

Critical wind speed estimates for individual trees from a field experiment

Abstract

Simultaneous measurements of wind speed and turning moment of a group of nine adjacent mature Sitka spruce trees were used for analysing the wind and tree interaction. A quadratic model was fitted to the data of turning moment and wind speed near the canopy top.

Predicted absolute mean turning moments for the nine trees were highly correlated with dbh^3 ($r = 0.98$) and stem weight ($r = 0.97$), which themselves are estimators for breaking and overturning. Predicted mean wind speeds for tree breaking are not correlated with individual tree properties. However, correlation of the predicted mean wind speeds for overturning suggest that dominant trees are at higher risk of tree failure.

For the experimental trees, dbh is the best estimator for predicting both the absolute turning moment and the risk of wind damage.

3.1 Introduction

Individual trees in a forest stand can differ significantly from each other regarding their properties, even in even-aged mono-cultures. Differences are the result of lifelong competition for resources including light, water, and nutrition (Oliver and Larson, 1990). At the same time mechanical stimulation is known to affect plant growth (Metzger, 1893; Stokes et al., 1995; Telewski, 1995; Stokes et al., 1997; Cleugh et al., 1998). Plant response to mechanical stimulation is termed *thigmomorphogenesis* after Jaffe (1973). In his experiments he showed that plants that were rubbed daily showed reduced height growth and increased

stem diameters, that resulted in higher rigidity of the plant stem. Since the main mechanical stimulus in natural conditions is the loading exerted by the wind, differences in tree growth are pronounced where sheltered and non-sheltered conditions are found in close proximity (James et al., 1994).

Forest canopies are very efficient in terms of wind energy absorption. The vast majority of momentum is absorbed in the upper part of the canopy (Baldocchi and Hutchison, 1987). Hence the drag that two neighbouring trees experience can be very different, due to differences in their height. Small suppressed trees benefit from a sheltered environment, that is created for them by their taller neighbours, which absorb most of the wind energy. Increased height growth goes hand in hand with diameter growth. Taller individuals in a stand have also bigger trunks and higher root mass (Levy et al., 2004) and therefore higher stiffness and improved anchorage (Nicoll et al., 2006).

This poses the question as to which individuals are the most vulnerable in a forest stand. Does the higher amount of biomass of the dominant trees fully compensate for the increased wind exposure? Or does their dominant and favourable position come at the cost of higher risk of failure. Do small trees accept the risk of mechanical failure and invest more biomass into height growth to reach higher light levels?

The vast majority of work in the literature, which dealt with the inter-stand variability of wind damage is based on post-damage surveys (e.g. Everham III and Brokaw, 1996; Coates, 1997; Evans et al., 2007). The disadvantage of such surveys is that the 'true' critical wind speed is unknown. Only the results of the wind damage process can be interpreted but not the process itself. Imagine that only one tree fails during a storm event for some reason. This will cause a sudden increase in wind loading inside the canopy, since the wind can penetrate deeper into the stand, which can trigger a chain reaction. This kind of wind damage causes street wise patterns of wind damage (e.g. Lines, 1953; Gardiner and Quine, 1994). At the same time not all tree failure can be accounted for by wind damage per se. In particular smaller trees are often damaged by falling bigger trees, and may bias the analysis (Peterson, 2004). Only in rare occasions wind speed measurements are available for above the forest during a destructive storm event (Oliver and Mayhead, 1974). Wind speed information is usually taken from the nearest weather station or is estimated from models (e.g. Lanquaye-Opoku and Mitchell, 2005). This procedure does not allow an accurate estimate of the stands critical wind speed at which damage occurs. The wind speed during a gale event

gradually builds up to a maximum. As no time information for tree failure is generally available, the only interpretation that post-damage surveys allow is that the threshold of wind damage was exceeded.

This chapter aims to estimate the critical wind speed at which tree damage will occur from simultaneously measured time series of wind speed and turning moment. A quadratic model is fitted to the data and the relationships are used to investigate whether a single tree property is able to explain the susceptibility of an individual tree to wind damage.

3.2 Material and methods

3.2.1 Experimental site

The field survey took place in a pure Sitka spruce (*Picea sitchensis* (Bong.) Carr.) stand in Clocaenog Forest, Wales (53°07'40" N, 3°42'96" W, 395 m a.s.l.) in 2005. Density of the stand was 292 trees ha⁻¹, mean height was 26.7 m, average diameter at breast height (*dbh*) was 35.8 cm, and mean slenderness (*h:dbh*) 76 (values calculated from measurements taken in 2002). For the four crown classes the slenderness values were 80±12 for dominant, 75±9 for co-dominant, 76±10 for subdominant, and 76±9 for suppressed trees. Each crown class contained 25 % of the total number of trees, where the trees were ranked by *dbh*. The last thinning of the stand was carried out in 1999, six years before this field survey. Urban et al. (1994) estimated the time scale for full adaptation to a stand intervention to be in the range of 5 to 10 years.

For the field survey nine adjacent trees were chosen as experimental trees which were approximately arranged in a 3 × 3 array (see Fig. 3.1). The nine trees cover a wide range of properties and all crown classes except the 'subdominant' are represented by the sample (see Tab. 3.1).

