

Validation of the ForestGALES model for a mature Sitka spruce forest

Abstract

ForestGALES is a decision support tool developed for the purpose of estimating the risk of wind damage in British forest plantations. Since the main species in British plantations is Sitka spruce and the traditional management is based on clearfelling/restocking, the model focuses on regular coniferous stand structures. With the increasing use of irregular silviculture systems in British forestry the model needs to be tested for such systems.

The performance of several modules of ForestGALES was tested using the data from a field experiment in a mature Sitka spruce plantation, for which ForestGALES predicts a return period for wind damage of one year. Since the stand withstood several gale events over the last several years the prediction seems to be too pessimistic.

The comparison of the measured experienced turning moments of nine trees revealed, that the wind energy was not distributed equally among the individuals, which is one of the main assumptions in the model. Dominant individuals were more exposed and experienced higher turning moments at the tree base than smaller trees. At the same time they create a sheltered environment for the smaller trees in their surrounding.

The incorrect estimate of the critical wind speed for the stand seemed to be caused by the assumption that members of the stand share the same properties. Although the experimental stand was regularly structured, it contained enough internal variability to invalidate this assumption from an aerodynamic point of view. The estimate of the wind climate is also too pessimistic, which results in a too pessimistic estimate of the likelihood of wind damage for the stand.

2.1 Introduction

Wind damage in forest plantations causes severe economic loss all over the world (Mitchell, 1995). Since Britain suffers from a more severe wind climate than many other parts of the world (Troen and Petersen, 1989), there have been many efforts in Britain to understand the principles that govern the wind and tree/stand-interaction (Fraser, 1964; Busby, 1965; Mayhead, 1973a,b; Miller, 1985). All the knowledge that has been gathered over more than four decades has been implemented into the PC based ForestGALES model. ForestGALES is a decision support tool to calculate the risk of wind damage for British forest stands (Gardiner et al., 2004, 2008). The model assists foresters to estimate the impact of their management on the stability of a stand. The model has been adapted for Canada, New Zealand, France, and Japan (Ruel et al., 2000; Moore and Quine, 2000; Cucchi et al., 2005; Kamimura and Shiraishi, 2007).

ForestGALES was designed for even-aged regularly structured mono-species plantations. Its equations were derived from tree pulling tests (Nicoll et al., 2006), field experiments (Gardiner, 1994, 1995), and wind tunnel studies (Gardiner et al., 1997, 2005). A comparison with the HWIND model showed good agreement between the two models (Peltola et al., 1997; Gardiner et al., 2000). However, there has been no systematic validation of the several modules with data from a single field experiment so far.

Here the data from a field study, in which experienced turning moments and wind parameters in an even-aged Sitka spruce plantation were simultaneously measured, are used to independently validate some of the modules of ForestGALES.

2.2 The ForestGALES model

2.2.1 General

ForestGALES is a PC-based wind risk model for British forests (Dunham et al., 2000; Gardiner et al., 2004). It replaced the wind hazard classification (WHC), a scoring system which had been in use since the mid eighties (Miller, 1985). The WHC comprises soil and windiness information to classify stands into six risk classes. The shortcomings of this scoring system are that it lacks objectivity and is not able to predict either the timing or amount of damage

(Quine and Bell, 1998). Furthermore it does not account for species differences, site cultivation, or silviculture. Since the initial development of the WHC, the understanding of wind damage has improved and since the design of the WHC did not allow the implementation of this knowledge, it became necessary to follow a new approach.

Development and improvement of ForestGALES is still in process. For Version 2.0 the wind climate module was revised, since it turned out to be too pessimistic (Gardiner et al., 2004). Since then, only minor modifications were implemented in the 2006 release (Version 2.1). The main modules of the model are the:

- tree characteristics and mechanics module,
- wind module, and
- wind climate module.

ForestGALES is configured for British conditions. Hence the focus is on the risk estimation for regular even-aged plantations, which is the most common stand type in Britain. Thus the model is still awaiting the implementation of mixed-species and irregular stands to make it work with more complex silviculture systems (such as single tree selection, shelterwood, group selection).

2.2.2 Resistive moments

Whether a tree fails during a gale or not depends on the relationship between wind-induced turning moment, the tree's stiffness and its anchorage. As soon as the wind-imposed turning moment exceeds either the critical breaking or the overturning moment the tree snaps or overturns, respectively. The trees breaking moment (M_{break} in Nm) is calculated from the tree properties as:

$$M_{break} = \frac{\pi}{32} \cdot f_{knot} \cdot MOR \cdot dbh^3 \quad (2.1)$$

where MOR (Pa) is the modulus of rupture, f_{knot} (–) is an empirical factor for taking the effect of knots into account, and dbh (m) is the tree diameter at breast height (1.3 m).

The overturning moment (M_{over} in Nm) is calculated using a linear relationship:

$$M_{over} = c_{reg} \cdot SW \quad (2.2)$$

where SW (kg) is the tree's stem fresh weight and c_{reg} (N m kg^{-1}) is an empirical species, soil and rooting depth specific regression coefficient, estimated from more than 2000 treepulling tests (Nicoll et al., 2006).

2.2.3 Wind loading

Roughness method

Two different approaches have been used in wind risk models to calculate the wind loading on trees. The first approach is known as the *wind profile method* and is for example used in the HWIND model (Peltola and Kellomäki, 1993; Peltola et al., 1999). This approach integrates the drag over the canopy height from the wind profile and crown properties. The second approach is the *roughness method*, which is used in ForestGALES and described in more detail below.

Two layers of air moving with different speed create shear stress (τ in N m^{-2}). The shear stress is related to momentum flux ($\overline{u'w'}$) and can be calculated from turbulence time series as:

$$\tau = \rho \cdot \overline{u'w'} \quad (2.3)$$

where u' and w' are the instantaneous deviations from the mean horizontal (\bar{u}) and vertical (\bar{w}) wind speed and $\overline{u'w'}$ is the covariance.

At the forest edge the turbulence characteristics are very different from those several tree heights inside the forest stand. It takes several tree heights before the turbulence has adapted to the underlying surface and steady state conditions are reached (Yang et al., 2006; Dupont and Brunet, 2008). From wind tunnel experiments Morse et al. (2002) found that by a distance of 14.5 tree heights inside the forest the turbulence has adjusted up to twice the canopy height. In the ForestGALES model edge effects are neglected after a distance of 10 tree heights or more downwind of the edge.

