

## The development of a wind risk model for irregular stands

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### Abstract

Modelling wind risk to forests has concentrated to date on damage within uniform stands. However, as continuous cover forestry becomes more widely practised, models will be required that can predict the risk of damage to individual trees within any stand structure. The key to building such models is developing an understanding of the response to wind loading of individual trees of different sizes. In earlier work on nine trees in a mature Sitka spruce stand (Wellpott, 2008) a turning moment coefficient ( $T_C$ ) was derived as a measure of the maximum turning moment experienced by a tree in response to a given wind speed. It was found that simple competition indices ( $CI$ ), derived from the proximity and relative size of neighbouring trees, could be used to estimate  $T_C$  for individual trees.

We have now analysed additional data collected within five different treatments in a Sitka spruce spacing experiment (Gardiner et al., 1997) and from a 2-storey larch stand (Wellpott, 2008). The wind loading, wind speeds and tree locations relative to their neighbours were available from both sites and provided  $T_C$  and  $CI$  for individual trees. Altogether 29 trees were compared across the three experiments and due to the large differences in tree height ( $h$ ) (8.7-31.9 m) the data were normalised by  $h^3$  ( $h$  = tree height) as suggested from earlier wind tunnel experiments (Stacey et al., 1994). We found that the data collapsed onto a single curve giving a strong relationship between  $T_C/h^3$  and  $CI$ . Further field measurements are underway in order to obtain a more comprehensive data set to fully validate the relationship.

The relationship between competition index and turning moment coefficient provides a method for calculating the response to individual trees to wind loading. This allows the calculation of differences in risk of damage across a stand and to build risk models for complex stand structures.

### 1. Introduction

Modelling wind risk to forests has concentrated to date on damage within uniform stands. For example, ForestGALES, which is a PC-based wind risk model parameterised for British conditions, calculates the probability of damage to the average tree within a uniform forest stand. However, as continuous cover forestry becomes more widely practised, models will be required that can predict the risk of damage to individual trees within any stand structure.

Key to building such models is developing an understanding of the response to wind loading of individual trees of different sizes. Wellpott (2008) measured turning moment on nine trees in a mature Sitka spruce stand, and derived a turning moment coefficient ( $T_C$ ) as a measure of the maximum turning moment experienced by a tree in response to a given wind speed:

$$T_C = M_{\max}/u^2$$

where  $M_{\max}$  (Nm) is maximum turning moment experienced in a 10 minute period, and  $u$  ( $\text{ms}^{-1}$ ) is the average wind speed at the canopy top for over that period.

Wellpott (2008) found that simple competition indices (CI), derived from the proximity and relative size of neighbouring trees, could be used to estimate  $T_C$  for individual trees (Fig. 1). See Appendix for details of the different competition indices.

This paper describes analysis of data from two additional forest stands, to test the wider applicability of the relationship found by Wellpott (2008).

