Variations in the dynamic modulus of elasticity with proximity to the stand edge in radiata pine stands on the Canterbury Plains, New Zealand

Arturo Bascuñán[1,2], John R. Moore[3,4] and John C.F. Walker[1*]

Abstract

To explore the effects of wind on tree form and wood quality, 30 transects were placed across each of three relatively narrow stands of *Pinus radiata*, aged 11, 17 and 25 years old, on the Canterbury Plains, New Zealand. The experimental design assumed that the major influence on stand edges to be the prevailing strong north-westerly winds that blow across this region. Outerwood dynamic modulus of elasticity (E_d) and tree height increased with distance from the stand edge, while taper reduced. The negative effect of wind extended into the stand the equivalent of one tree height, regardless of the age of the stand, with the least stiff trees (i.e., those with the lowest E_d) located at the stand edge. Surprisingly, larger effects were observed at the downwind edge of these stands, although the reasons for this are not clear. Results from this study indicate that for those stands investigated trees located at the stand edge, or within a distance equivalent to one tree height from the edge, may be of marginal value for structural timber.

Introduction

Traditional research into the effects of wind on forests has focussed on stand stability and wind damage, whereas logically wind must have a more pervasive influence. This preliminary study considers the response of softwood trees (*Pinus radiata*) to their local environment, in terms of the adage that form follows function. Previous research (see Telewski (1995) for a summary) has found that wind stress has a substantial influence on both the external and internal characteristics of trees: morphological consequences include increased radial growth and reduced height while non-visual biomechanical effects include increased microfibril angle and the amount of compression wood, and reduced modulus of elasticity (E) of the wood.

The most visual wind-induced developmental responses are a leaning stem and the formation of compression wood on the underside that acts to return the apical meristem to the vertical position (Timell, 1986). For example, at Mt Macedon in Victoria, Australia, Nicholls (1982) found that wind action resulted in approximately 70% of trees in a 23-year-old radiata pine stand leaning by 5° or more. Nicholls (1982) and Telewski (1989) found that wind exposure was associated with an increase in microfibril angle in radiata pine and *Abies fraseri* trees respectively; in the former case this was attributed to a large amount of compression wood.

Two earlier studies of radiata pine in Canterbury are relevant to the work reported here. Grabianowski *et al.* (2004) noted that within a narrow stand of 27-year-old radiata pine in Eyrewell Forest, Canterbury, the outerwood stiffness of trees exposed to the strong northwest wind was lower than in trees growing downwind and so more protected from the wind: exposed trees were 11% less stiff when the stand density was 625 trees/ha, and 21% less stiff when the stand density was only 100 trees/ha. Subsequently, Lasserre *et al.* (2005) noted that outerwood stiffness in 11-year-old radiata pine at Dalethorpe in the Canterbury foothills decreased by some 1.7 GPa or 34% as the initial planting density was reduced from 2500 to 833 trees/ha.

In this study we test the hypothesis that visual features and intrinsic wood properties of trees at the edge of a stand differ from those in the interior. Trees in the interior should be taller, less tapered - having a higher height to diameter ratio - and have wood that has a higher modulus of elasticity. It is assumed that these differences reflect differences in wind exposure at different points within the stand.

Materials and methods

The study area was near Hororata on the Canterbury plains, 60 km west of Christchurch, New Zealand (latitude 43°34'S, longitude 171°55'E, elevation 210 m a.s.l.). The Canterbury Plains were formed by the outwash of gravels from the Southern Alps. Soils are shallow, lightly-structured and underlain with free-draining gravels. They are usually classified as Lismore silt loam and are of low fertility (Kear *et al.*, 1967). These soils have a low moisture storage capacity and are prone to drought. Canterbury's climate is strongly influenced by north-westerly winds that create a steep moisture gradient from the main divide of the Southern Alps (annual rainfall about 5000 mm) in the west to the dry eastern margins of the intermountain basins and coastal areas (annual rainfall 800 to 500 mm).