The shear stress is apportioned equally onto the individual trees of the stand, so that when D (m) is the average spacing, each tree has to withstand an average shear of $\tau \cdot D^2$ (Raupach, 1994). After Thom (1971) the force can be treated as

if it was acting at the height of the zero-plane displacement (d). Therefore the mean turning moment (M_{mean} in Nm) a tree has to withstand can be calculated as:

$$M_{mean} = \tau \cdot d \cdot D^2 \quad (2.4)$$

Above the zero-plane displacement (d) a logarithmic wind profile for a neutrally layered atmosphere is assumed:

$$u(z) = \frac{u_*}{k} \cdot \ln \left(\frac{z - d}{z_0} \right) \quad (2.5)$$

where u (m s^{-1}) is horizontal wind speed, u_* (m s^{-1}) is friction velocity above the canopy, k (0.4) is the dimensionless Von Karman constant, d (m) is the zero plane displacement, and z_0 (m) is roughness length. The values for d and z_0 are a function of the area index of the canopy, which is related to the leaf area index (Raupach, 1994). Friction velocity is related to shear stress as:

$$\tau = -\rho \cdot u_*^2 \quad (2.6)$$

where ρ (1.226 kg m^{-3}) is air density.

Gustiness

Turbulence above plant canopies shows the characteristics of a mixing layer rather than those of a boundary layer (Raupach et al., 1996). Among other attributes, the mixing layer is defined by coherent structures, which establish from Helmholtz instabilities and dominate the exchange of scalars and momentum transport between the biosphere and the atmosphere (Green et al., 1995; Kruijt et al., 2000). Gardiner (1994) used the variable interval time averaging (VITA) technique to show that the appearance of those structures coincides with peaks in time series of turning moment.

It is believed that trees are adapted to the mean wind speed but get damaged by maximum wind speeds occurring during gust events. Taking this into account is done by implementing a scaling factor called gust factor (GF). This factor is defined as fraction of maximum to mean turning moment:

$$GF = \frac{M_{max}}{M_{mean}} \quad (2.7)$$

The independent variables to calculate the GF in ForestGALES are spacing, tree height, and distance to edge:

$$GF = f(\text{spacing, tree height, distance from edge}) \quad (2.8)$$

For trees that are far enough from the edge ForestGALES estimates the factor to be in the range of 10 to 12 (Gardiner, 1994). The equations for calculating the gust factor were derived mainly from wind tunnel studies (Gardiner et al., 1997).

Critical wind speed

The wind speeds for breaking ($u(h_C)_{break}$) and overturning ($u(h_C)_{over}$) are calculated by inserting the equations for the resistive moments into the wind profile equation. h_C is the height of the canopy top. The two resulting equations are (Gardiner et al., 2000):

$$u(h_C)_{break} = \frac{1}{k \cdot D} \left(\frac{\pi \cdot MOR \cdot dbh^3}{\rho \cdot 32 \cdot GF \cdot (d - 1.3)} \right)^{\frac{1}{2}} \cdot \left(\frac{f_{knot}}{f_{edge} \cdot f_{CW}} \right)^{\frac{1}{2}} \cdot \ln \left(\frac{h - d}{z_0} \right) \quad (2.9)$$

$$u(h_C)_{over} = \frac{1}{k \cdot D} \left(\frac{c_{reg} \cdot dbh^2 \cdot h}{\rho \cdot GF \cdot d} \right)^{\frac{1}{2}} \cdot \left(\frac{1}{f_{edge} \cdot f_{CW}} \right)^{\frac{1}{2}} \cdot \ln \left(\frac{h - d}{z_0} \right) \quad (2.10)$$

where f_{edge} , and f_{CW} are parameters that take the position relative to the stand edge and the additional turning moment due to overhanging crown mass into consideration.

The results are scaled to 10 m above the zero plane displacement plus the roughness length ($d + z_0$) in the forest. The wind speed values can then be related to the conditions of the weather stations of the Meteorological Office using DAMS.

2.2.4 Wind climate

Calculating the return period for a certain wind speed requires information on the wind climate (wind speed distribution) of the site. The ForestGALES model uses DAMS (**D**etailed **A**spect **M**ethod of **S**coring) to calculate the two parameters of a Weibull distribution for hourly mean wind speed (Bell et al., 1995). DAMS is calculated from site information such as elevation, topographic exposure, aspect, funnelling effects, and general wind zone based on the analysis of long term tatter flag measurements at more than 1,000 locations (Quine and White, 1994). The score is available for Britain on a 50×50 m grid resolution. The method was validated against wind speed data from six 10 m masts in complex terrain and compared with two airflow models (WAsP and MS-Micro/3). The good agreement of the different methods underlines the aptitude of this approach (Suárez et al., 1999). The shape parameter (γ) is assumed to be constant for the whole of Britain (1.85). The second parameter (α), called the scale parameter, is calculated using an empirical linear regression equation, which was derived from long term wind speed measurements (Quine, 2000).

The probability density function (*pdf*) and the cumulative distribution function (*cdf*) of the Weibull distribution are defined as:

$$pdf(u) = \frac{\gamma}{\alpha} \cdot \left(\frac{u}{\alpha}\right)^{(\gamma-1)} \cdot e^{-\left(\frac{u}{\alpha}\right)^\gamma} \quad u \in [0; +\infty] \quad (2.11)$$

$$cdf(u) = 1 - e^{-\left(\frac{u}{\alpha}\right)^\gamma} \quad (2.12)$$

where $\gamma (-)$ defines the shape and $\alpha (-)$ the scale of the distribution. The number of hours per year that exceed a specific value can be calculated as:

$$n(u) = (1 - cdf(u)) \cdot 365.25 \cdot 24 \quad (2.13)$$

and the return period ($rp(u)$) is defined as the reciprocal ($rp(u) = n(u)^{-1}$).

2.3 Material and methods

2.3.1 Experimental site

The study site was located in Clocaenog Forest, North Wales (53°04'N, 3°35'W). The site is located on a gentle slope facing south (2%-5%) about 400 m above sea level. Mean annual precipitation exceeds 1300 mm. The soil type is an intergrade iron pan and the surface is uneven due to the ploughing. The rooting depth is 50 cm.

The light regime on the forest floor is good enough to allow ample natural regeneration to be recruited, which was at the time of the experiment about 10 years old. Seedling growth beneath a canopy is a precondition for a successful implementation of continuous cover forestry (CCF) (Hale et al., 2004). Therefore the stand can be described as a stand in transformation towards CCF (Pommerening and Murphy, 2004; Mason and Kerr, 2004).

The silviculture history of the site is not known in detail. It is suggested that the site was originally heather moor, ploughed to a depth of 15 to 20 cm, and was planted at 5' × 5' spacing as a 2/1 or 2/2 row mixture of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and Scots pine (*Pinus sylvestris* L.) or lodgepole pine (*Pinus contorta* Dougl. ex Loud.) in the years 1948 and 1951. Today the stand is pure Sitka spruce with a density of 292 trees ha⁻¹. The stand had a line thinning in the 1970s, followed by a selective thinning in 1993 (removing 80 to 100 m³ ha⁻¹) and another selective thinning in 1999/2000 (removing 100 to 120 m³ ha⁻¹).