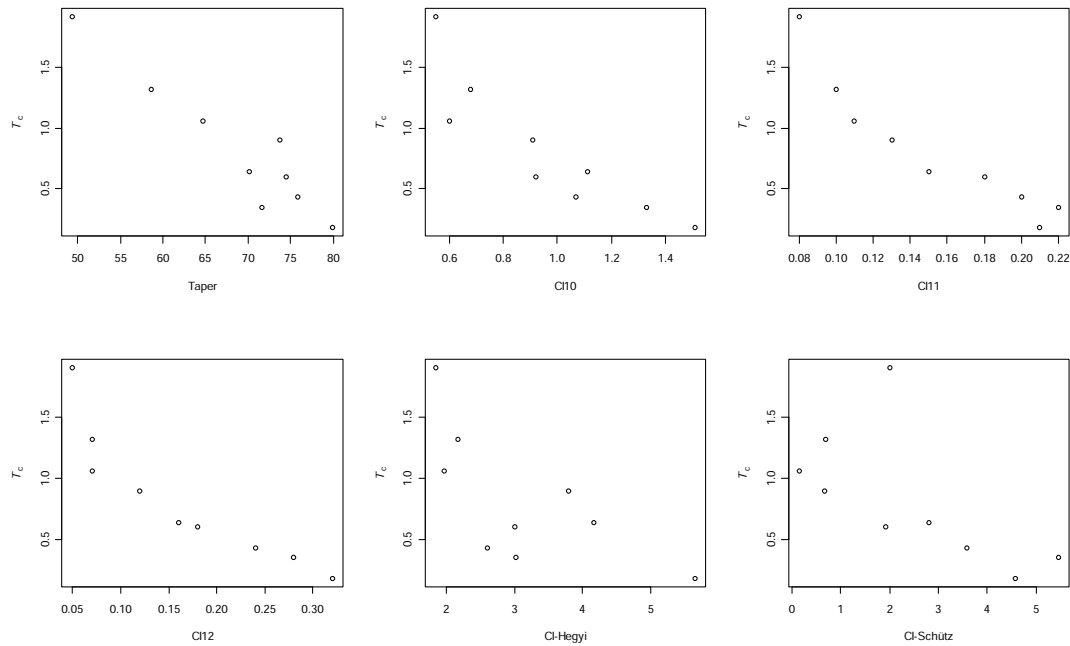


Fig. 1: Turning moment coefficients ( $T_C$ ) plotted against taper ( $h/d$ ) and five competition indices for the nine trees at Clocaenog, redrawn from Wellpott (2008)

## 2. Methods

Data were available from two additional forests, of varying species and structure, as described below. In all stands, turning moments were measured using orthogonal strain transducers, and each tree was calibrated by applying a known load. Wind speed was measured at the canopy top. Diameter at 1.3 m ( $d$ ) of all trees in each plot was measured. For details of experimental setup, refer to Gardiner et al. (1997) and Wellpott (2008). Measurements of wind loading and wind speeds were analysed to calculate  $T_C$ . Mapped tree positions within all plots were processed using Voronoi polygons to objectively identify the neighbours for each sample tree, enabling calculation of competition indices. Of those indices presented by Wellpott (2008), the three based on proximity and  $d$  (CI10, CI11 and CI12; see Appendix) were calculated for all sample trees. CI-Hegyí and CI-Schütz were not used as they also require crown dimensions and, based on the Clocaenog data, offered no improvement over the simpler indices.

*Kershope*

In 1989, Gardiner et al. (1997) measured the wind loading on 11 trees in a Sitka spruce spacing experiment at Kershope Forest, Cumbria (55° 7' N, 2° 42' W). The stand was planted in 1967 at 1.8 x 1.7 m spacing (3200 stems ha<sup>-1</sup>), and respaced in 1975 to various spacing patterns and densities. Summary characteristics of the five plots used in this study are given in Tables 1 and 2. The number of data runs obtained for each sample tree is shown in Table 2. Where more than one run was obtained for a particular tree, values of  $T_C$  presented represent an average of individual runs.

Table 1: Stand characteristics for the three sites

	Clocaenog	Kershope	Kyloe	Kyloe
Species	Sitka spruce	Sitka spruce	European larch	Sitka spruce
Age (yrs)	54	22	59	Not known
Mean height (m)	27	12	25	11
Spacing (m)	5.9	1.8 - 4.9 <sup>†</sup>	9.2	Not recorded
*Height range (m)	22.8 - 31.9	10.4 - 12.7	21.0 - 27.6	8.7 - 11.3
*Diameter range (m)	28.5 - 59.8	14.2 - 22.6	33.7 - 40.6	12.1 - 21.4
* $h/d$ range	0.49 - 0.80	0.47 - 0.88	0.54 - 0.68	0.53 - 0.77

\* sample trees only

<sup>†</sup> see Table 2

Table 2: Plot characteristics and sample trees at Kershope

Plot number	Treatment*	Spacing (m)	Spacing:height	Tree ID (No. of data runs)		
1715	1	1.8	0.14	25 (1)	71 (13)	121 (1)
1709	2	2.4	0.21	34 (1)	70 (4)	
1710	3	2.8	0.24	56 (4)	64 (3)	
1713	4	3.4	0.32	26 (3)	45 (4)	
1707	6	4.9	0.45	21 (4)	43 (1)	

\* see Gardiner et al. (1997) for treatment descriptions

## Kyloe

Measurements were made in 2006 in Kyloe Wood in Northumberland (55° 38' N, 1° 55' E). This was a European larch stand (age 59 years), with a naturally-regenerated Sitka spruce understorey in part of the stand. Wind loading was measured on nine trees: two from the single storey larch, four from the overstorey larch, and three from the understorey Sitka spruce. Stand characteristics are included in Table 1. Understorey trees were excluded from the calculation of Voronoi polygons, in order that the presence of an understorey tree would not cause an overstorey tree to be excluded as a neighbour.

