predict the risk of wind damage in specific areas is described.

A more fundamental approach to wind risk assessment

The derivation of the probability of occurrence of wind damage from historical records of damage events requires complete records of all events occurring over many years and few changes in the forest area and structure (Quine 1995). Two main problems arise during application of risk factors derived from historical damage events to the current plantation estate. Firstly, past incidence of wind damage is a function of crop type, and current forest structure and management regimes are likely to differ from those of the original plantation estate. Secondly, the geographic location of areas providing information on the level of risk may be different from the current areas of interest. The levels of attritional and catastrophic risk reported by Somerville (1995) were derived from an area corresponding to approximately 20% of the current plantation estate. As an example of changes in geographical location, 63% of the forest area analysed by Somerville was located in the Central North Island. In 1995 only 36% of the New Zealand forest estate was located in this region (Ministry of Forestry 1995).

While analysis of historical records has allowed the overall probability of occurrence of wind damage to be estimated, subject to the caveats discussed above, it has not provided an indication of the point in the rotation when damage is most likely to occur. A tree's vulnerability to wind damage will change with wind climate and changes in the morphology of the tree as it grows (Quine 1995). Siting, growth and management of a tree all influence its vulnerability. It is appropriate then to express the susceptibility of a tree to wind damage in terms of the threshold (or critical) wind speed required to uproot or break the tree. Accordingly, the risk of wind damage at a particular site can be defined as the probability of the threshold wind speed being exceeded at that site.

Since 1994 researchers at the New Zealand Forest Research Institute and at the British Forestry Commission, Northern Research Station have worked on the development of an integrated modelling system that uses airflow modelling technology and fundamental engineering theory to predict the risk of wind damage to forests as a function of geographic location, site variables and stand structure. The system comprises two main submodels: the Stand/Tree Failure Model and the Airflow Model

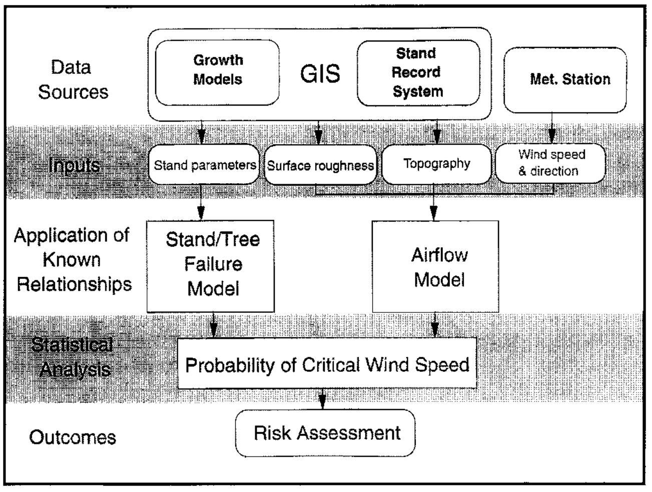

Figure 1. Flow diagram showing the components of the system for assessing the risk of wind damage. The inputs to and the outputs from the stand/tree failure and airflow models are managed in a geographic information system (GIS). The risk of wind damage is the probability that the critical wind speed for damage will be exceeded.

(Figure 1). These models predict the minimum site wind speed at which a tree with average dimensions within a stand (the "mean tree") is likely to fail, while the probability that this wind speed will be reached or exceeded is determined using functions fitted to time series of historical wind speed data. Inputs into these models are obtained from stand records, growth models, meteorological stations and digital terrain models (DTM) which are managed in a Geographic Information System (GIS). The principle output from the system is a map delineating areas of common wind risk.

Stand/Tree Failure Model

Wind damage occurs, and a tree can be assumed to fail, when the overturning moment caused by the wind exceeds the maximum resistive moment that the tree can provide (Petty and Swain 1985). The maximum resistive bending moment is the maximum resistance offered by the root and soil plate to uprooting or by the stem to breaking. Previous studies in which trees were winched over to the point of failure demonstrated strong correlations between the maximum resistive bending moment and measures of tree size expressed as dbh, stem volume and stem weight (Fraser 1962; Smith *et al.* 1987; Frederickson *et al.* 1993). More than 180 records of winched-over radiata pine and Douglas-fir trees of different age growing on different soil types have been collected. From this database, strong linear relationships for predicting maximum resistive bending moment, in terms of stem volume and soil type, have been developed. An example is shown in Figure 2. Significant differences in resistive bending moments have been found between trees growing on clay soils and those growing on pumice, stony and sandy soils.