3.2.2 Tree failure moments

Tree failure can be distinguished into two main categories, breaking and overturning. The required turning moments for the two types are named breaking moment (M_{break} in Nm) and overturning moment (M_{over} in Nm). The trees critical moment (M_{crit} in Nm) is defined as the lower of these two values. Since no permission was granted for destructive treepulling tests of the experimental

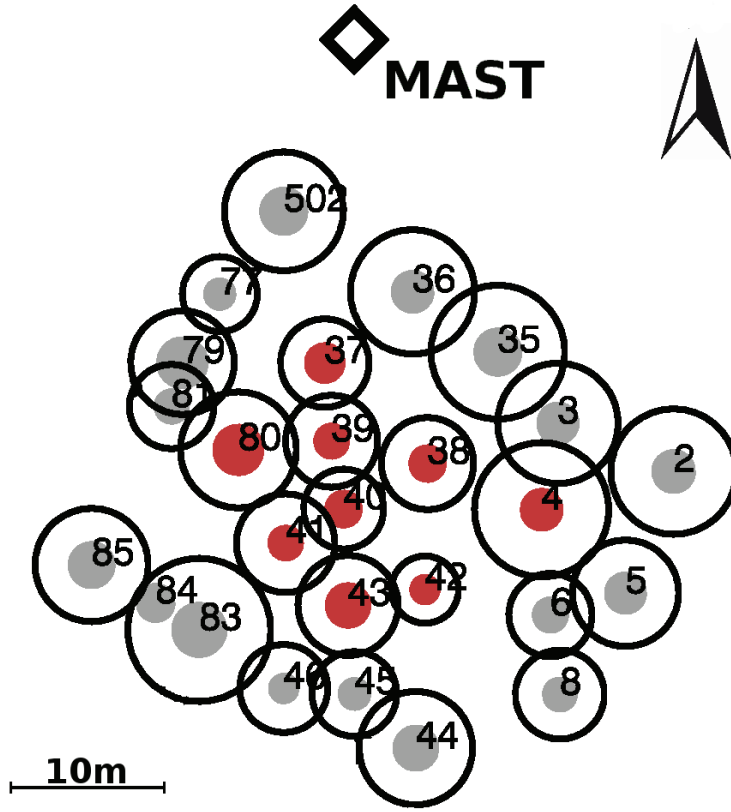


Figure 3.1: Map showing the nine experimental trees (red) and their direct neighbours (grey). The black circles indicate the average crown radii. Note that the meteorological mast was located inside the forest stand. Since the experimental trees were located at the edge of the plot, the coordinates of the trees adjacent to the mast were not measured.

trees, these moments were calculated from tree properties and relationships from the literature. The breaking moment of the individual tree was calculated as (Gardiner et al., 2000):

$$M_{break} = \frac{\pi}{32} \cdot MOR \cdot diam_{at\ base}^3 \quad (3.1)$$

where MOR (3.4×10^7 Pa) is the modulus of rupture (Lavers, 1969) and $diam_{at\ base}$ (m) is the tree's base diameter calculated as function of dbh and tree height (h) (Gardiner, 1992):

$$diam_{at\ base} = \frac{dbh}{((h - 1.3)/h)^{0.6}} \quad (3.2)$$

The overturning moment (M_{over}) is calculated as a function of stem weight:

$$M_{over} = c_{reg} \cdot SW \quad (3.3)$$

where SW (kg) is the tree's fresh stem weight and c_{reg} (N m kg^{-1}) an empirical species and soil specific regression coefficient, which was estimated from more than 2,000 treepulling tests (Fraser and Gardiner, 1967; Nicoll et al., 2006). For c_{reg} a value of 162 N kg^{-1} was used, which is the one for Sitka spruce growing on 'Gleyed mineral soils' and with a rooting depth of 40–80 cm (Nicoll et al., 2006). The stem volume was modeled using individual tree height, dbh , and age using a model which was derived for British Sitka spruce trees assuming a density of 850 kg m^{-3} (Lavers, 1969). The stem weight of three of the experimental trees exceed the maximum stem weight, that had been used for the model in the original publication (Nicoll et al., 2006).

The estimated breaking and overturning moments for the nine experimental trees are listed in Table 3.1 (see also Fig. 3.2). The pairs appear similar for six out of the nine trees and differences are less than 5%. The similarity of breaking and overturning moments has been described in the literature (Petty and Worrell, 1981; Cremer et al., 1982), which suggests that the development of roots and stem is balanced (Dunham and Cameron, 2000). For the three heaviest trees (4,43,80) the differences are more pronounced (26%, 9%, 15%). For tree 39 and 42 the overturning moment is higher than the breaking moment. For the seven other trees the overturning moment is lower than the breaking moment. The fact that from the predictions more trees are likely to overturn rather than break is in agreement with post damage observations in nearby stands from the years 2005 and 2007 where more trees were overturned than snapped (Jens Haufe, personal communication).

3.2.3 Wind measurements

The wind profile in the forest was measured with eight cup anemometers (NRG#40, NRG Systems, US) mounted onto a 30 m mast (TallTower, NRG Systems, US), which was located about 30 m north from the experimental trees. Wind direction was measured at 27 and 15 m above ground using wind vanes

Table 3.1: Properties of the experimental trees in Cloccaenog Forest. Values in parentheses give the normalised rank from all trees in the experimental plot based on measurements in 2002. The total number of trees in the stand is 292. (ID: tree number, dbh : diameter at breast height, h : tree height, cr-base: height of crown base, cr-class: crown class, M_{break} : breaking moment, M_{over} : overturning moment, M_{crit} : critical moment)

ID	dbh (cm)	h (m)	$h:dbh$ (-)	stem weight (kg)	cr-base (m)	cr-class	M_{break} (kNm)	M_{over} (kNm)	M_{crit} (kNm)
4	59.8 (1.00)	29.6 (0.89)	49.5 (1.00)	2989	13.9	dom	774	484	484
37	42.2 (0.82)	31.1 (0.96)	73.7 (0.54)	1651	16.0	dom	270	267	267
38	38.9 (0.69)	27.3 (0.60)	70.2 (0.71)	1220	17.2	co-dom	214	197	196
39	35.4 (0.51)	26.9 (0.53)	76.0 (0.45)	1008	15.5	co-dom	161	163	161
40	37.6 (0.63)	28.0 (0.72)	74.5 (0.51)	1181	15.5	co-dom	193	191	191
41	34.0 (0.41)	24.3 (0.13)	71.5 (0.65)	834	15.8	surp	144	135	135
42	28.5 (0.08)	22.8 (0.04)	80.0 (0.30)	558	15.2	surp	85	90	85
43	47.2 (0.96)	30.5 (0.94)	64.6 (0.88)	1987	19.5	dom	379	321	321
80	54.5 (0.99)	31.9 (0.98)	58.6 (0.97)	2735	16.0	dom	582	443	443