### 3. Results

Fig. 2 shows  $T_C$  plotted against CI10, CI11 and CI12 for Kershope and Kyloe. It can be seen that for all graphs, there is a general decrease in  $T_C$  as CI increases, although there is substantially more scatter than shown by the Clocaenog trees (Fig. 1).  $T_C$  values from Kershope are an order of magnitude smaller than those at Clocaenog.  $T_C$  values from Kyloe span a wide range and overlap with the other two sites. Values of competition indices for the three sites are of the same order of magnitude.

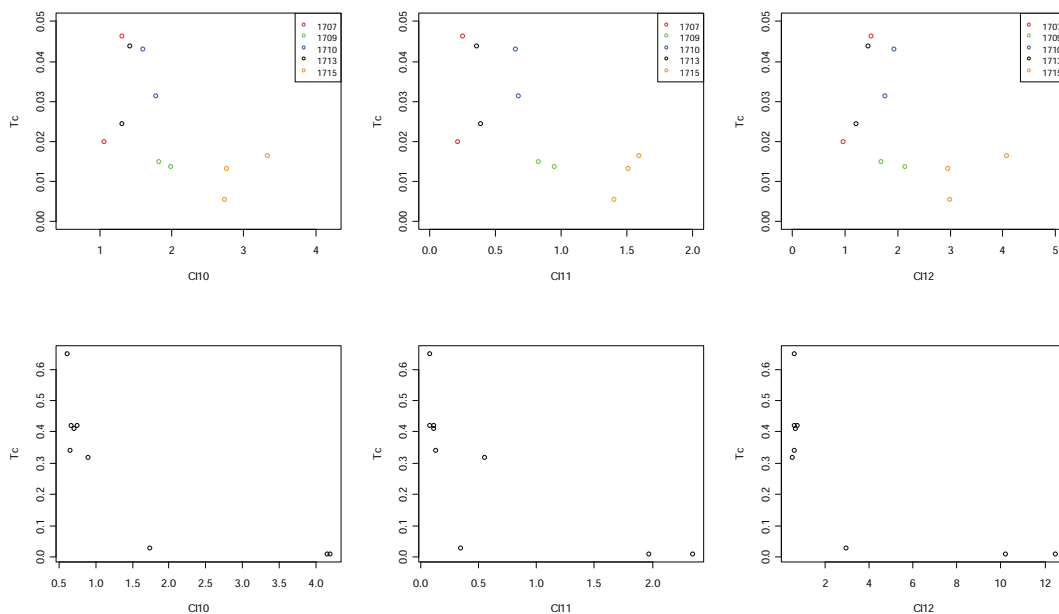


Fig. 2: Turning moment coefficients ( $T_C$ ) plotted against three competition indices for the experimental trees at Kershope (top three panels) and Kyloe (lower three panels); note the difference in scale for the y-axis; the y-axis in Fig. 2 has been multiplied by  $10^6$  for clarity of presentation

To accommodate the large difference in tree height across the three sites (8.7 to 31.9 m), the turning moment coefficient data from all sites were normalised by  $h^3$  ( $h$  = tree height) as suggested from earlier wind tunnel experiments (Stacey et al., 1994). These

are presented in Fig. 3, and it can be seen that the values of  $T_C/h^3$  for all sites fall within the same range.

The relationship between  $T_C/h^3$  and both CI11 and CI12 showed some separation between the three sites. For CI10, however, the data collapsed onto a single curve, giving a strong relationship between  $T_C/h^3$  and CI. The solid line shown on Fig. 3 represents a preliminary best-fit to the data, and can be used to estimate  $T_C$  from CI for an individual tree where the diameter and proximity of neighbours are known. The turning moment experienced by that tree for a given wind speed can then be calculated.