The overturning moment has two components: the lateral force applied to the tree crown by the wind and the moment created by the mass of the offset stem and crown. A relationship which can be used to calculate the maximum applied moment due to the wind acting on the tree has been derived by combining engineering theory (Raupach 1992) with data from wind tunnel tests (Gardiner *et al.* 1995). Figure 3 shows an example of the application of this relationship to a stand which has been thinned at a mean crop height of 18 m. It can be seen that the threshold wind speed decreases over time and that there is a rapid decrease following thinning. The Stand/Tree Failure Model calculates the maximum resistive bending moment for the "mean tree" within a stand and then determines the threshold wind speed that will cause this tree to fail. This model has also been incorporated into the stand growth simulation package STANDPAK (Whiteside 1990).

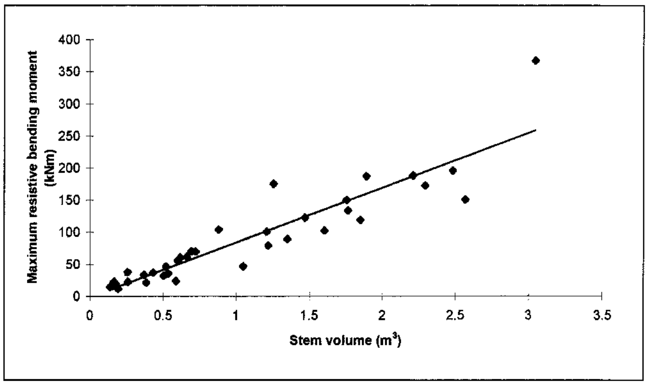

Figure 2. Relationship between maximum resistive bending moment and stem volume for trees growing on yellow-brown pumice soils.

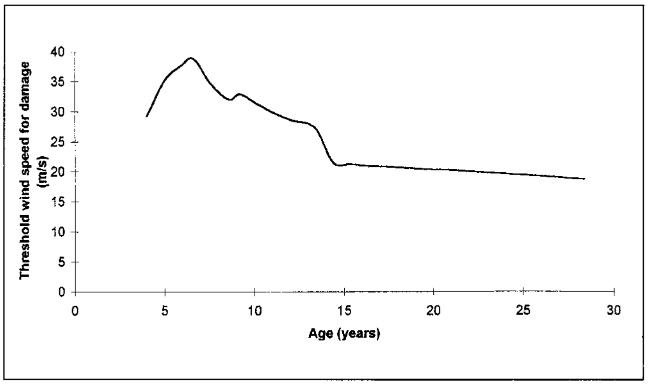

Figure 3. The predicted relationship between age and critical wind speed for a radiata pine stand which is production thinned at age 14 (mean crop height 18 m).

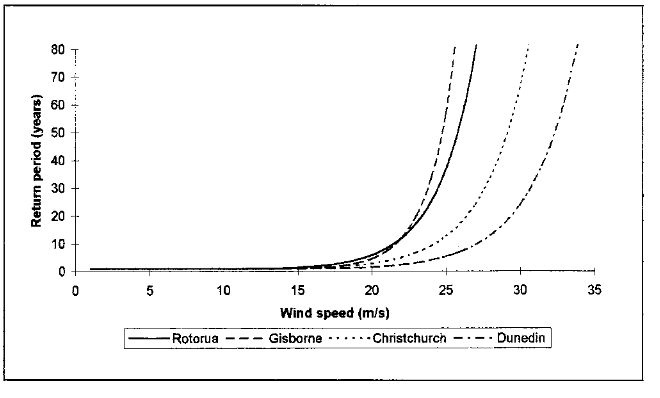

Figure 4. The relationship between wind speed and recurrence (expressed as return period) for four airport meteorological stations: Rotorua, Gisborne, Christchurch and Dunedin.

Airflow Model

The risk of wind damage is dependent on the location of a tree with respect to local and large-scale topography.