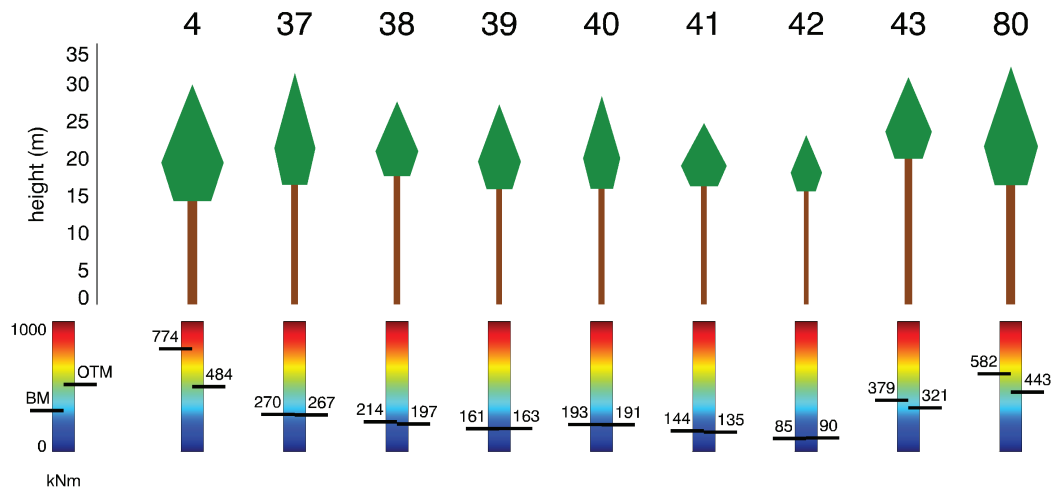


Figure 3.2: Scaled illustration of the nine experimental trees for the purpose of comparison. The numbers next to the colourbars are the breaking (left hand side) and overturning moments (right hand side).

(NRG#200P, NRG Systems, US). The upper four cup anemometers were logged every 3 s using a 21X data logger (Campbell Scientific, Logan, US). The lower four cup anemometers were logged by a Holtech logger (Durham, UK) once a minute.

3.2.4 Measurement of turning moment

The turning moments the experimental trees experienced were measured with strain transducers screwed into the trees at about 1.3 m height (Blackburn, 1997; Moore et al., 2005). Every tree was equipped with two strain transducers, which were arranged orthogonally to allow measurements in the xy-plane. Each strain transducer was calibrated individually by pulling the tree in the two directions in alignment with the position of the instruments on the trees. This provides calibration coefficients which allow calculation of the turning moments from the strain transducer signal. The time resolution of the measurements was 4 Hz.

3.2.5 Data treatment

The relationship between wind speed and turning moment was calculated on 10 min time intervals. The 3 s wind speed measurements at 30.8 m were averaged and the absolute maximum of the corresponding turning moment time series was extracted for each of the nine trees. An example of a 60 min long time series of

wind speed and turning moment is shown in Figure 3.3 and illustrates how the wind speed and turning moment values were extracted for the analysis of the wind tree interaction.

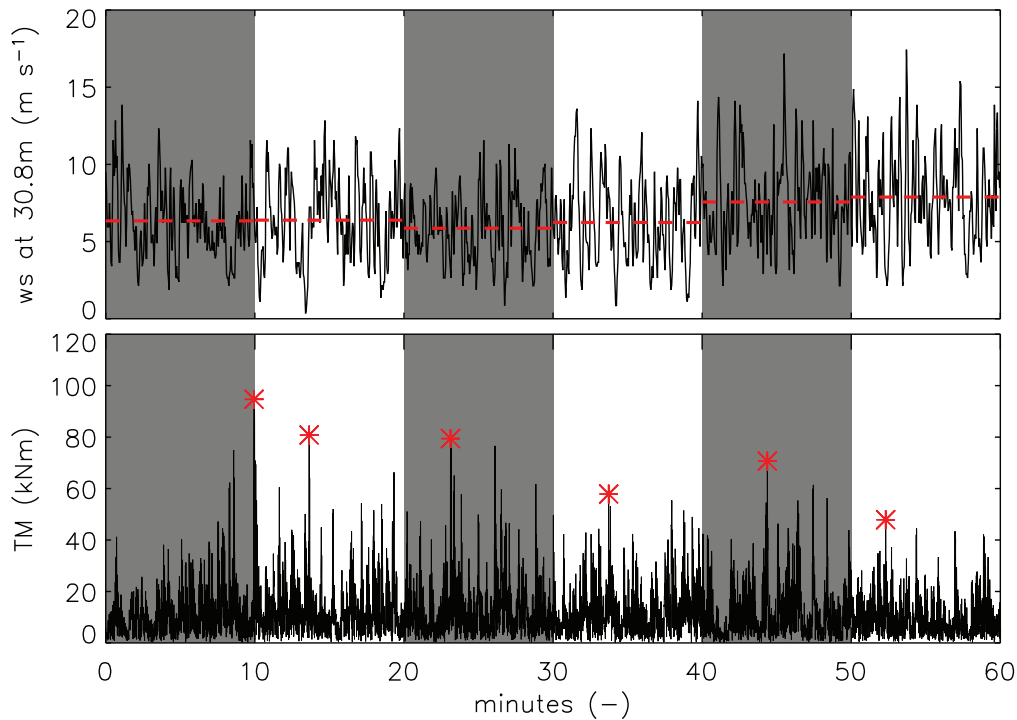


Figure 3.3: Time series of wind speed at 30.8 m (upper) and turning moment of tree 4 (lower) (date: 24.Aug.2005, 3–4 am). Dashed red lines are the 10 min average wind speed and the red asterisks represent the 10 min maximum turning moments which were extracted from the time series for further analysis.