The northwest wind is a major constraint to forestry in Canterbury (Somerville, 1989; Studholme, 1995), with the risk of mass windfall being even greater than that of fire. Wind is especially severe in spring when the contrast between equatorial and polar temperatures is greatest

[1]*School of Forestry, University of Canterbury, Private Bag 4800, Christchurch, New Zealand*
[2]*Present address: Barbastro 11201, Vitacura, Chile*
[3]*Ensis, P.O. Box 29-237, Christchurch, New Zealand*
[4]*Present address: Centre for Timber Engineering, Napier University, Edinburgh, UK*

***Corresponding author**: Email: j.walker@fore.canterbury.ac.nz*

(Brenstrum, 1989). On average there are 52 days a year when gusts reach 63 km/hr or more, and three days a year when gusts reach 96 km/hr or more. Spring is the main tree growing season in Canterbury and therefore new wood cells are formed when wind-induced stress on the cambium is greatest. Data spanning the period 1993 to 2003 from the two meteorological stations located nearest to the site show that the mean wind speed from all directions was approximately 14 km/h for the Darfield station and 21.5 km/h for the Snowdon station (Table 1). The mean speed of winds from the northwest sector (292.5 to 337.5) was 22.4 km/h and 37.2 km/h for the Darfield and Snowdon stations, respectively. At both stations, the wind blew from the north-westerly direction approximately 25% of the time.

Table 1. Mean wind speed and frequency by sector for meteorological stations located at Darfield and Snowdon.

Sector	Darfield		Snowdon	
	Mean wind speed (km/h)	Frequency (%)	Mean wind speed (km/h)	Frequency (%)
N	12.1	12.4	21.9	26.1
NE	16.4	21.9	11.3	11.3
E	16.6	6.9	13.1	8.4
SE	14.2	6.0	7.7	4.1
S	15.5	7.9	10.1	13.9
SW	17.3	11.7	10.6	7.8
W	16.2	8.5	8.4	1.3
NW	22.4	24.8	37.2	27.1
Overall	14.0	100.0	21.5	100.0

Three relatively narrow stands of radiata pine were chosen representing three age classes (11, 17 and 25 years old). All stands were established at a spacing of 4 by 2 m (1250 stems/ha) with the 2m length running northwest and thinned to a nominal stand density of 600 stems/ha at age 6-7 years. Stands had their long-axis orientated approximately perpendicular to the north-westerly wind. In the original scheme two further 17 year-old stands were to be sampled, one at Windwhistle, a few kilometres closer to the Alps, and another at Dunsandel, a few kilometres closer to the coast. On reflection, these stands would have introduced further variables (contrasts in rainfall, soils and wind). Only the windier, wetter stand at Windwhistle was sampled. While this stand has not been incorporated in the statistical analysis, the data are included in the tables as the observations at Windwhistle reinforce the trends observed at Hororata. Stand characteristics are given in Table 2.

Thirty transects, approximately 100 m apart, were placed across each stand parallel to the northwest wind direction. Along each transect, 20 trees were selected for measurement at known intervals, approximately every 12.5 m. Where the stand width exceeded 240 m, 10 trees were measured at 12.5 m intervals along the same transect but approaching the centre from both the windward and leeward sides of the stand, thus leaving the middle of the stand un-assessed. Diameter at 1.4 m above ground (DBH) and total height were measured. Stem lean was noted as either "no lean" or "lean>5°", but the actual degree of lean was not measured. Tree taper was calculated as the ratio of tree height (m) to DBH (m).

Outerwood dynamic modulus of elasticity (E_d) was measured on the selected standing trees using TreeTap, an acoustic tool developed at the University of Canterbury. This instrument measures the time taken for an acoustic wave to travel a known distance, i.e. the transit time. Three probes with spikes were driven through the bark and into the wood. A launch probe (the one that is tapped with a metal hammer) was placed in the stem 0.4 m above the ground and the two receiver probes at heights of 0.6 m and 1.8 m. The acoustic velocity was calculated from the average transit time and distance between the two upper piezoelectric (stop) probes: eight readings were taken on both the windward and leeward sides of the stem. The dynamic modulus of elasticity of outerwood was calculated from the following equation:

$$E_d = p \quad V2 \qquad (1)$$

where p is the green density (i.e., the mass of fresh wood per unit volume) of outerwood and V is the acoustic velocity. Green density was not measured, but was assumed to be

Table 2. Characteristics of the three stands sampled in the study.

Stand Location	Elevation (m)	Stand age (years)	Density (trees/ha)	Stand width (m)	Mean DBH (cm)	Mean HT (m)
Hororata	230	11	600	240	18.7	12.3
Hororata	181	17	600	360	24.9	16.3
Hororata	230	25	620	240	35.0	23.0
Windwhistle	390	17	600	225	33.9	18.7

constant between trees and to have a value of 1000 kg m^{-3}.