The critical hourly mean wind speed for wind damage, as calculated by the ForestGALES model is 14 m s⁻¹, which corresponds to a return period of less than one year according to the modelled wind climate. However, there are no signs of wind damage and the fact that the last note on wind damage is dated back to 1997, demonstrates that the stand is more stable than anticipated. Since the stand has already passed its rotation period and since the risk of wind damage is considered very high, the suggested best practise would be clear felling of the stand (Miller, 1985).

The study site is part of a silviculture project of the Forestry Commission Wales and the University of Wales, Bangor, monitoring the transformation of plantations to irregular stands. Within this project mensurational and positional data for all trees in the plot (1 ha size) are available for the year 2002.

Table 2.1: Stand characteristics for the experimental stand in Clocaenog Forest. For further details see text. (*dbh*: diameter at breast height, DAMS: Detailed Aspect Method of Scoring, WHC: wind hazard classification score; tree measurements were taken in 2002)

Species	Sitka spruce
Planting year	1951
Density	292 trees ha ⁻¹
mean <i>dbh</i>	35.8 cm
mean height	26.7 m
Top height	28.4 m
Basal area	30.8 m ² ha ⁻¹
Volume	400 m ³ ha ⁻¹
Yield class	20
DAMS	20
WHC	2

2.3.2 Experimental trees

Nine trees in the plot were chosen as experimental trees (see Fig. 2.1). Those trees were located in the north-east corner of the experimental plot and approximately arranged in a 3 × 3 array. The individual tree properties cover a wide range. Height for the nine trees is in the range of 22.8 to 31.9 m and the diameter at breast height (*dbh*) is in the range 28.5 to 59.8 cm. The values for the nine experimental trees are summarised in Table 2.2.

Table 2.2: Mensurational data for the nine experimental trees (*h*: tree height, *dbh*: diameter at breast height; measurements were taken in 2005).

ID	<i>h</i> (m)	<i>dbh</i> (cm)
4	29.6	59.8
37	31.1	42.2
38	27.3	38.9
39	26.9	35.4
40	28.0	37.6
41	24.1	31.8
42	22.8	28.5
43	30.5	47.2
80	31.9	54.5

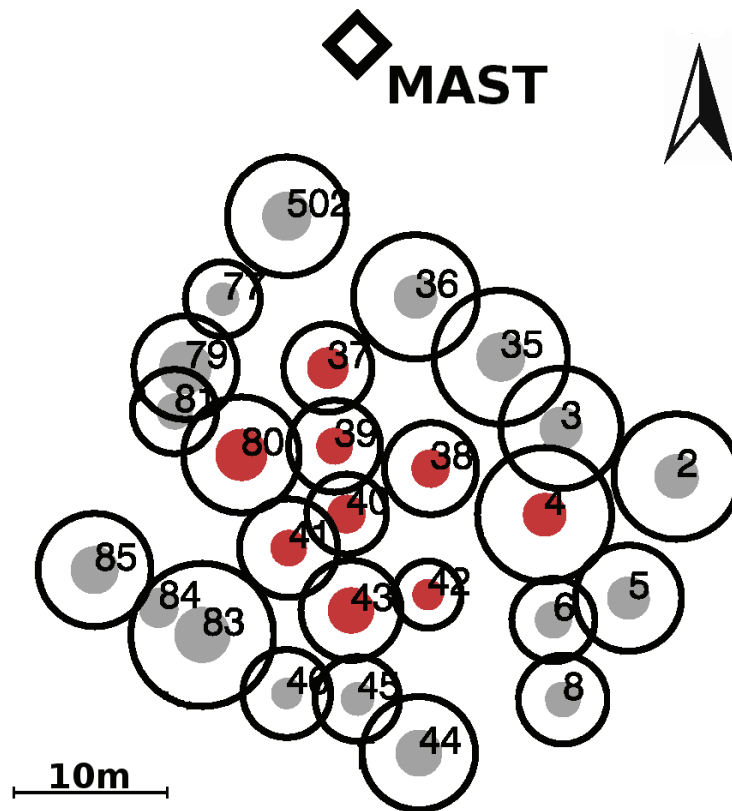


Figure 2.1: Detailed sitemap showing the nine experimental trees (red dots) and their direct neighbours (grey dots). Black circles represent the average crown radii. The meteorological mast was located within the forest stand. Since the experiment was located at the edge of the experimental plot the positions of those trees in proximity of the mast were not measured.

2.3.3 Strain transducers

The turning moments, which the nine experimental trees experience, were measured using strain gauges. These were glued onto strain transducers of the type designed by Guy Blackburn during his PhD project at the Northern Research Station (Blackburn, 1997). A more detailed description of the design and the overall performance of the sensors can be found in Moore et al. (2005). Every experimental tree was equipped with two strain transducers, which were screwed perpendicularly into the tree at about 1.3 m.

Strain gauges change their resistance when the strain transducer is squeezed or pulled as it happens when the tree sways. Because the changes in resistance are very small, the transducers were incorporated into a Wheatstone bridge to obtain a satisfactory resolution.

The signal outputs of the strain transducers were measured with three CR10 data loggers (Campbell Scientific, Logan, US) with a time resolution of 4 Hz. Each CR10 logged six strain transducers. All data loggers were part of a RS485-network. An industrial computer running LOGGERNET software (Version 2.1, Campbell Scientific) was also part of the network and stored all data, which were gathered by the data loggers, as plain text files (ASCII).

Each strain transducer was calibrated individually, by stepwise pulling the trees into two directions with a hand winch (Lugall 4000-20SH-UK, METRELL, UK) while measuring the applied force with a S-type load cell (Model 616, Tedeo Huntleigh, US). The relationship between strain transducer signal and applied turning moment was linear.

The whole system was too power demanding to run it permanently. Therefore it was switched on manually when a gale was approaching based on the weather forecast. In total more than 400 hours of data were gathered during the time period May to November 2005.

Strain data analysis

The strain transducers respond to changes in air temperature and tree growth. However, the time scale of the temperature induced signal changes is very long compared to the signal from the tree swaying. Because all of the analysis was carried out at time intervals not longer than 60 minutes, linear detrending of the raw signal is assumed to be appropriate to remove this background trend. For every time interval the offset is also removed. The offset was defined as the most frequently occurring value estimated from a histogram analysis. In the final step the individual calibration coefficients were applied to the raw data.