Gardiner (1995) pointed out that the occurrence of coherent structures (gusts) coincides with the maxima in time series of turning moments. However, for this field study a linear relationship between 3 s gust speed and 10 min wind speed was observed, which allows a simple scaling between those two values (see Fig. 3.4). The meteorological tower was located ca. 30 m away from the centre of the nine experimental trees. Due to the limited spatial extent of coherent structures we cannot be sure that the maximum wind speeds at the meteorological tower are exactly the same as those that the trees were exposed to. Hence the 10 min mean wind speed is assumed to be a more robust parameter for the analysis of the wind and tree interaction.

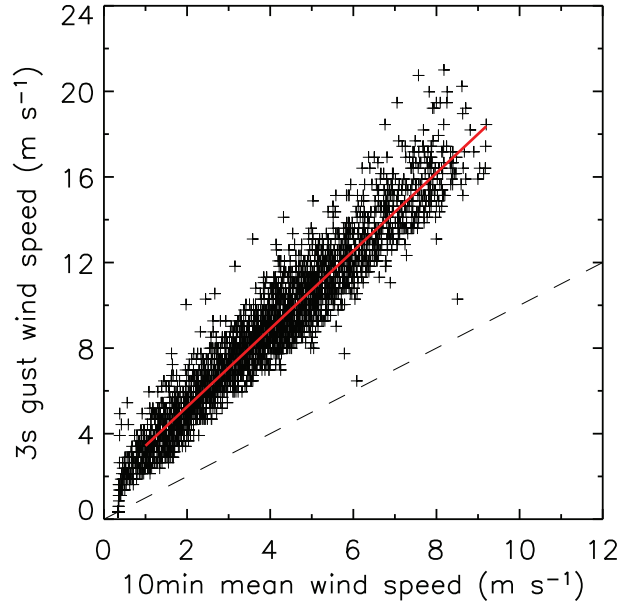


Figure 3.4: 3 s gust speed at 30.8 m height plotted versus 10 min mean wind speed the red line is the best fit of a linear regression model ($f(x) = x \cdot 1.82 + 1.61$, $R^2 = 0.91$, $n = 2743$).

3.2.6 Wind loading on individual trees

The turning moment at the tree base is composed of two components. One component results from the drag on the tree crown due to the wind (M_{drag}). The other component results from the overhanging crown mass as the tree top deflects and the centre of mass is moved from its rest position ($M_{\text{crown mass}}$). The total turning moment at the tree base is the sum of these two components:

$$M = M_{\text{drag}} + M_{\text{crown mass}} \quad (3.4)$$

For modelling purposes, the crown mass is often regarded as a single point mass located at the center of the canopy (Fraser and Gardiner, 1967). Hence its contribution to the total turning moment can be calculated as:

$$M_{\text{crown mass}} = \frac{1}{2} h \cdot g \cdot m_{\text{crown}} \cdot x_{\text{center of canopy}} \quad (3.5)$$

where h (m) is tree height, g (9.81 m s^{-2}) is the gravitational constant, m_{crown} (kg) is the crown weight and $x_{\text{center of canopy}}$ (m) is the horizontal stem displacement at the center of the canopy. Except for the displacement (x) all terms in the above

equation are constant. Gardiner (1992) gives an analytical solution for the static tree bending, which only requires a 'load parameter' as input. Displacement at the center of the canopy is a linear function of this 'load parameter'. In comparison to the drag induced turning moment, the contribution of the crown mass is small and in the range of 5% to 10% of the total turning moment (Gardiner et al., 1997). Therefore it is feasible to describe the stem displacement as a function of the drag.

For the analysis of the M_{drag} term a simplified form of the general drag formula was used. The drag formula in its original form is:

$$M_{\text{drag}} = \rho \cdot \int_0^z C_D(z) \cdot A(z) \cdot u(z)^2 dz \quad (3.6)$$

where ρ (1.226 kg m^{-3}) is air density, $C_D(-)$ the drag coefficient, A (m^2) is frontal crown area, u (m s^{-1}) horizontal wind speed, and z (m) height above ground. Unlike rigid obstacles, trees are flexible and streamline in high winds (Mayhead, 1973; Rudnicki et al., 2004). Hence crown area and drag coefficients themselves are functions of wind speed. However, several wind tunnel studies showed a linear relationship between drag and a single squared reference wind speed (Gillies et al., 2002; Vollsinger et al., 2005). The data from this experiment suggest the same relationship holds for at least the range of wind speeds for which measurements are available. Since the above wind tunnel studies exceeded the maximum wind speed from this field experiment, it seems reasonable to assume this relationship to be valid over a wider range.

Neglecting the drag coefficient and changes in projected crown area M_{drag} can be described with a quadratic model approach:

$$M_{\text{drag}} = b \cdot u^2 \quad (3.7)$$

where M_{drag} (kNm) is the drag induced turning moment at the tree base and u (m s^{-1}) is a reference horizontal wind speed. From the discussion above, it can be concluded that the crown mass term is proportional to the drag, since it accounts for most of the turning moment at the tree base. Hence, Equation 3.7 can also be used to describe the total turning moment (M) at the tree base:

$$M = \underbrace{b \cdot u^2}_{M_{\text{drag}}} + \underbrace{c \cdot u^2}_{M_{\text{crown mass}}} = a \cdot u^2 \quad (3.8)$$

where the parameter a incorporates the effects of drag and crown mass.

By inverting Equation 3.8 the wind speed can be calculated as function of turning moment (M). Inserting the estimated turning moments for breaking and overturning from Table 3.1 gives the possibility to calculate the corresponding wind speeds:

$$u = \sqrt{\frac{M}{a}}. \quad (3.9)$$

This simple modelling approach neglects some major aspects of the wind and tree interaction such as the streamlining of the trees in high wind and the leaf area profile. However, the most severe simplification is probably the fact that this approach ignores the dynamic behaviour of the tree. Trees can be described as harmonic damped oscillators (Holbo et al., 1980; Mayer, 1987). Their response to wind loading near their eigenfrequency can be 10 fold higher than at other frequencies (Kerzenmacher and Gardiner, 1998; Moore, 2002). Most of the deviations from the model fits are probably due to the dynamic nature of the wind and tree interaction.