Within each transect, the position of each tree was assigned to one of the following three classes:

- *Stand edge*: the outermost row of trees located on the periphery of the stand; that is those trees that were fully exposed to the direct effects of any wind.
- *1H zone*: all trees that were less than one tree height (1H) from the stand edge. This region represents trees that wind-tunnel studies (Gardiner *et al*. 1997) have shown to be exposed to higher wind loading. This region included the stand edge trees.
- *Forest interior*: all trees located more than one tree height from a stand edge. Trees growing in this region were assumed to have greater protection from the effects of wind than those in the other two zones.

For each transect, mean values of tree height, taper and E_d were calculated for each of the three positions, and these data were then analysed using linear mixed effects models. The effect of position (edge, 1H zone, or interior), side of the stand (windward or leeward), and stand age (11, 17 or 25 years old) were included in the model as fixed effects, while transects within each stand were modelled as random effects. The model also accounted for the nested structure of the data. The values of E_d for the windward and leeward sides of edge trees were compared for each stand using paired t-tests. The coefficient of variation (ratio of standard deviation to the mean) for E_d was calculated for each stand using all 600 trees measured in the stand. A second calculation was also performed using only those trees growing in the forest interior.

Results

Morphological characteristics

Across all three stands, both tree height and taper differed significantly with position relative to the edge ($F_{2,445}$=20.47, p<0.0001 and $F_{2,445}$=27.51, p<0.0001, respectively). Trees growing at the stand edge were on average between 4.4% and 16.6% shorter than those located in the forest interior (Table 3). On average, edge and 1H zone trees (except in the 11-year-old stand) on the leeward side of the stand were taller than the corresponding trees located on the windward side. Taper was significantly greater ($F_{1,445}$=4.84, p=0.028) on the windward side of stands due to the lower heights of trees. It was greatest at the stand edge and decreased progressively towards the stand interior.

Wood properties

Estimated mean outerwood E_d increased from 5.9 GPa in the 11-year-old stand, through 8.9 GPa for the 17-year-old stand, to 11.7 GPa in the 25-year-old stand. The coefficient of variation (CV%) for E_d, based on all 600 trees sampled per stand, ranged from 18.3% to 20.2%. When considering only those trees in the stand interior, the coefficient of variation still ranged from 18.2% up to 19.4%. Results from the mixed effects model showed that there was suggestive, but inconclusive evidence, that age had an effect on E_d ($F_{1,1}$ = 75.66, p=0.075). There was no difference in E_d between sides of the stand ($F_{1,445}$ = 0.064, p=0.800). However, the position of a tree relative to the edge of the stand accounted for a significant proportion of the variation in outerwood E_d ($F_{2,445}$ = 40.14, p<0.0001) and the effect of position depended on the side of the stand being considered ($F_{2,445}$ = 6.75, p=0.001). Trees at the stand edge and in the 1H zone had values of outerwood E_d that were 5-28% lower than trees in the forest interior (Table 4). Surprisingly, the decrease in E_d between the interior and the leeward edge was greater than between the interior and the windward edge.

Twenty percent of the trees were leaning (> 5°) with most leaning away from the direction of the northwest wind. The incidence of lean was greatest in the 25-year-old stand and lowest in the 11-year-old stand (Bascuñán, 2004). Because of this lean, stiffness was measured on opposite sides (i.e., NW and SE) of the stem. The difference in E_d between sides of the tree increased with tree age, tree lean

Table 3. Mean height and taper of trees located at the stand edge, in the 1H zone, and in the forest interior.

Stand Age (years)	Side of stand	Height (m)			Taper (Height/DBH)		
		Stand edge	1H zone	Forest interior	Stand edge	1H zone	Forest interior
11	Leeward	11.1	11.3	12.3	55.3	60.5	67.1
	Windward	11.1	11.4	12.7	50.6	55.9	68.4
17	Leeward	15.9	16.0	16.6	58.4	62.8	71.2
	Windward	14.6	15.3	16.4	59.3	63.0	67.9
17 (Windwhistle)	Leeward	18.5	18.1	18.9	48.2	50.5	58.1
	Windward	15.5	16.8	19.1	38.4	48.1	58.0
25	Leeward	22.2	22.1	23.4	53.1	62.2	69.1
	Windward	19.9	20.2	23.2	45.2	54.4	71.0

and with increased exposure (greater for edge trees). In most cases the leeward side of the tree had the higher value of E_d (Table 4). This is the side of a leaning tree that normally contains compression wood, and would have been expected to have a lower E_d.