2.3.4 Wind measurements

A 30 m mast (TallTower, NRG Systems, US) was erected in the forest stand in August 2004. The mast was equipped with eight cup anemometers (NRG#40, NRG Systems, US; heights (m): 5, 10, 15, 18, 21, 24, 27, 30.8) and two wind vanes (NRG#200P, NRG Systems, US; heights (m): 15, 27). The four upper cup anemometers and the wind vanes were logged every three seconds (0.33 Hz). The lower four anemometers were logged once every minute.

For the second half of the field experiment (from the 23rd of August 2005) data from an Ultra-Sonic anemometer (USA-1, METEK GmbH, Germany), which

was mounted at 29.8 m height, are available. The data from the sonic were streamed to a serial port of the industrial PC and stored in hourly files using the manufacturer's software (tcopy.exe). The measurement time resolution of the sonic anemometer was set to 10 Hz.

A 10 m mast equipped with a single cup anemometer (A100R, Vector Instruments, Rhyl, UK) and a wind vane (A200P, Vector Instruments, Rhyl, UK) was erected on a clear felled site (53°03'N, 3°28'W) about 3.5 km away from the 30 m mast (see Fig. 2.2). For every hour average wind speed, average wind direction, 3 s maximum wind speed (gust speed) and corresponding wind direction was logged. Data are available for the time period May 2004 until February 2006.

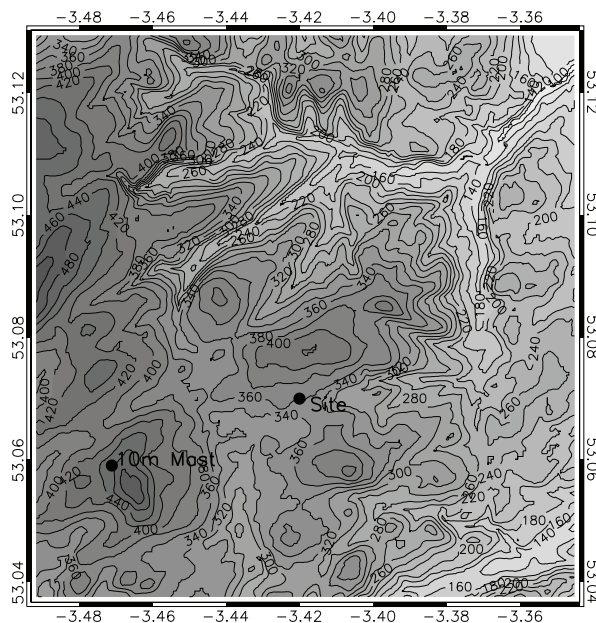


Figure 2.2: Contour map (10 km \times 10 km) showing the area around the experimental site and the 10 m mast. Isolines are in 20 m elevation steps.

2.3.5 Wind climate

The wind speed distribution at the site was estimated using the wind data from the 10 m mast and an approximately 15 year long time series from the Meteorological Office station in Rhyl (UK Meteorological Office, 2006). The method used to lengthen the time series from the 10 m mast was the standard *Measure-Correlate-Predict* (MCP) analysis (Derrick, 1992). The concurrent hourly data from the two sites were used for 30° sectorwise linear regression analysis. The sector-specific regression coefficients were applied to create an

extended time series for the Clocaenog site. The time series from Rhyl covers the time period 1st of February 1992 until 30th of June 2007. Data availability for this period is 97%. The overall coefficient of correlation for the overlapping time interval is 0.76. The wind speed distribution of the extended time series is plotted in Figure 2.3.

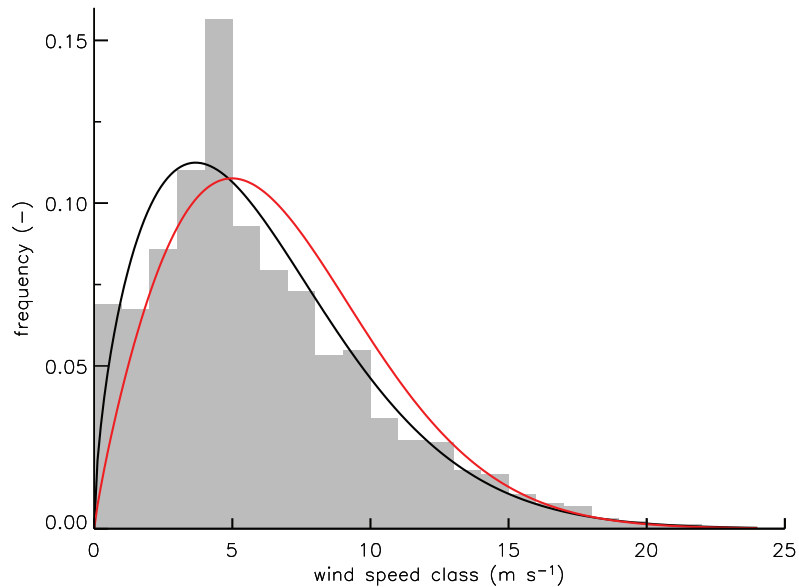


Figure 2.3: Estimated hourly mean wind speed distribution at the 10m mast in Clocaenog Forest (grey bars; bin size 1 m s^{-1}) and fitted Weibull distribution (black line, $\alpha = 1.60$, $\gamma = 6.77$). The red line is the Weibull distribution from the ForestGALES model using DAMS ($\alpha = 1.85$, $\gamma = 7.60$).

2.3.6 Gale events

Since the start of the field experiment in 2005 the stand got hit by two notable gale events. On the 8th of January 2005 the hourly mean wind speed measured at the 10 m mast reached 16.2 m s^{-1} . For the same hour the maximum gust speed was 27.0 m s^{-1} . This storm event was named *Gudrun* by the Norway weather service and caused severe wind damage in Scandinavian countries. For Sweden the amount of thrown or damaged timber was estimated to be approximately 75 million cubic meter, which equals about the annual harvest of the country (SMHI, 2005).

Another severe storm, which was named *Kyrill* by the German Weather

Service (DWD), took place on the 18th of January 2007. At this time the 10 m mast had already been dismantled. However, at the Meteorological Office weather station in Rhyl higher wind speeds compared to the event in 2005 were recorded. The station recorded 17.8 m s^{-1} and 36.0 m s^{-1} as hourly wind speed and maximum gust speed, respectively. Therefore it is likely that the wind speed in Clocaenog was also higher compared to the 2005 event. In comparison to *Gudrun* the track of the low pressure field passed further south and therefore the main damage during *Kyrrill* occurred in central Europe. In most northern federal states of Germany the damage exceeded the one of the *Lothar* storm in 1999 (EFI, 2007).

The two graphs in Figure 2.4 show the time series of wind speed, direction, and air pressure at sea level for the two gale events. In the experimental stand (including the buffer zone) only $1.25 \text{ trees ha}^{-1}$ were overturned in the 2007 event (Jens Haufe, personal communication).