3.3 Results

3.3.1 Model fitting

The 10 min mean wind speed at 30.8m was used as independent variable for the model. Preliminary data analysis showed that wind direction had an influence on the model. Therefore analysis was limited to the wind sector 180° to 270° , which contained 62% to 69% of the available data for the trees and represent the prevailing wind direction. For the identification of outliers a linear regression analysis was performed of the \log_{10} – transformed turning moment and the squared wind speed. An outlier was identified if the data point deviated more than 0.5 from the regression line in the log-transformed representation. Due to more scatter than for the other trees for tree 41 more than 8% of the data were removed in this step. For the other eight trees no more than 3% of the data were rejected for analysis (mean: 1.4%).

The models were fitted using a least square approach. The data points and the fitted models for the nine experimental trees are shown in Figure 3.5.

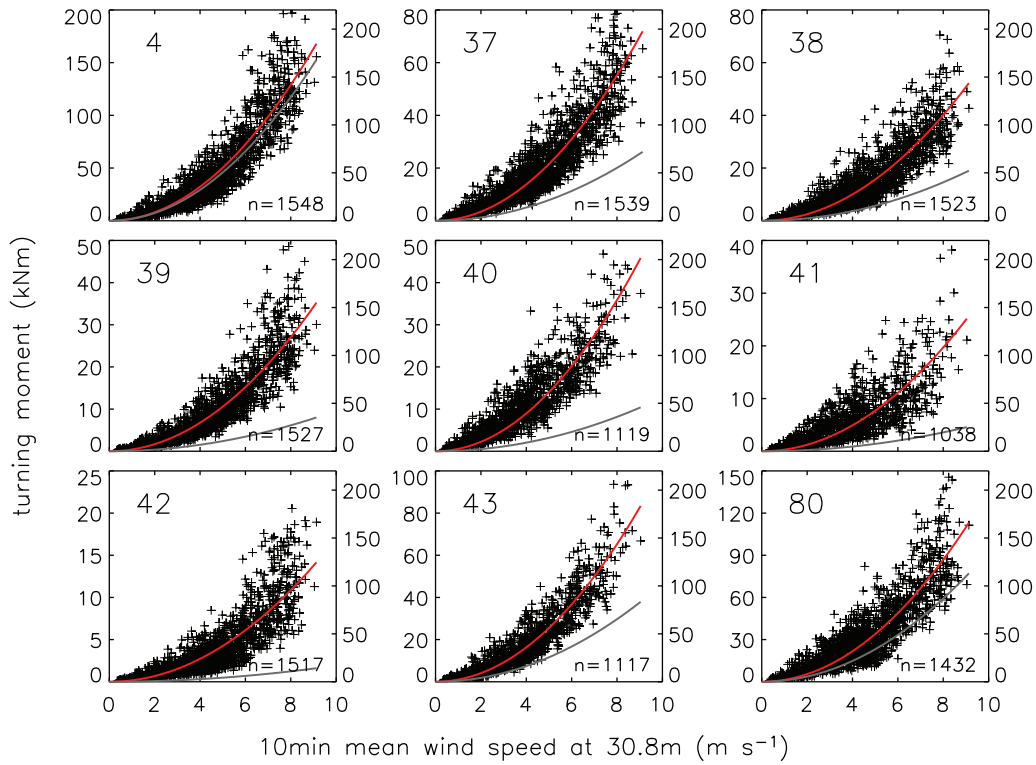


Figure 3.5: Measured 10 min maximum turning moment versus mean wind speed at 30.8 m height for the nine experimental trees. n is the number of data points used for the analysis. The red lines are the best fit of a quadratic model ($f(u) = a \cdot u^2$). The grey lines are identical to the red ones, except that they refer to the y-axis on the right hand side of the plots, which is the same for all plots and allows direct comparison of the models. Data points and red lines refer to the y-axis on the left hand side, which is adjusted for each graph.

For all of the nine models more than 1,000 data points were available for curve fitting. The differences in the total number of data points are due to some equipment failure during one of the field visits. The ratio of explained to unexplained variance (R^2) is for eight out of the nine models higher than 0.75. An exception is tree 41, for which R^2 is just 0.59. The standard error of the model parameter was estimated via the bootstrap technique with a resample size of 10,000. The statistical characteristics of the nine models are summarised in Table 3.2. The high values for the coefficient of determination (R^2) confirms that the model is able to explain most of the variation.

Although the coefficients of determination are high, the data still show a considerable amount of scatter around the model fit. Figure 3.6 is a boxplot

Table 3.2: Model parameter (a) of the quadratic models ($M = a \cdot u^2$) in Figure 3.5. Standard errors for a are given in parentheses and were estimated using the bootstrap technique with 10,000 repetitions. R^2 is the coefficient of determination.

ID	n	a (SE)	R^2
4	1548	2.015 (0.062)	0.84
37	1539	0.863 (0.027)	0.81
38	1523	0.627 (0.046)	0.78
39	1527	0.423 (0.029)	0.81
40	1119	0.561 (0.025)	0.75
41	1038	0.300 (0.036)	0.59
42	1517	0.170 (0.009)	0.75
43	1117	1.020 (0.049)	0.86
80	1432	1.357 (0.054)	0.77

representation of the residuals for the wind speed class $7-8 \text{ m s}^{-1}$. The residuals are normalised by the trees critical moment. Although the limits for the 1st and 3rd quartile are for no tree higher than 5%, there are still values that exceed 15%. The variation of the turning moments has to be kept in mind when critical wind speeds are discussed later in the chapter. The discussion will focus on the predicted critical mean wind speed.