Discussion

The lower outerwood E_d of trees on the leeward side of the stand was an unexpected result. The atypical higher stiffness of the leeward edge trees in the 25-year-old stand could possibly be attributed to the single row of trees on the other side of a public road. This could have provided a partial extension to the stand as well as offering some protection from the easterly winds. The 6% reduction in stiffness observed on the leeward edge of this stand would probably have been greater in the absence of these trees. In both cases it would be desirable to harvest these trees and measure mechanical and anatomical properties on both sides of the stem.

As expected trees at stand edge were more tapered than those in the 1H zone, which in turn were more tapered than those in the forest interior. Furthermore, on the windward side of the stand trees were more tapered than those growing on the leeward side. At the same time, trees at the stand edge were less stiff than those in the 1H zone, which in turn were less stiff than those in the forest interior, i.e. the more exposed the tree the less stiff the tree. Interestingly, the trees on the leeward side of the stand were less stiff than those to windward. A possible explanation that winds from southerly direction are as significant as the stronger north-westerly winds is not plausible: based on data from the Darfield station, the wind blows from the SE-S-SW directions approximately 26% of the time as against 69% of the time from the NE-N-NW directions. There is no obvious explanation for the lower down-wind stiffness.

Other possible reasons for differences in form and wood properties between edge and interior trees are contrasting microclimates at stand edges and interiors, and differences in available light and temperature (Chen *et al*., 1993). In addition, competition for soil moisture is presumably less at or near the stand edge and thus radial growth is greater. Further research would be required to examine these issues.

Compression wood forms on the underside of the leaning stem and opposite wood forms on the upper side. For this reason TreeTap readings were taken on the leeward and windward sides of each tree in order to exaggerate any differences arising from the presence of compression wood and opposite wood. In a wind-free environment the crowns of edge trees are asymmetric with more branch mass facing outwards such that edge trees tend to lean outwards: in that case softwood edge trees would develop compression wood on the side of the stem that faces the outside of the stand in response to the lean. The stands in this study are subject to a strong northwest wind. For these stands the natural outward lean of the stems at the upwind edge of the stand is countermanded by the prevailing wind and the stems lean away from the light, i.e., trees fully exposed to the northwest wind lean with the wind and away from the light. At the leeward edge of the stand the stems lean outwards, away from the northwest wind and *toward* the light. In both of these cases measurements of acoustic velocity indicate that the opposite wood on the upper side of the stems is less stiff than the compression wood on the underside. This deserves further research.

The CV% for outerwood stiffness for trees in the interior of individual stands (18.2% to 19.4%) is approximately three times greater than typical within-stand variation in wood density (Cown, 1999). This highlights the greater effectiveness of segregating logs based on their outerwood stiffness than segregating stands based on outerwood density.

Table 4. Mean dynamic modulus of elasticity of trees located at the stand edge, in the 1H zone, and in the forest interior.

Stand Age (years)	Side of stand	E_d (GPa)			E_d of stand edge trees (GPa)	
		Stand edge	1H zone	Forest interior	SE side (leeward)	NW side (windward)
11	Leeward	4.7	5.2	6.0	4.81*	4.67
	Windward	5.5	5.7	6.1	5.82***	5.18
17	Leeward	8.0	8.4	9.0	8.08ns	7.84
	Windward	8.4	8.7	9.1	9.12***	7.71
17 (Windwhistle)	Leeward	7.3	8.1	9.1	7.49ns	7.10
	Windward	7.5	8.2	9.1	7.80	7.11
25	Leeward	10.8	12.1	12.5	10.78ns	11.34
	Windward	11.0	10.7	11.5	11.76***	10.3

Significance (as compared to trees at the windward edge) is indicated by the following:
*** = $p<0.001$, *** = $p< 0.01$, * = $p<0.05$, ns $p>0.05$.

In this dataset the estimated mean outerwood E_d increased from 5.9 GPa in the 11-year-old stand, through 8.9 GPa for both 17-year-old stands, to 11.7 GPa in the 25-year-old stand. Forestry has never been highly profitable on the Canterbury Plains and stands were planted primarily to support stock grazing and arable farming. One can debate the critical stiffness threshold for structural timber, but if it is taken as being 7-8 GPa then much of the wood grown during the first 17 years will be marginal. Furthermore, as this study demonstrates, planting narrow stands with their long-axes perpendicular to the prevailing wind will reduce the amount of timber in the higher stiffness classes as a greater proportion of the wood will come from trees growing at the stand edge or in the 1H zone. Edge trees can be expected to have an Ed that is approximately 1 GPa lower than trees growing in the interior of the stand, and recovery of structural grades will be reduced.

