feature

Influence of exposure and elevation on radiata pine branch size, log velocity, sweep, taper and value

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Abstract

Radiata pine log velocity (related to wood stiffness), branch size, taper, log sweep and overall log value were assessed in 112 plots on two topographically diverse sites in the South Island of New Zealand. Log velocity decreased, branch size increased and sweep also increased with increasing altitude and decreasing TOPEX, however these relationships differed significantly between sites. Taper increased and value per log decreased with increasing altitude. These latter two relationships did not differ significantly between the two sites studied. The results suggest that exposure to wind should be represented in predictive models of log quality, but that reasons for differences in relationships between sites need to be identified before such models can be applied globally.

Introduction

Log values vary across landscapes, and exposure to wind may partly contribute to this variation. Forest managers can improve harvest plans and increase profits by predicting distributions of log characteristics within forest estates, and so models that facilitate these predictions are highly desirable.

Exposure to wind has been shown to influence both tree form (Jacobs, 1954; Watt *et al.* 2005) and wood quality (Bascunan *et al.* 2006) of radiata pine as well as many other tree species (Telewski, 1995). However, limited research has been conducted that relates wind exposure to tree form, wood quality and value gradients within a stand, in complex topography.

Jacobs (1954) reported that increased flexure stress induced by wind decreased height growth and increased diameter growth in *Pinus radiata*, as a result increasing taper. Slenderness (taper) has been reported to have a significant influence on standing tree stiffness (Waghorn *et al.*,2007; Mason, 2006; Watt *et al.*, 2006). Moreover, Koizumi *et al.* (1989) reported that *Larix kaempferi* (*L. leptolepis*) had greater mean stem stiffness on sites protected from prevailing winds compared to exposed sites and Quirk *et al.* (1975) found that flexure stress increased the grain angle in *Pinus radiata*, which can be a cause of timber instability (twist) on drying (Xu, 2000; Cown *et al.*, 1992).

Stiffness is often estimated by measuring the velocity of sound in logs. Research using *Pinus radiata* clones shows a strong correlation (r^2=0.96) between dynamic stiffness measured using a tool that measures velocity of sound in logs and static stiffness determined from traditional static bending (Lindström *et al.*, 2002). Although velocity is relatively unaffected by knots and other defects, standing tree velocity measuring tools (time of flight tools) only measure the sound velocity within the outermost growth rings in standing trees (Gorman *et al.*, 2003). Values of logs are often partly related to “log velocity” in New Zealand, with some companies refusing to buy logs that have velocities below a given benchmark.

Two recent studies on *Pinus radiata* in Canterbury supported earlier work relating to log velocity and wind exposure. Grabianowski *et al.* (2004) found a noticeable difference in standing tree velocity between the windward and leeward sides of two parallel strips of trees, suggesting an influence of wind on internal properties of trees. Furthermore, Bascuñán *et al.* (2006) found that outerwood velocity reduced with increased exposure to wind, concluding trees exposed to wind may be of marginal value for structural timber.

In order to capture influences of wind within predictive models of log quality, forest managers need an easily accessible, quantitative surrogate for wind exposure.

Topographic exposure (topex) and altitude have been found to be closely correlated with wind speed in complex topography (Ruel *et al.*, 2002; Quine and White, 1994; Miller, 1987; Howell, and Neustein, 1965). Topex is a variable which represents the degree of shelter afforded to a location (Chapman, 2000). Standard topex is calculated by measuring the inclination to the skyline at the eight principal points of the compass (Pryat, 1969). The topex value is the sum of these eight TOPEX sector values (Quine and White, 1994). High TOPEX scores indicate higher ground in the vicinity of the measurement site, and the site is therefore assumed to be sheltered. Small scores indicate that the site is exposed (Quine and White, 1994). Guidelines relating topex scores to exposure have been published giving an indication of relative exposure at a given standard topex score (Table 1).

When measuring standard topex, declinations (negative angles) have not been included in the assessment (Quine and White, 1994). Accurate measurements of declinations to surrounding landforms are required and mature trees often obstruct the view to the horizon (Quine and White, 1994).