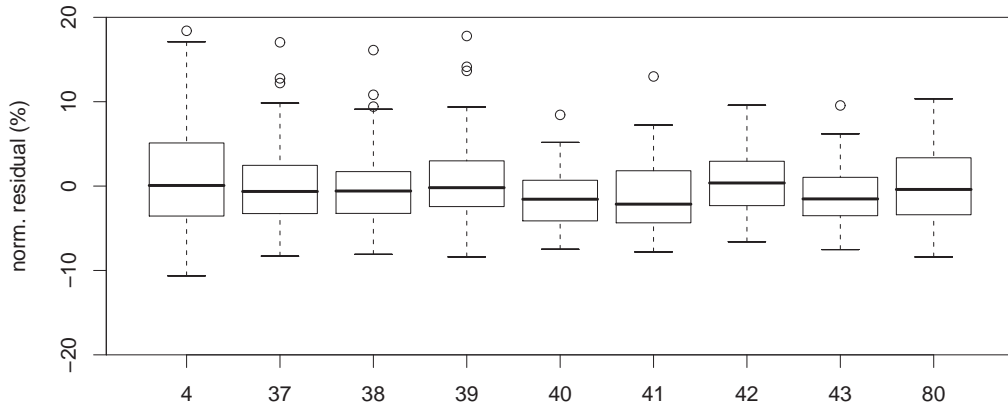


Figure 3.6: Normalised residuals ($(M - \hat{M})/M_{crit}$) for the wind speed class $7-8 \text{ m s}^{-1}$ for the nine experimental trees. Horizontal lines indicate the median. Boxes cover the 1st and 3rd quartile. Vertical bars extend 1.5 times the interquartile range to either side of the boxes. Open symbols represent data values that exceed this range.

3.3.2 Turning moment as function of tree characteristics

In Figure 3.7 from the model fits estimated mean turning moments are plotted versus the tree characteristics from Table 3.1. The reference wind speed was set to 8 m s^{-1} at 30.8 m. All five plots indicate that bigger trees - in terms of either *dbh* or height - experience higher turning moments than smaller ones. However, the two parameters are not independent. Pearson and Kendall's rank correlation coefficients for the relationships between *dbh* and tree height are 0.80 and 0.72, respectively.

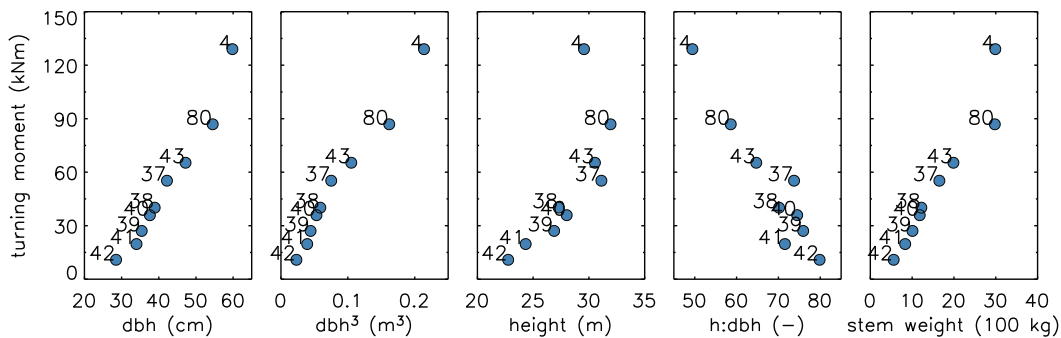


Figure 3.7: Predicted mean turning moments for the experimental trees in Clocaenog Forest for a reference wind speed of 8 m s^{-1} at 30.8 m height calculated from the models.

Kendall's rank correlation coefficients (τ) for the predicted mean turning moments and the two independent variables *dbh* (also dbh^3) and stem weight are 1.0, which indicates a perfect ranking. For the height and slenderness τ is 0.72 and -0.78, respectively.

3.3.3 Critical wind speed

The highest 10 min mean wind speed measured in the field survey was 9.1 m s^{-1} . The predicted corresponding mean turning moments for this wind speed is in average 24.5% (range: 16.4% - 34.5%) of the critical moments of the trees. Therefore, the models need to be extrapolated over a wide range to predict critical wind speeds, making the estimates susceptible to errors. For the purpose of inter tree comparison, the predicted mean turning moments are normalised by the tree's critical moment (\hat{M}/M_{crit}) from Table 3.1. This allows the representation of all nine models in a single plot (see Fig. 3.8). The critical wind speed is reached, when the curves reach unity.

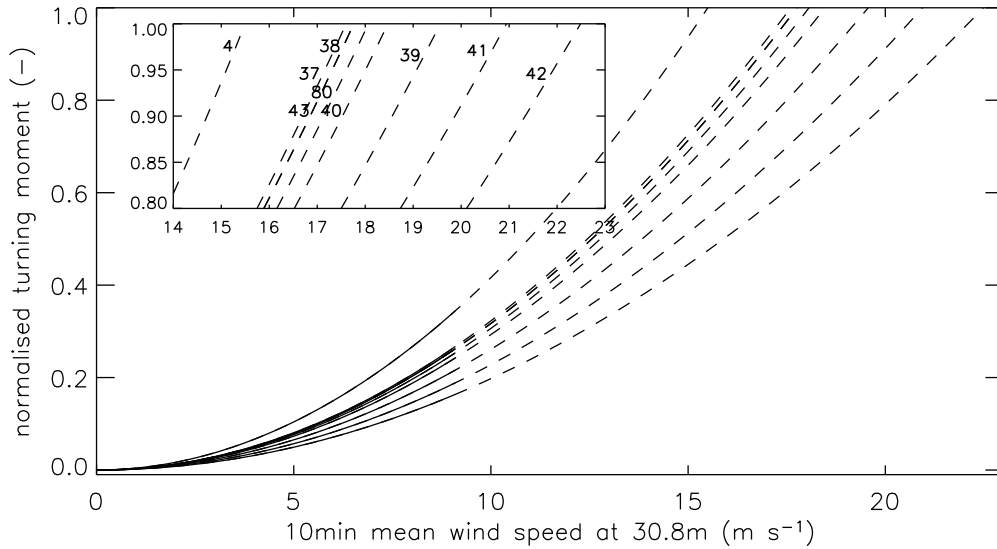


Figure 3.8: Summary of the best fits of the wind turning moment relationships from Figure 3.5. The y-axis is the normalised turning moment (\hat{M}/M_{crit}). The solid lines go up to 9.1 m s^{-1} , the range which is covered by measurements. Dashed lines indicate extrapolated values. The small figure is a 'blow-up' of the bigger plot for the purpose of clarification. Numbers are the tree IDs.