From the regression analysis of hourly wind speed data between the 10 m and the 30 m mast, it is possible to estimate the wind speed at the experimental plot for the two gale events. The cup anemometer at 30.8 m is the one closest to the height for which ForestGALES estimates the critical wind speed ($d + z_0$). The analysis showed that the wind direction has a significant impact on the slope of the regression line. Therefore only data points that fall within the wind sector 225° to 270° are used (see Fig. 2.5), which covers the wind direction of the peak wind speeds for the two gale events. The estimated wind speeds at 30.8 m in the stand for the two events are 11.1 m s^{-1} (*Kyrrill*) and 12.2 m s^{-1} (*Gudrun*). Neither of the two values exceeds the one predicted by ForestGALES.

2.3.7 Model validation

The measurements made in this field study enabled the testing of several assumptions of the ForestGALES model regarding the stand characteristics, gust factor, wind loading, and wind climate. The impact of the uncertainties of the different modules on the models output is discussed.

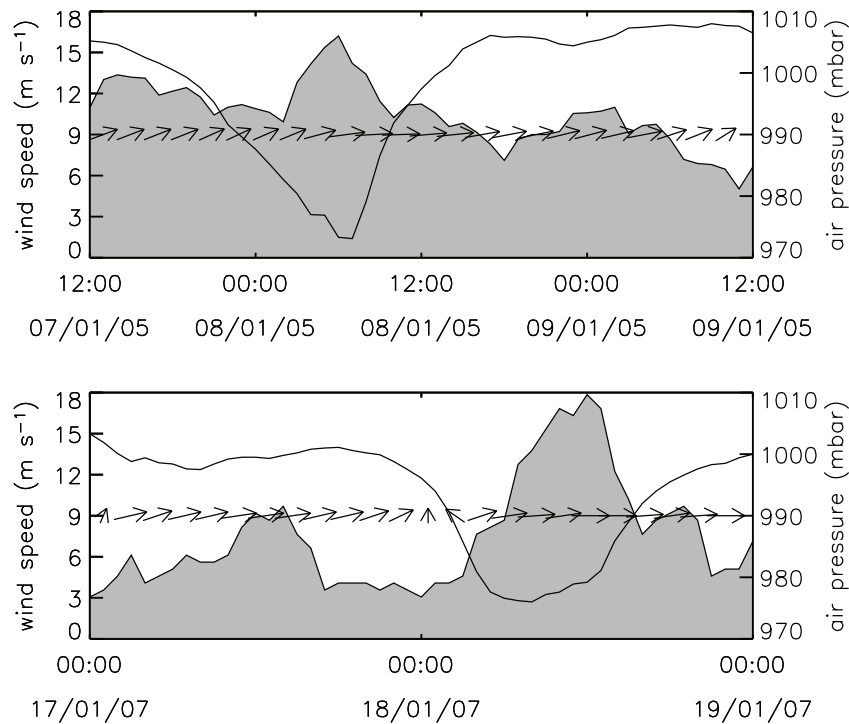


Figure 2.4: Time series of hourly mean wind speed (filled area), wind direction (arrows), and atmospheric air pressure at sea level (line) for the storm events *Gudrun* (8.Jan.2005) and *Kyrill* (17.Jan.2007). The wind data from the first event were measured at the 10 m mast in Clocaenog Forest. For the second event the original wind speed data from the Meteorological Office weather station Rhyl (53°03'N, 3°28'W) were used, because the mast in Clocaenog Forest had already been dismantled. Air pressure data for both events are taken from the Rhyl station.

2.4 Results

2.4.1 Stand and tree characteristics

In the ForestGALES model mean height is calculated from stand top height, because of the wider availability of this parameter in British forestry (Edwards and Christie, 1981). Top height (h_{100}) is defined as the mean height of the 100 largest trees in the stand, where the term largest relates to the *dbh*. For Sitka spruce the regression is:

$$h_{mean} = h_{100} \cdot 1.0467 - 2.1452 \quad (2.14)$$

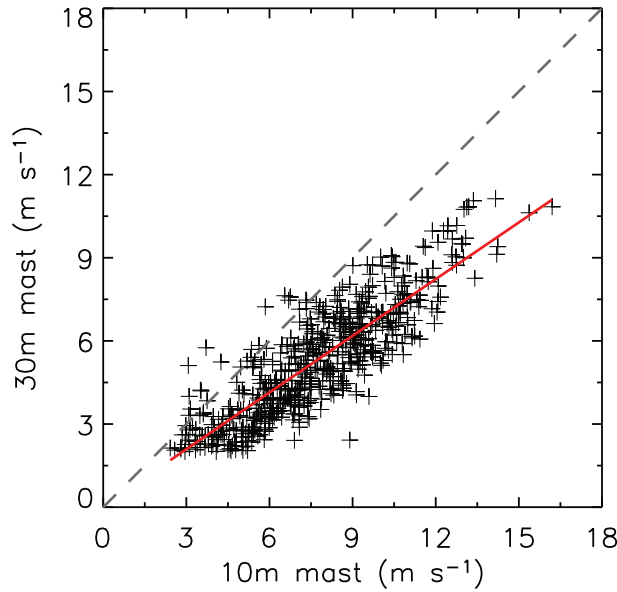


Figure 2.5: Scatter plot of hourly mean wind speed at the 30 m mast (cup anemometer at 30.8 m) plotted versus the 10 m mast. Only data values for the wind sector [225:270] degrees were used ($f(x) = x \cdot 0.68 + 0.05$, $R^2 = 0.85$, $SE = 1.1$, $n = 539$).

Figure 2.6 shows the distributions of tree height and *dbh*. Top and mean height are 28.5 m and 26.8 m, respectively. The calculated value using the above regression results in a value for mean height of 27.7 m, which is 0.9 m taller than the measurements. The overestimation of mean height results in an overestimation of the zero plane displacement and stem weight. The first results in a longer cantilever arm for the acting wind force, which itself increases the turning moment at the tree base. The second factor counteracts this effect. A taller tree has a higher value of stem weight and therefore an increased resistance to overturning.

2.4.2 Gust factor

The comparison of two wind risk models by Gardiner et al. (2000) revealed that the gust factor (*GF*) is a parameter to which the ForestGALES model is very sensitive to. Therefore an accurate estimation of this parameter is crucial for the performance of the model. The *GFs* were calculated from 10 min time series as ratios of maximum to mean value of measured turning moment. In Figure 2.7 the measured *GFs* are plotted versus the 10 min mean wind speed at 30.8 m height.