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Dr Colin O’Loughlin was editor for this refereed article

Table 1 - Exposure classification by standard TOPEX method (adapted from Wilson, 1984; Miller et al. 1987)

Range of TOPEX Scores	Relative Exposure
0-10	Severely exposed
11-30	Very exposed
31-60	Moderately exposed
61-100	Moderately sheltered
100+	Very sheltered

However, studies using topex to distance, a modification of standard topex where a distance limit is set on landform horizons, have been conducted where the topex value was estimated using map-based methods (Harrison, 1988; Hannah *et al.* 1995). Topex to distance was found to be better than standard topex as an estimator of exposure.

The objective of this study was to determine whether standing tree log velocity, log sweep, log taper, branch size and log value were consistently related to elevation and topex at two sites in the Nelson and Marlborough regions of New Zealand

Methods

Sites

Site one was located in the Nelson region (Kainui, E2506608, N5694062) and site two was in the Marlborough region (North bank of the Wairau River, E2568057, N5972453) The Kainui and Wairau sites had altitude ranges of 350-700m and 130-580m respectively (Figures 1 and 2). The sites received similar annual rainfall (1300mm), however the Wairau site was prone to summer water deficits. The parent material for both sites was predominantly greywacke, soils, which under the New Zealand soil classification scheme were classed as Oxidic Brown and Sandy Brown at Kainui and Wairau respectively. Both sites were managed under intensively pruned regimes with similar age, genetics, stocking and silvicultural history. The site at Wairau was planted in 1980, while the Kairau site was planted in 1982.

The study used 82 and 92 pre measured pre-harvest inventory plots at Kainui and Wairau respectively. 30 plots were sampled to measure standing tree stiffness and DBH at each site (Table E). Plots were selected to cover a range of different TOPEX scores. The distribution of TOPEX scores of the sampled plots was similar to that of the distribution of TOPEX scores of all the plots in the study site.

The average numbers of trees in each plot at Kainui were 15.1 and 17 at Wairau. Standing tree stiffness was measured with the Faakop (TreeSonic). Two measurements were recorded for each tree, one on the wind ward side of the tree and the other on the leeward side. Each recorded measurement was the average of several velocity readings observed, as it was difficult to get consistent reading. DBH was also measured for each tree.

Wind exposure measurements

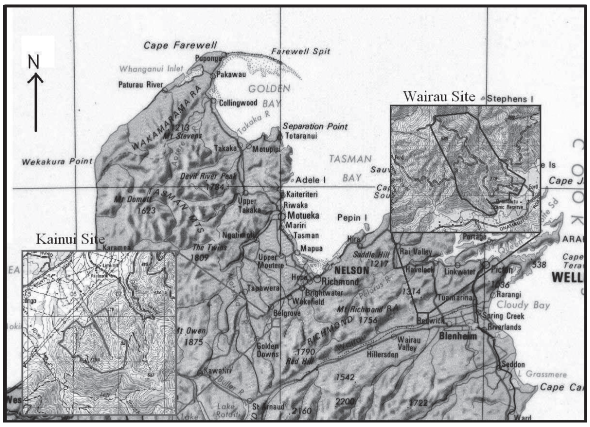

Figure 1 - Locations of study sites

Topex to distance (1 km) (excluding declinations), and altitude were calculated for each plot in both study areas by the TOPEX calculator[3] in ESRI® Arcmap™ 9.0 Geographic Information System (GIS). Additional TOPEX to distance scores (1 km and 0.5 km) including declinations, were calculated for each plot measured for stiffness in both sites using map based methods (1:50 000 topographical maps).

Topex to distance (1 km) including negative values was calculated for all plots in the Wairau study site, and Topex to distance (0.5 km) including negative values was calculated for all plots in the Kainui study site. From here on variations of topex will be labelled as defined in Table 2. TOPEX 2 and TOPEX 3 were not calculated for all plots in Kainui and Wairau respectively as preliminary analysis showed that they would not add significant value to a predictive model of log quality in either site.