Narrow stands and small woodlots exaggerate the dilemma confronting pine plantations: the corewood zone is large and of poor quality. In addition, the current trend of low initial stockings where tree height is comparable to spacing means that in the early years the edge effect is lost and a large proportion of the stand is exposed to the full force of the wind. This can be seen in classic wind-tunnel experiments (Fraser, 1964; Papesch, 1984) which show that the bending moment is halved as the ratio of height to spacing decreases from 0.4 to 0.25 m/m (for a 4 m spacing this implies an increase in tree height from 10 m to 16 m). Such wide spacings are likely to be prolonging the period of corewood formation.

Acknowledgement

Thanks to Hugh Stevenson at Selwyn Plantation Board Limited for providing access to the stands in which the work was carried out and for supplying hourly wind speed data from two adjacent weather stations. Dr Rod Ball (Ensis, Rotorua) assisted with the analysis of the data. Helpful comments and suggestions were provided by two anonymous reviewers.

References

Bascuñán, A. 2004: The influence of wind on radiata pine tree shape and wood stiffness. M.For.Sci. thesis, University of Canterbury.

Brenstrum, E. 1989: Canterbury's damaging nor'wester. *New Zealand Geographic*, 1: 110-111.

Chen, J., Franklin, J.F. and Spies, T.A. 1993: Contrasting microclimates among clearcut, edge and interior of old-growth Douglas-fir forest. *Agricultural and Forest Meteorology*, 63:219-237.

Cown, D.J. 1999: New Zealand Pine and Douglas-Fir: suitability for processing. *Forest Research Bulletin* No. 216, Rotorua.

Fraser, A.I. 1964: Wind tunnel and other related studies on coniferous trees and tree crops. *Forestry*, 18: 84-92.

Gardiner, B.A.; Stacey, G.R.; Belcher, R.E.; Wood, C.J. 1997: Field and wind tunnel assessments of the implications of respacing and thinning for tree stability. *Forestry*, 70: 233-52.

Grabianowski, M.; Manley, B.; Walker, J.C.F. 2004: Impact of stocking and exposure on outerwood acoustic properties of Pinus radiata in Eyrewell Forest. *New Zealand Journal of Forestry*, 49(2): 13-7.

Kear, B.S.; Gibbs, H.S.; Miller, R.B. 1967: Soils of the downs and plains, Canterbury and North Otago, New Zealand. *N.Z. Soil Bureau Bulletin* 14, DSIR Soil Bureau, Wellington.

Lasserre, J.-P.; Mason, E.G.; Watt, M.S. 2004: The influence of initial stocking on corewood stiffness in a clonal experiment of 11 year-old *Pinus radiata D. Don. New Zealand Journal of Forestry*, 49(2): 18-23.

Nicholls, J.W.P. 1982: Wind action, leaning trees and compression wood in *Pinus radiata D. Don. Australian Journal of Forest Research*, 12: 75-91.

Papesch, A.J.G. 1984: Wind and its effects on (Canterbury) forests. PhD thesis, University of Canterbury.

Somerville, A. 1989: Tree Stability and Forest Management Practices. In A. Somerville, S.J. Wakelin & L.J. Whitehouse (Eds.), Workshop on Wind Damage in New Zealand Exotic Forests.*FRI Bulletin* 146. New Zealand Forest Research Institute, Rotorua. pp 38-58.

Studholme, W.P. 1995: The experience of and management strategy adopted by the Selwyn Plantation Board, New Zealand. In M.P. Coults & J. Grace (Eds.) *Wind and Trees*. Cambridge University Press, Cambridge. pp 468-78.

Telewski, F.W. 1989: Structure and function of flexure wood in Abies fraseri. *Tree Physiology*, 5: 113-22.

Telewski, F.W. 1995: Wind-induced physiological and developmental responses in trees. In M.P. Coults & J. Grace (Eds.) *Wind and Trees*. Cambridge University Press, Cambridge. pp 237-63.

Timell, T.E. 1986: *Compression Wood in Gymnosperms* (Vol. I). Springer-Verlag, Berlin.