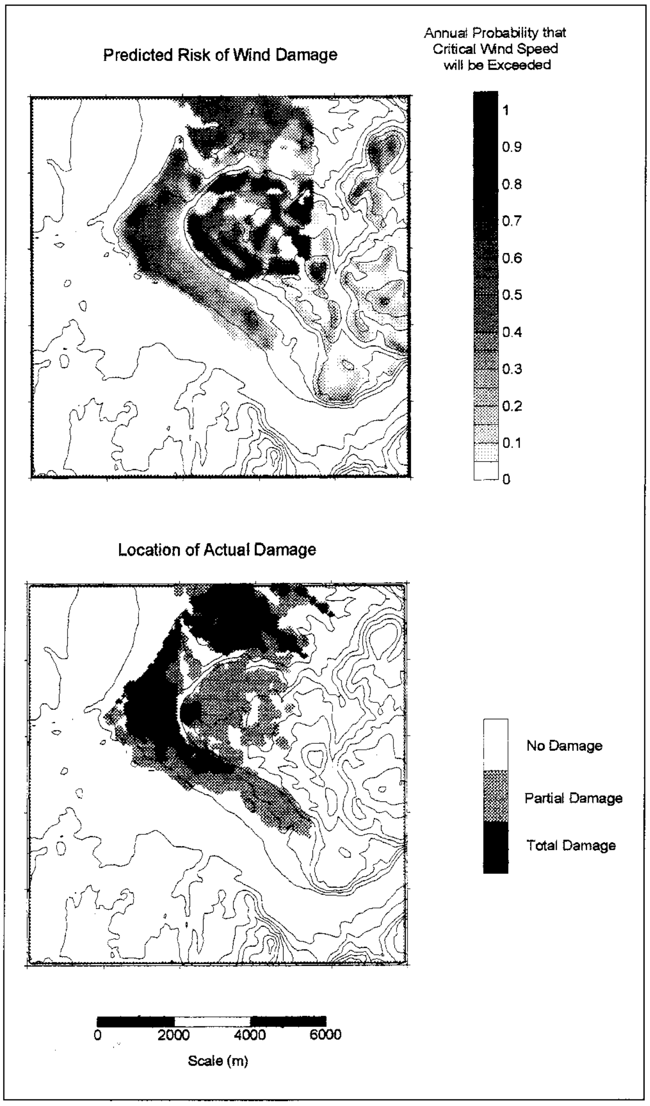

Figure 5. Comparison between areas of predicted wind risk and areas of actual damage for the Kinleith Forest case study site.

In complex terrain, wind speed and direction are both influenced by topography with wind being accelerated over hill tops and funnelled through valleys. The level of risk at a particular location can be assessed from comparisons between site wind speed and the wind speed at a reference point (usually a meteorological station). Comparisons can be made in a number of ways ranging from simple statistical tests of significance through to complete meteorological analysis. Four computer models designed to predict the effects of local topography on the pattern of airflow have been evaluated. Predicted wind speed and direction were compared with observations made at two sites; Cowal Peninsular in Scotland and the Manawatu Gorge in New Zealand. Results of these tests (unpublished data) indicate that in very complex (i.e. steep) terrain, prediction errors were significantly larger than those encountered by Walmsley *et al.* (1990) in more simple terrain.

The probability that the threshold wind speed will be equalled or exceeded at a given forest site can be determined by performing an extreme value analysis (Cook 1985) on a time series of meteorological data from the nearest long-term recording station. An example of the relationship between wind speed and recurrence at the Rotorua, Gisborne, Christchurch and Dunedin airport stations is shown in Figure 4. For the stations indicated, the return period of a given wind speed is lowest at Dunedin airport. The non-linear nature of the relationship means that a small change in the critical wind speed can lead to a major change in the risk of wind damage.

Topography, soil type, tree height, diameter and stocking can vary significantly over short distances. The overall wind risk assessment system uses these variables to generate maps delineating areas of common wind risk. Use of a Geographic Information System (GIS) will allow rapid integration of the many different data sources, including those which are temporally and spatially dynamic.

A prototype version of the risk assessment system has been applied to case study sites in Glenbervie, Kinleith, Mangatu and Mohaka Forests where wind damage has occurred. In Mohaka and Kinleith Forests, which had less complex topography, there was a good correlation between the definition of areas of predicted high risk and areas of actual damage (Figure 5). At Glenbervie and Mangatu, the correlation was not so good, due mainly to the inability of the Airflow Model to accurately predict wind speed in complex terrain. Accurate prediction of wind speed in complex terrain clearly requires further research effort.

It is intended that forest managers will eventually use the wind risk assessment system to evaluate sites, species and management in terms of the risk of wind damage.

Conclusions

Assessments of the risk of wind damage derived from historical records should be treated with caution. Results may not apply to parts of the current estate located in regions from which data has not been obtained, or to forests whose structure and management do not correspond to those of the stands from which the historical records were obtained.

A more fundamental approach is being developed in which both the threshold site wind speed causing damage, and the probability that it will be exceeded, are determined. This approach will allow evaluation of the effects of geographic location and changes in species selection, silviculture and rotation age on the risk of wind damage.

The risk of wind damage increases dramatically with a slight reduction in the critical wind speed. Operations such as late production thinning will therefore increase wind risk. At sites where the effect of topography on wind speed can be accurately modelled, it is possible to predict areas of high risk.

Acknowledgements

The development of the fundamentally-based system for assessing the risk of wind damage in New Zealand forests has been funded jointly by the Foundation for Research, Science and Technology and by CHH Forests Ltd, Fletcher Challenge Forests Ltd, P.F. Olsen and Company Ltd, Selwyn Plantation Board Ltd and Wenita Forest Products Ltd. The assistance of the British Council in providing funds to facilitate travel between New Zealand and Great Britain is also gratefully acknowledged.