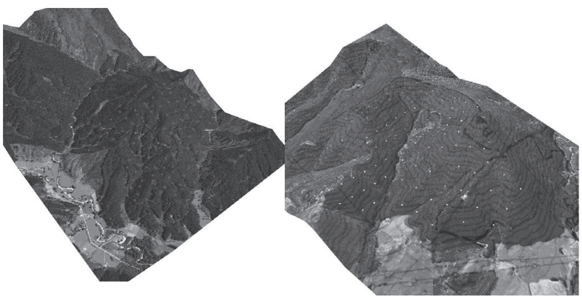

Figure 2 - Topography where plots were located at Wairau (left) and Kainui (right).

[3] *Dunningham, A., Ensis, P.O. Box 3020, Rotorua.*

Table 2 - Standard labelling of different TOPEX variation

TOPEX Variations	Label
TOPEX to distance (1 km) excluding declinations	TOPEX
TOPEX to distance (1 km) including declinations	TOPEX 2
TOPEX to distance (0.5 km) including declinations	TOPEX 3

The trees within the 30 plots established at each site, capturing a range of TOPEX scores and altitudes were measured using the Fakopp (TreeSonic) tool. The time of flight (ToF) values of the outerwood of the windward and leeward sides of the trees were recorded. The sample size (number of trees) for each site was 453 and 510 respectively (Table 3)

Time of flight measurements (μs m^{-1}) were converted into velocity (km s^{-1}) measurements using the following equation:

$$\text{Velocity (km s-1)} = \frac{1}{t / 1000} \quad (1)$$

t = transit time (?s m-1) between two probes one metre apart.

Tree form (branch size, sweep, taper) and value was assessed from the analysis of the 2006 pre-harvest inventory (PHI) assessment (Table 3) using MARVL (Method for Assessment of Recoverable Volume by Log types; Deadman and Goulding, 1979). The data were not grown forward in MARVL to eliminate noise; instead the analysis was run on the date of assessment.

Branch size, sweep and value were estimated at a plot level, not a tree level. Average plot branch and sweep score was derived from the MARVL analysis. Value assessments were also estimated out at a plot level. Value was assessed in three ways; $/ha, $/log and log grade (as a % of total recoverable volume, TRV). This was done to give an indication of absolute value of the log, as well as value independent of stocking. Value assessments excluded pruned volume as pruned height varied within the study sites due to prescription differences between compartments.

Taper was calculated by dividing height over DBH, using measured height trees and DBH in the 2006 PHI assessment. Taper estimates were limited on average to two trees per plot, as is the standard procedure in PHI assessments[4]. These two estimates were averaged for each plot.

Preliminary paired t test analysis showed no significant difference ($P>0.05$) in the transit time between the windward and leeward sides of the trees sampled in both sites. Transit time measurements (μs m^{-1}) were converted into velocity (km s^{-1}) measurements using equation 1 and then the two velocities for each tree were averaged.

[4] *Marion Hughes, Weyerhaeuser New Zealand Inc, pers comm.*

Table 3 - Sample size of sampled plots (stiffness) and plots analysed (Form and value)

	Kainui*		Wairau**	
	Plots	Trees	Plots	Trees
Stiffness	30	453	30	510
Form and value	82	1238	92	1564

*Plot size 0.06 **Plot size 0.08

All data analyses were conducted using SAS (SAS 2000). Stiffness, Branch score, sweep score, value and taper were all analysed using the SAS general linear models (GLM) procedure, applying a multi-linear model. Model quality was judged by the smallness of the residual mean square, minimal bias in residuals when plotted against predicted values and candidate independent variables, and normality of residual frequency distributions. Coefficients were only included if they were significantly different from zero. Velocity was further analysed using procedure MIXED in SAS, allowing for the fact that measurements were of individual trees while the sampling unit was a plot.