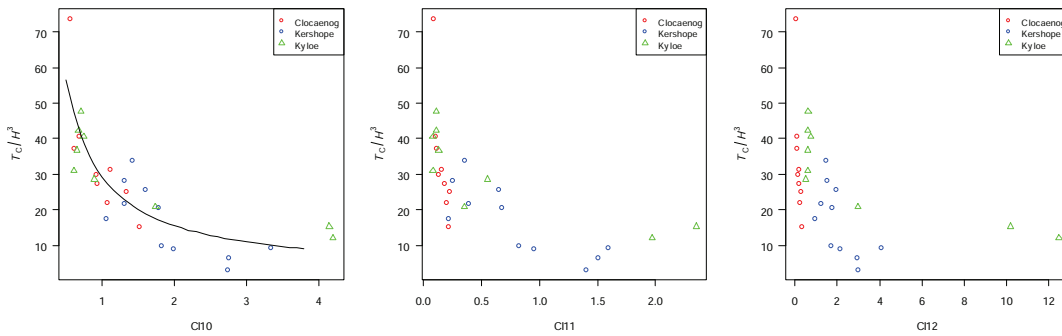


Fig. 3: Normalised turning moment coefficients ( $T_C/h^3$ ) plotted against three competition indices for the experimental trees at Clocaenog, Kershope and Kylee; note that the y-axis has been multiplied by  $10^6$  for clarity of presentation; a preliminary fit has been made to the data in the first panel (black line), which has the relationship  $T_C/h^3 = 1.79 + 27.4/CI10$

#### 4. Discussion

The scatter at Kershope is unsurprising as the data are essentially from five different plots, rather than from a single plot as at the other two sites. Spacing/height varies from 0.14 to 0.45, and differences between individual sample trees within a plot at Kershope are largest in the more widely spaced plots.

The wide range of  $T_C$  values recorded at Kylee is consistent with the difference in tree size between the overstorey and understorey. The low values of  $T_C$  measured for the understorey Sitka spruce trees (0.01 to 0.03) were very similar to those recorded for the trees at Kershope (0.01 to 0.05), which were of a similar size (Table 1).

#### 5. Conclusions

The collapse of the data sets from Clocaenog, Kershope and Kylee onto a single line is very encouraging, particularly given the differences in both species and structure of the forest stands. Competition indices, which are used widely within forest growth modelling, offer a potentially useful tool for apportioning wind energy across individual trees of different sizes within a forest stand. This allows us to calculate the differences in risk

of damage across a stand and to build a risk model for complex stand structures. Further field measurements are underway in order to obtain a wider data set to fully validate the relationship.

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## Appendix

Formulae for calculation of the competition indices presented in the report.

From Rouvinen and Kuuluvainen (1997):

$$CI_{10} = \sum_{i=1}^n \frac{d_j/d_i}{D_{ij}} \quad CI_{11} = \sum_{i=1}^n \frac{d_j/d_i}{D_{ij}^2} \quad CI_{12} = \sum_{i=1}^n \frac{(d_j/d_i)^2}{D_{ij}}$$

From Hegyi (1974):

$$CI_{Hegyi} = \sum_{i=1}^n \frac{(R_j/R_i)^{1.3}}{D_{ij}^{0.4}}$$

From Schütz (1989):

$$CI_{Schütz} = \sum_{i=1}^n 0.5 - \frac{D_{ij} - (R_j + R_i)}{(R_j + R_i)} + 0.65 \cdot \frac{h_i - h_j}{D_{ij}}$$

where:

$d$  is tree diameter at 1.3 m (cm)

$i, j$  represent subject and neighbour tree, respectively

$D_{ij}$  is distance between subject and neighbour tree (m)

$h$  is tree height (m)

$R$  is mean crown radius (m)

$n$  is number of neighbours

For  $CI_{\text{Schütz}}$ , a neighbouring tree is only counted as a competitor if the calculated value is larger than zero.

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