References

Booth, T.C. 1977. Windthrow Hazard Classification. Forestry Commission Research Information Note 22/77/SILN.

Chandler, K. C. 1968. Climate damage to forests of the Tapanui district. New Zealand Journal of Forestry: 98-110.

Cook, N. J. 1985. The Designer's Guide to Wind Loading of Building Structures: Background, Damage Survey, Wind Data and Structural Classification. Building Research Establishment Report. Butterworth, Sevenoaks.

Dunlop, J. 1995. The permanent sample plot system — user manual. FRI Bulletin 187, New Zealand Forest Research Limited, Rotorua.

Fraser, A. I. 1962. The soil and roots as factors in tree stability. Forestry **35:** 117-127.

Frederickson, T. S., R. L. Hedden, and S. A. Williams. 1993. Testing loblolly pine windfirmness with a simulated wind stress. Canadian Journal of Forestry Research **23:** 1760-1765.

Gardiner, B. A., G. R. Stacey, R. E. Belcher, and C. J. Wood. 1995. Field and wind tunnel assessments of the implications of respacing and thinning for tree stability. Submitted to Forestry.

Irvine, A. I. 1970. The significance of windthrow for *Pinus radiata* management in the Nelson district. New Zealand Journal of Forestry 15(1): 57-68.

Littlejohn, R. N. 1984. Extreme winds and forest devastation resulting from Cyclone 'Bernie'. Weather and Climate 4: 47-52.

Miller, K. F. 1985. Windthrow Hazard Classification. Forestry Commission Leaflet 85. HMSO, London.

Ministry of Forestry. 1995. A national exotic forest description as at April 1, 1994. Ministry of Forestry, Wellington.

Petty, J. A. and C. Swain. 1985. Factors influencing stem breakage in conifers in high winds. Forestry **58** (1): 75-84.

Prior, K. W. 1959. Wind damage in exotic forests in Canterbury. New Zealand Journal of Forestry **8:** 57-68.

Quine, C. P. 1995. Assessing the risk of wind damage to forests: practice and pitfalls. *In* Wind and Trees (editors Coutts, M. P. and Grace, J.). Cambridge University Press, Cambridge. pp 379-403.

Quine, C. P. and I. M. S. White. 1993. Revised windiness scores for the windthrow hazard classification: the revised scoring method. Forestry Commission Research Information Note 230. Forestry Commission, Edinburgh.

Raupach, M. R. 1992. Drag and Drag Partition on Rough Surfaces. Boundary-Layer Meteorology 60: 375-395.

Smith, V. G., M. Watts, and D. F. James. 1987. Mechanical stability of black spruce in the clay belt region of northern Ontario. Can. J. For. Res. **17**, 1080-1091.

Somerville, A. R. 1989. Tree wind stability and management practices. *In* Somerville, A. R., Wakelin, S. and Whitehouse, L (editors) Workshop on wind damage in New Zealand exotic forests. FRI Bulletin 146, Ministry of Forestry, Rotorua. pp 38-58.

Somerville, A. R. 1995. Wind damage to New Zealand State forest plantations. *In* Wind and Trees (editors Coutts, M. P. and Grace, J.). Cambridge University Press, Cambridge. pp 460-467.

Walmsley, J. L., I. B. Troen, D. P. Lalas, and P. J. Mason. 1990. Surface-Layer flow in complex terrain: comparisons of models and full-scale observations. Boundary-Layer Meteorology 52: 259-281.

Wendelken, W. J. 1955. Root development and wind-firmness of the shallow gravel soils of the Canterbury Plains. New Zealand Journal of Forestry 7: 71-76.

Wendelken, W. J. 1966. Eyrewell Forest: A search for stable management. New Zealand Journal of Forestry: 43-65.

Whiteside, I. D. 1990. The STANDPAK modelling system for radiata pine. *In* New approaches to spacing in plantation forestry: proceedings of a IUFRO symposium held at the Forest Research Institute, Rotorua, New Zealand, April 10-14, 1989. Ministry of Forestry, FRI Bulletin No. 151.

Wilson, H. H. 1976. The effect of the gale of August 1975 on forestry in Canterbury. New Zealand Journal of Forestry 21: 133-40.

New Zealand Forestry

invites you to submit material for inclusion in this publication

We accept:

- articles on a wide variety of forestry topics;
- comment on forestry or Institute of Forestry affairs;
- items on current events;
- letters to the editor;
- items from local sections;
- advertising.

Comments, letters, news items, and Institute news need to be with the Editor at the beginning of the month prior to publication.