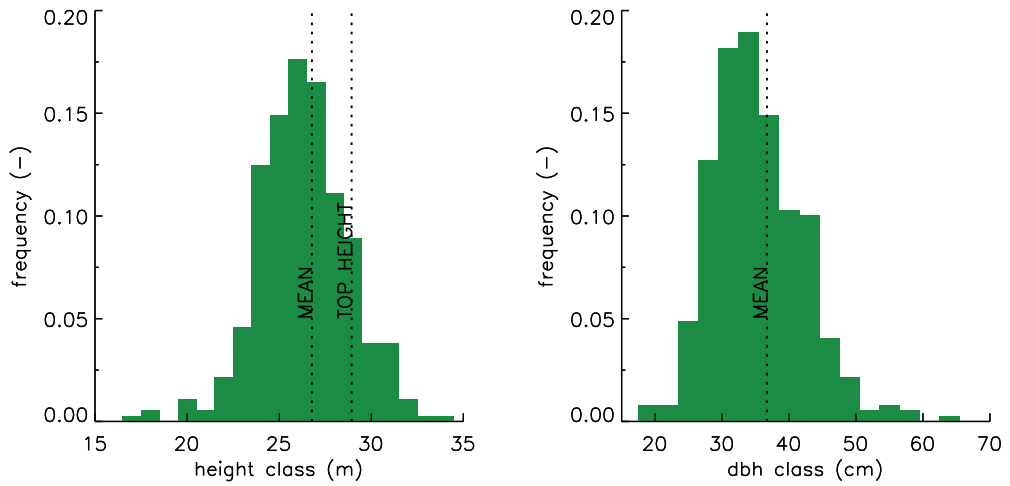


Figure 2.6: Frequency distributions of tree height (1 m bin size) and *dbh* (3 cm bin size) for the experimental stand in Clocaenog Forest. Total number of trees in the stand was 292.

The value for GF calculated by ForestGALES (using Eq. 2.8) is 10.1, based on average spacing, measured tree height (from Eq. 2.14) and assuming that edge effects are negligible.

All of the nine plots show large scatter. And although some data points exceed the ForestGALES value by more than 50%, the vast majority of points lie below the ForestGALES value and so do all mean values. In similar field studies Gardiner (1995) "found a consistent ratio of 10–12 between extreme and mean forces on plantation trees", which also exceed the measured ratios of this experiment.

The plots in Figure 2.7 show no trend within the range of measured wind speeds. All mean values are in the interval 6.5 to 8.2. The four smallest mean values correspond to the four tallest trees (80,37,43,4) and the five highest values correspond to the group of smaller trees (40,38,39,41,42). A negative correlation of tree height and GF would explain the differences in GF s from this study and the one from Gardiner (1995), whose trees were only 12 m (median) tall. Gardiner et al. (2005) present results from wind tunnel studies which also suggest that the individual gust factor varies with tree height.

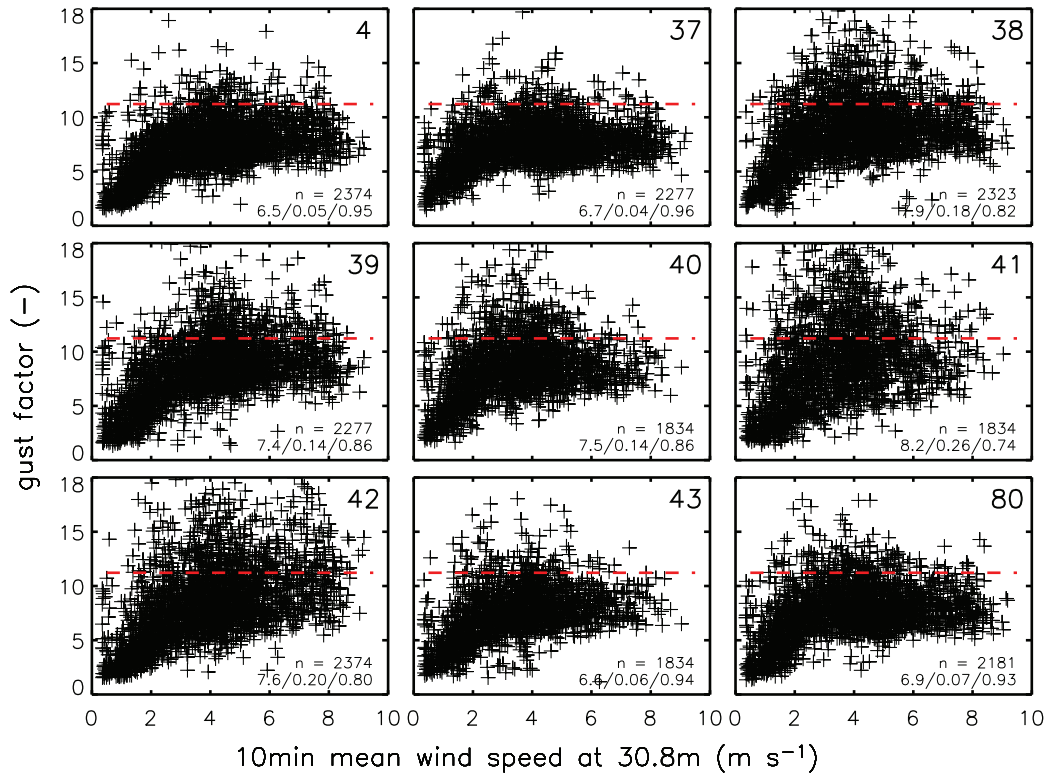


Figure 2.7: Plots of the gust factor for the nine experimental trees as function of wind speed. The red dashed line represents the value calculated by ForestGALES (10.1). The three values in the lower right-hand corner of each plot are the overall mean and the relative fraction of values exceeding and undercutting the ForestGALES value. n is the number of data points for each plot.

2.4.3 Wind loading per tree

ForestGALES assumes that the atmospheric shear stress (τ) is partitioned equally onto the individual trees of the stand and that the zero plane displacement (d) is the acting height of the force. The bulk of momentum absorption takes part in the upper part of the canopy, which leads to very low wind speeds in the trunk space. To take this into account the gaps between the trees (see Fig. 2.1) were filled artificially. The projected area a tree occupies is calculated by a Voronoi algorithm using the coordinates of the trees (Aurenhammer and Klein, 2000). The derived polygons cover the area in which every point is closer to the subject tree than to any other tree. The polygons leave no unaccounted space, so that the complete ground area is apportioned onto the trees. Figure 2.8 shows the Voronoi polygons for the nine experimental trees. The areas are listed

in Table 2.3.