TOPEX and altitude were collinear. Therefore if they were both found to be significant in a model, an additional test was carried out to ascertain whether both predictors should be included. The test involved assessing the significance of the relationship between ε_1 and ε_2, where ε_1 denotes residuals from the model of Y on X1 (the variable most related to Y) and ε_2 denotes residuals from a model of X2 on X1 (Cook & Weisberg 1999).

Independent variables were subjected to scaled power transformations (Cook & Weisberg 1999, equation 2) where their relationships with dependent variables were found to be curvilinear.

$$X^{(\lambda)} = \begin{cases} (x^{\lambda}-1)/\lambda & \lambda \neq 0 \\ \log(x) & \lambda = 0 \end{cases} \quad (2)$$

The value of λ ranges typically between -1 and 3 to produce a variety of curvilinear shapes. Values of λ were adjusted to minimise bias.

Results

As values of altitude increased and/or TOPEX decreased (thereby suggesting exposure was greater), log velocity decreased, branch size increased, sweep increased, taper increased, and log value decreased (Figures 3-7). Variables entering the models are shown in Table 4. The models indicate that log quality generally declined with elevation and TOPEX, a dummy variable was required to distinguish between sites for models of velocity, branch size and sweep. Table 5 shows the optimum λ values for scaled power transformations applied to independent variables in the models, while table 6 shows the significance (probabilities of type I errors) of the relationships between dependent variables and independent variables when the models were fitted.

Branch size was affected by altitude and TOPEX even after DBH was included in the model.

Models of stiffness, branch size, and sweep differed significantly between sites, as indicated by the use of dummy variables, while those of log taper and value and value did not.

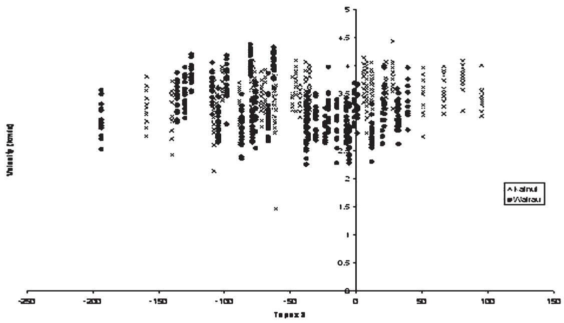

Figure 3 - Standing tree velocity (km/sec) plotted against TOPEX 3 for the two sites