Estimated mean critical wind speeds for breaking, overturning, and general tree failure (critical turning moment) are 19.8 m s^{-1} , 18.8 m s^{-1} , and 18.7 m s^{-1} . The standard deviations for the three values are 1.56 m s^{-1} , 2.20 m s^{-1} , 2.06 m s^{-1} , indicating that the values for the breaking moments are more similar than for the two other. Tree 4 has the lowest critical wind speed (15.5 m s^{-1}) and tree 42 the highest (22.5 m s^{-1}). From Figure 3.8 the nine trees can be divided into three different groups. The first group consists of five trees (37,38,40,43,80), which all have very similar critical wind speeds within an interval of 0.9 m s^{-1} (17.6 m s^{-1} to 18.5 m s^{-1}). Tree 4, the tree with the lowest slenderness value in the sample, is separated from this group and has a lower critical wind speed. To the right of the group of five individuals are trees 39, 41, 42. Their critical wind speeds are 19.6 m s^{-1} , 20.9 m s^{-1} , 22.5 m s^{-1} . These three trees are the shortest of the group of the nine experimental trees (39: 26.9 m, 41: 24.3 m, 39: 22.8 m)

In Figure 3.9 the predicted mean wind speeds for the three moments (breakage, overturning, critical) are plotted versus several tree characteristics. The predicted critical mean wind speeds for breaking are not significantly correlated with any tree property. Absolute correlation coefficients for the breaking moment are in the

Table 3.3: Predicted wind speeds for breaking (u_{break}), overturning (u_{over}), and tree failure (u_{crit}) derived from the model calculations.

ID	u_{break} (m s^{-1})	u_{over} (m s^{-1})	u_{crit} (m s^{-1})
4	19.6	15.5	15.5
37	17.7	17.6	17.6
38	18.5	17.8	17.8
39	19.6	19.7	19.6
40	18.6	18.5	18.5
41	21.7	20.9	20.9
42	22.5	23.1	22.5
43	19.3	17.8	17.8
80	20.7	18.1	18.1
mean	19.8	18.8	18.7
SD	1.56	2.20	2.06

range 0.06 to 0.33. The fact that the predicted mean turning moment increases linearly with dbh^3 as described above, results in similar wind speeds for breaking for the nine trees. At the same time the standard deviation of the predicted mean wind speed for breaking is small compared to the estimates for the overturning wind speeds.

For the relationships between the predicted critical wind speeds or overturning wind speeds the absolute correlation coefficients are higher than they are for u_{break} . The absolute value for the relationship between u_{crit} and stem weight is 0.81. All correlation coefficients, except those for slenderness, have negative values, what indicates that bigger and taller trees are at higher risk of failure than small trees.

All calculated correlation coefficients are listed in Table 3.4. Since dbh^3 and stem weight are linearly related to the breaking and overturning moment, the Pearson correlation coefficient was calculated for these variables. For the three other parameters Kendall's rank correlation coefficient was calculated, since these parameters are not linearly correlated with the breaking or overturning moment.

3.4 Discussion

The absolute turning moments experienced by the nine experimental trees are very different. For a reference wind speed of 8 m s^{-1} at 30.8 m, tree 4 has to

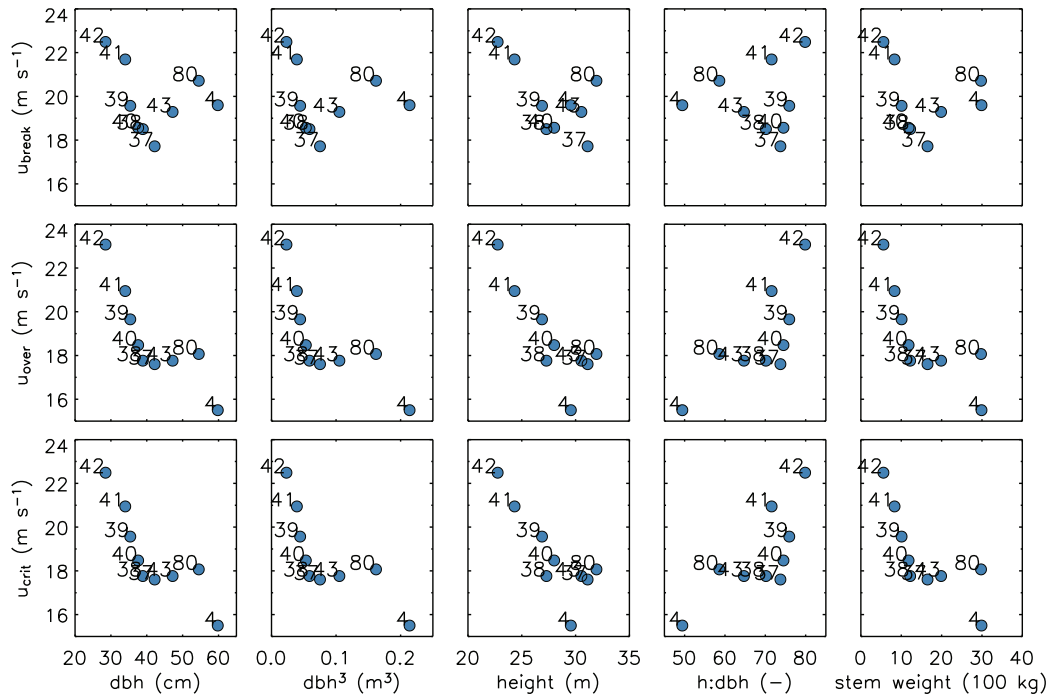


Figure 3.9: Predicted 10 min mean wind speed at 30.8 m for breaking (u_{break}), overturning (u_{over}), and general tree failure (u_{crit}) plotted versus individual tree properties (dbh , dbh^3 , height, slenderness, and stem weight).