The assumption that the shear stress partitioning is scaled by the projected occupied area can be tested with the data from this experiment. Rearranging of Equation 2.4 gives:

$$\tau_{calc,i} = \frac{M_{mean,i}}{A_{Voronoi,i} \cdot d} \quad (2.15)$$

where $\tau_{calc,i}$ (N m^{-2}) is the atmospheric shear stress apportioned to tree i , M_{mean} (N m) is the measured mean turning moment, $A_{Voronoi,i}$ (m^2) is the projected crown area, and d (m) is the zero plane displacement. All terms in the above equation were measured in this field study.

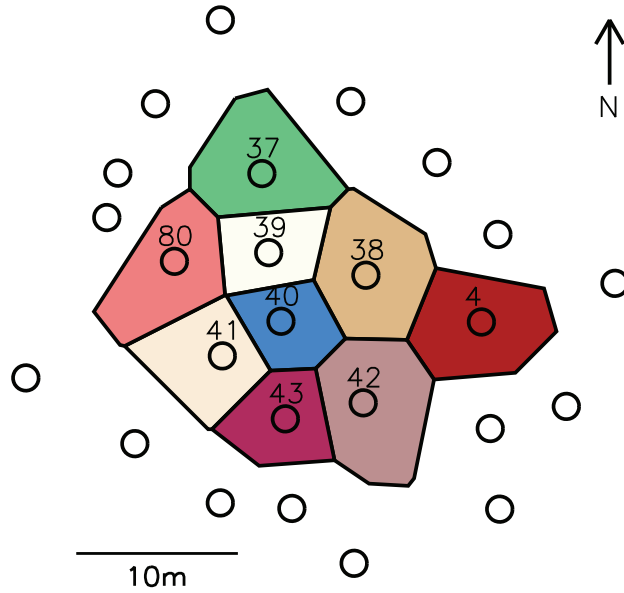


Figure 2.8: Projected occupied areas of the nine experimental trees calculated by the Voronoi algorithm. Circles indicate tree positions.

One of the windiest hours for which measurements are available was in the early morning of the 24th of August 2005 between 3 and 4 am. Hourly mean wind speed and shear stress at canopy top were 6.7 m s^{-1} and 4.9 N m^{-2} , respectively. The zero plane displacement was estimated to be at 18.7 m ($0.7z/h_C$). For three trees (38,41,42) the ratio of calculated and measured shear stress is below unity. Only for tree 39 the value matches exactly unity. For the remaining five trees (4,37,40,43,80) the values are higher than one. The ratio of calculated and

measured shear stress is in the range 0.2 to 2.9. These values indicate that tree 4 has to withstand 10 times more shear stress per unit crown area than tree 42. The high variability of the ratios shows that the crown area cannot be assumed to be the only scaling factor when it comes to the partitioning of shear stress.

Table 2.3: Projected crown area calculated by the Voronoi algorithm ($A_{Voronoi}$), calculated shear stress per crown area (τ_{calc}), and fraction of calculated and measured shear stress for one windy hour (24.Aug.2005 3–4am; hourly mean wind speed at 30.8 m was 6.7 m s^{-1} and measured shear stress was 4.9 N m^{-2}).

ID	$A_{Voronoi}$ (m^2)	τ_{calc} (N m^{-2})	τ_{calc}/τ_{meas} (-)
4	46.2	14.0	2.9
37	49.0	5.8	1.2
38	50.0	4.2	0.9
39	28.9	4.9	1.0
40	26.6	6.3	1.3
41	38.1	2.6	0.5
42	51.1	1.1	0.2
43	31.0	10.5	2.2
80	43.8	9.4	1.9

Since the sonic anemometer was very close to the canopy top it is questionable whether the measured momentum flux is representative for the constant flux layer above the canopy. The estimation of the zero plane displacement also includes an error. To avoid this, the comparison can be normalised by calculating the fraction of the trees individual shear stress per crown area value over the sum of the collective:

$$\tau_{fraction,i} = \frac{\frac{M_{mean,i}}{A_{Voronoi,i}}}{\sum_{i=1}^{n=9} \frac{M_{mean,i}}{A_{Voronoi,i}}} \quad (2.16)$$

where i is the individual index for the nine experimental trees and n is the number of experimental trees. In contrast to Equation 2.15, this equation does not require turbulence data. Since sonic data are only available for measurements after the 23rd of August, a bigger data pool is available for this analysis. The only restriction is that for the time interval in question data for all of the nine trees have to be available.

The results for all time intervals with a wind speed higher than 3 m s^{-1} are presented in Figure 2.9. If it was true that the amount of absorbed momentum is only scaled by crown area then all nine trees should have the same value ($1/9 = 0.\bar{1}$). The ranking is similar to the one in Table 2.3. Tree 4 has values greater than all other trees by more than 0.05, followed by trees 80, 37, 43, and 38. Those trees are ranked as the five tallest in the sample.

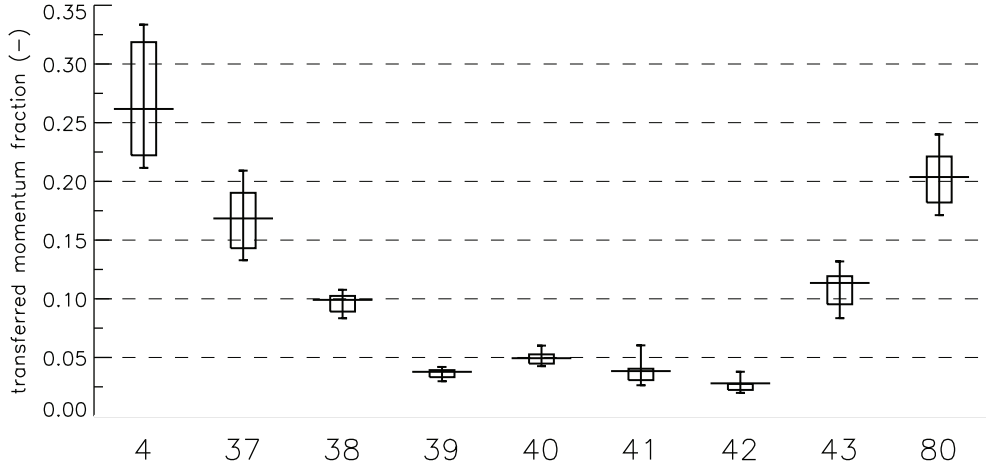


Figure 2.9: Comparison of the relative hourly mean shear stress partitioning (horizontal lines) onto the nine experimental trees. The boxes and vertical lines represent the 25th/75th and 10th/90th percentiles ($n = 324$).