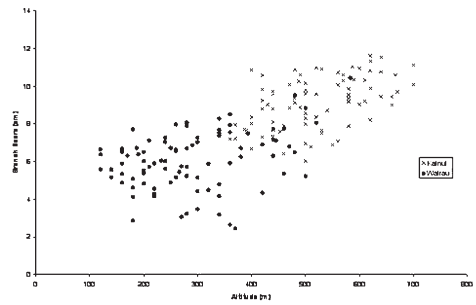

Figure 4 - Branch size (cm) versus altitude by study site

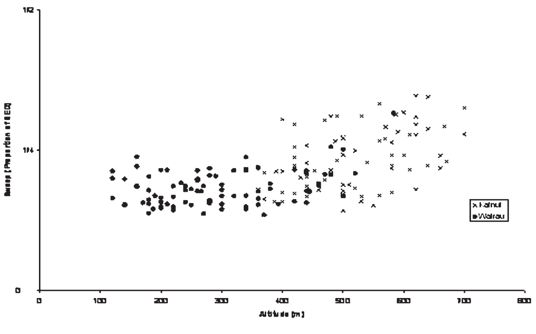

Figure 5 - Sweep (proportion of SED) versus altitude by study site

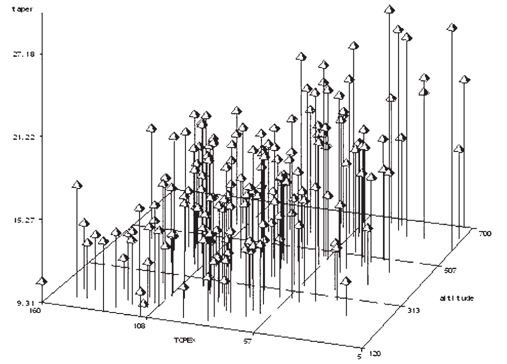

*Figure 6 - Taper (MTH/DBH*10) versus altitude and TOPEX*

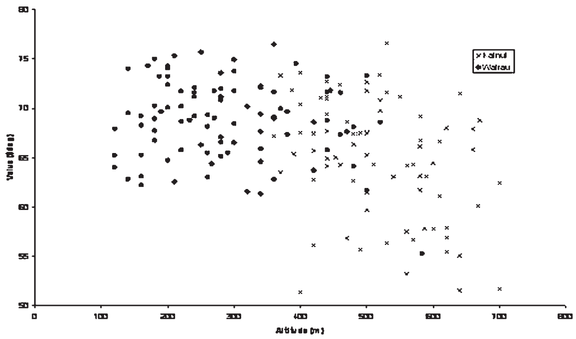

Figure 7 - Value versus altitude by site

Discussion

Significance of these results

Findings reported here indicate that while altitude and TOPEX were related to several important attributes affecting log value, these relationships varied between sites. Either more direct measurements of wind exposure and local temperatures need to be found, or managers will have to recalibrate these models for their particular landscapes using local data. It may be feasible to fit regional or even global models of impacts of exposure on log quality variables with datasets that cover a much wider range of sites, but reasons for differences between sites such as those found in this study will have to be understood and represented in the models.

TOPEX and altitude are imperfectly related to actual wind exposure. Zobel and Van Buijtenen (1989) reported that predictors of site quality (altitude and topex) combine many things that can each, on their own, influence wood properties. However, observed effects were due almost totally to interactions (Zobel and Van Buijtenen 1989), making it hard in a study of this nature to implicate one variable as the primary cause of observed relationships. Moreover, Worrell and Malcolm (1990) reported that the relationship between growth and form and altitude was a complex one as most factors that influence tree growth also varied with altitude. Furthermore, NcNab (1993) in Moore *et al.* (2006) suggested that topex was likely to be

Table 4 - Models created during the study. A=Altitude, T=TOPEX, T3=TOPEX 3, K=Kainui dummy variable (1=Kainui, 0=Wairau), W=Wairau dummy variable (1=Wairau, 0=Kainui), DBH=Diameter at breast height.

Dependent Variable	Model	R^2
Velocity	2.92+0.002090**A**+1.344**K**-0.002887**A**×**K**+0.000000234**T3**-0.006197**DBH**	0.25
Branch Size	-1.527 + 0.129**DBH** + 3.339**K** + 0.00391**A** -0.0123**K**×**T**	0.70
Sweep	-2.539 - 21.84**K** + 22.28**A** - 0.000549**T**×**K** - 19.81**A**×**W**	0.34
Value	69.45 - 0.00000422**A**/1000	0.22
Taper	12.50 + 0.004439**A** - 0.00001659**A**×**T**	0.41

Table 5 - Values of for scaled power transformations within each model

	Independent Variables	
Dependent variable	Altitude	TOPEX 3
Velocity		3
Branch Size		
Sweep	0.9	
Value	3.5	
Taper	1.2	

Table 6 - Probabilities of type I errors for coefficients in models

Variable	Alt	Kainui	Kainui*TOPEX	TOPEX3	DBH	Wairau*Alt	Alt*TOPEX	Kainui*Alt
Velocity	0.0001	0.004		0.0004	0.0001			0.0001
Branch Score	0.001	0.001	0.005		0.001			
Sweep Score	0.007	0.019	0.0006			0.02		
Taper	0.0001						0.0003	
Value	0.0001							

correlated with other environmental factors including soil moisture status.

Furthermore, altitude is commonly correlated with temperature, and some of the relationships between variables affecting log value and altitude found during this study may be due to temperature rather than exposure.

Relationships between exposure variables

TOPEX was relatively independent of altitude compared to TOPEX 2 and TOPEX 3. These relationships suggested that TOPEX was explaining variation within the site not captured by altitude. Altitude had the strongest overall relationship with all the wood quality, tree form and value measures assessed across both sites. However, TOPEX 3 and TOPEX 2 at Kainui and Wairau respectively showed the strongest relationships with log variables of any of the TOPEX variations analysed. Altitude had the largest influence on the observed trends, however variations of TOPEX explained site variation not captured by altitude. This extra variation could be localised differences in wind exposure.