Table 3.4: Pearson (r) and Kendall's rank correlation (τ) coefficients for the plots in Figure 3.9.

parameter	type	u_{break}	u_{over}	u_{crit}
dbh	τ	-0.28	-0.72	-0.72
dbh^3	r	-0.15	-0.76	-0.78
height	τ	-0.33	-0.56	-0.56
$h:dbh$	τ	0.06	0.50	0.50
stem weight	r	-0.25	-0.80	-0.81

withstand 129 kNm at the tree base. For the same wind speed tree 42, experiences only 11 kNm, which is less than 10 % of the value for tree 4. These huge differences are caused by differences in exposure and the fact that a vast amount of wind energy is absorbed in the upper parts of the canopy. Tree 4 is a dominant tree, which overtops its adjacent neighbours. Since the tree is taller the cantilever arm of the wind drag is longer compared to a smaller tree, which also increases the turning moment at the tree base. The smaller trees in the sample benefit from a sheltered wind environment, which is due to the wind energy absorption

in the upper parts of the canopy (Baldocchi and Hutchison, 1987). Within the number of experimental trees, the tallest one (80: 31.9 m) exceeds the smallest one (42: 22.8 m) by more than 9 m.

The turning moments for a reference wind speed appear to scale with tree properties which determine the rigidity and anchorage of the tree. Resistance to breakage increases linearly with dbh^3 and the anchorage does so as function of stem weight. The Pearson correlation coefficients for the two relationships M vs. dbh^3 and M vs. $stemweight$ in Figure 3.7 are 0.98 and 0.97, respectively. The linear scaling with dbh^3 as an independent parameter indicates that the strain ($\Delta L/L$) at the outer surface is similar for all nine trees. The uniform stress hypothesis states that trees grow to even out the stress for all parts of the tree by allocating biomass in areas that experience higher stress than average (Mattheck, 1990, 1991). The results from this study suggest that this principle is not only applicable for the parts of a single tree but also for adjacent trees in a stand. The last thinning of the stand was conducted 6 years before this field survey. This time frame is long enough for the individual tree to adapt to the new wind exposure conditions (Urban et al., 1994).

The linear scaling shows that there is a balance between exposure to wind loading and resistance to wind damage. The highest calculated critical turning moment for tree 4 (484 kNm) is 5.7 times higher than the lowest one in the sample for tree 42 (85 kNm). However, the big difference makes it hard to imagine that tree 42 would survive if it was one of the tallest members of the stand. Tree 4 already experiences a turning moment of 85 kNm at a wind speed of 6.5 m s^{-1} . This underlines the fact that the survival of smaller trees depends on the presence of taller neighbours, which create a sheltered environment for them. The removal of the dominant trees would leave the stand in a very vulnerable state. A nearby stand in which the frame trees (dominant trees) were removed by mistake suffered from significant wind damage during two gale events in 2005 and 2007 (Haufe, 2007).

For the predicted mean wind speed required to overturn the trees, all absolute values of the correlation coefficients exceed or are equal to 0.68. The fitted models estimate lower critical wind speeds for bigger trees, in terms of dbh or height. The results suggest that, in general, bigger trees are at a higher risk of wind damage, which is in agreement with results from Peterson (2004). However, the three tallest trees (4,43,80) exceeded the maximum stem weight of the treepulling data base that was used for modelling the stem weight - overturning moment

relationship (Nicoll et al., 2006). The fact that the estimated breaking moment of tree 4 is 1.6 fold higher than the overturning moment contradicts observations, that these two values are usually similar (Somerville, 1979; Petty and Worrell, 1981; Gardiner et al., 2000). On the other hand Byrne and Mitchell (2007) found a linear relationship between overturning moment and stem weight for Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), which had stem weight up to almost 3000 kg. There is no obvious reason why the relationship should change for higher stem weight for Sitka spruce as long as the rooting depth is not restricted due to for example a high water table. However, without information from destructive tree pulling tests, this problem cannot be examined in any more detail.

The analysis showed that *dbh* is the best estimator for predicting absolute experienced turning moment and for estimating the risk of wind damage for the experimental trees. The correlation coefficients for *dbh* are higher than they are for slenderness, which is a common parameter for estimating the stability of stands (Cremer et al., 1982; Blackburn and Petty, 1988; Valinger et al., 1993).

3.5 Conclusions

The wind and turning moment relationship for nine mature Sitka spruce trees were analysed with data from a field experiment. The data were used to fit quadratic models for the relationship between wind speed and turning moment, which except for one tree, exceeded 0.75 for the R^2 value.

The measured turning moment increases linearly with the breaking and overturning moments over the whole range of tree properties. However, trees which are exposed to higher wind loading and hence higher turning moments compensate for this by higher resistance. Therefore the differences in experienced turning moment are much more pronounced than they are for the predicted critical wind speeds.

The predicted wind speeds for breaking were only weakly correlated with any of the tested tree properties. For the overturning moment and the critical turning moment the correlation coefficients were higher. For the estimators *dbh*, height, and stem weight, the correlation coefficients are negative, while they are positive for slenderness. This indicates that dominant and co-dominant trees have the highest risk of failure by overturning.

dbh or its derived parameter dbh^3 , had the best correlation for predicting the

absolute experienced turning moment and the critical wind speed for trees within the range of tested estimators.

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