Influence of Exposure on standing tree stiffness

Standing tree velocity (correlated with stiffness) was negatively correlated with altitude at Kainui. As higher altitudes are generally more exposed to wind, these findings were consistent with previous research which has found a relationship between wind exposure and stiffness (Bascuñán *et al.*, 2006; Grabianowski *et al.*, 2004).

Conversely, at the Wairau site standing tree velocity was not well correlated with altitude. One possible cause of this could be seasonal water deficits which are a common occurrence in the summer months in the Marlborough region, resulting in drought stress. Many studies (see review by Zobel and Van Buijtenen, 1989) have reported that drought stress in the summer months can increase the proportion of latewood, resulting in wood with higher density and stiffness. Trees in Marlborough were exposed to dry desiccating winds during periods of drought stress, which explain the lack of a clear trend with altitude at the Wairau site.

Standing tree velocity increased with TOPEX at both sites, suggesting that wind sway may influence this important variable, but the relationships were imprecise (Figure 3).

Influence of Exposure on Tree form

The Kainui site showed a strong relationship (given the type of study) between tree taper and both TOPEX 3 and altitude (Figure 6). Moreover, TOPEX was often an important additional independent variable in models of variables affecting log value (Table 4). These findings are consistent with previous research examining exposure and tree form. Watt *et al.* (2005) found that TOPEX had a direct relationship with branch size, while Jacobs (1954) reported that taper increased with increasing wind sway when comparing guyed trees with those left free to sway.

The direct influence of TOPEX on sweep has not been documented in previous studies. Nonetheless, it is an important measure of tree form because high value log grades usually impose sweep restrictions, with swept logs (usually > SED/4) being down graded. Results reported here suggest that exposure may increase sweep severity. Furthermore, the results suggested that exposure directly affected branch size, as a significant relationship was still present when DBH was accounted for.

At the Wairau site, however, significant ($p<0.05$) relationships between branch size and altitude, and sweep and altitude, were weak (Figures 4 and 5). One possible cause of this could be the complexity of the topography at the Wairau site compared to that of Kainui. Quine and White (1994) reported that TOPEX can overestimate the degree of shelter in deeply incised complex topography (in such sites as the Wairau), as it fails to identify the potential for funnelling of the wind in valleys. Moreover, it is possible that the influence of altitude on wind exposure could also be reduced due to valley and gully funnelling.

Influence of Exposure on Value

Weak, although significant ($p<0.001$), negative relationships were found between altitude and log value. However, the significance of this relationship was leveraged at Wairau on a single point. Not only did it have the highest elevation off all the plots analysed, it also had the lowest TOPEX score (5), indicating it was severely exposed (Table 1). This finding suggested that there was little difference between sheltered and moderately exposed sites, as defined by their topex score. However, severely exposed sites yielded significantly lower value (both $/ha and $/log) compared to more sheltered sites.

Future research

This study has highlighted possible areas for future research. In order to confirm wind exposure as a direct cause of the observations in this study, validation of wind exposure related to TOPEX and altitude in these sites (and others) is needed. A better understanding of wind behaviour in complex topography is also needed to further validate and understand TOPEX's relationship with wind exposure, for example the effects of funnelling in gullies and leeward turbulence.

Future studies that would complement and build on the work conducted in this study could be:

- Wind exposure and its influence on corewood development over time. .
- The interaction between wind exposure and drought stress and its influence on the proportion of late wood in standing trees. .
- Fitting of models of log quality variables versus topex and altitude over a wider range of conditions with larger datasets.

Conclusions

Velocity decreased, branch size increased and sweep also increased with increasing altitude and decreasing TOPEX, however these relationships differed significantly between sites.

Taper increased and value per log decreased with increasing altitude. These relationships did not differ significantly between the two sites studied.

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