2.4.4 Wind profile method

An alternative to the *roughness method* is the *wind profile method*, which is implemented into the HWIND model (Peltola et al., 1997; Gardiner et al., 2000; Blennow and Sallnäs, 2004). This approach calculates the wind loading from the frontal crown area, the wind profile, and a streamlining function. The general drag formula is:

$$F_D = \rho \cdot \int_0^z C_D(z) \cdot A(z) \cdot u(z)^2 dz \quad (2.17)$$

where ρ (1.226 kg m^{-3}) is air density, C_D (–) the dimensionless drag coefficient, A (m^2) frontal crown area, u (m s^{-1}) horizontal wind speed, and z (m) is height above ground. The drag coefficient was calculated as:

$$C_D = n \cdot u^{-s} \quad (2.18)$$

where n and s are the parameters from a wind tunnel study conducted by Mayhead (1973a). The values for n and s are 2.35 and 0.51, respectively.

The turning moment at the base of the tree is the integral of the drag multiplied by the height:

$$M = \int_0^z F_D(z) \cdot z \, dz \quad (2.19)$$

The crown of the trees is modelled to be diamond shaped with its maximum radius at 0.3 times of the total crown length (Pretzsch et al., 2002). The radius at the crown base is 0.6 fold the maximum radius. Figure 2.10 shows the profiles of the horizontal wind speed, the frontal crown area, the calculated drag, and corresponding turning moment.

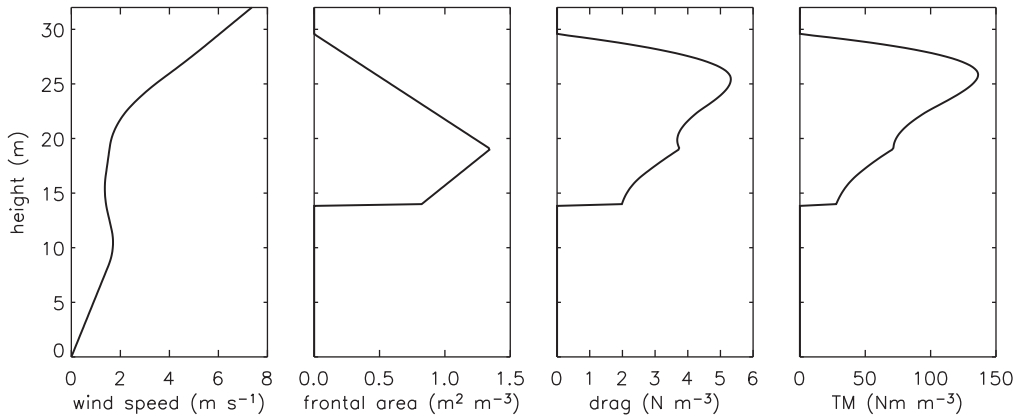


Figure 2.10: Application of the wind profile method for tree 4 for the 24.Aug.2005 (3–4 am). Plots from left to right: Wind profile, frontal crown area, drag, and turning moment.

A comparison of modelled and measured turning moments for one hour is shown in Figure 2.11. Four of the sample trees (41,39,40,38) are well predicted by the model. For the taller trees (37,43,80,4) the models performance is not that good. In three out of the four cases the model overpredicts the turning moment and in case of tree 4 the model underestimates the value. Reasons for this might be the distance between the 30 m mast and the experimental trees. The wind measurements do not necessarily represent the force that the instrumented trees

experience. The meteorological mast was a tilt up type tower. For reasons of practicability the mast was erected on an extraction track. Naturally the stand and canopy density at this spot is lower than the average of the stand, hence the wind might penetrate deeper into the canopy. This might explain some of the discrepancy between the modelled values and the measurements.

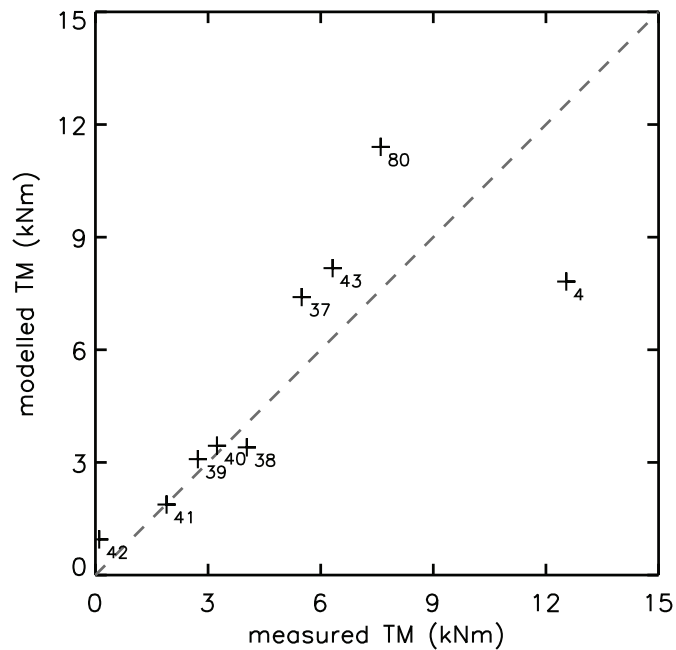


Figure 2.11: Calculated versus modelled hourly mean turning moments for the hour 3–4 am on the 24.Aug.2005. Hourly mean wind speed at 30.8 m was 6.7 m s^{-1} .

2.4.5 Sensitivity of parameters

For estimating the sensitivity of some input parameters, their values were changed by $\pm 10\%$ (see Tab. 2.4). The model is most sensitive to changes in height and *dbh*. If either of these parameters is changed by 10% from the original value the predicted critical wind speed deviates by $\pm 3 \text{ m s}^{-1}$. Changing of the spacing and gustfactor results in smaller changes in critical wind speed.

Table 2.4: Sensitivity analysis on the changes in predicted critical wind speed for changes of 10% for several ForestGALES parameters.

Parameter	change (%)	critical wind speed (m s^{-1})
h_{100}	+10	11
h_{100}	-10	16
dbh	+10	16
dbh	-10	11
D	+10	14
D	-10	13
GF	+10	13
GF	-10	14

2.5 Discussion

2.5.1 Performance of ForestGALES

ForestGALES predicts the return period for wind damage for the experimental stand in Clocaenog Forest to be less than one year. The fact that there has been no observation of wind damage for almost a decade proves that these calculations are too pessimistic.

The two Weibull distributions, the one from the DAMS calculations and the other one from the 10 m mast, show differences in the low wind speed range up to 12 m s^{-1} . Above this value the two distributions are very close. In the wind speed classes that are considered to be near the critical wind speed the differences are very small. The relative differences become minimal at 18.4 m s^{-1} . Both distributions suggest that the predicted critical wind speed of 14 m s^{-1} , which corresponds to 20.5 m s^{-1} at the 10 m mast, is exceeded frequently. The stand recently withstood two severe gale events without suffering any damage. However, the regression analysis between the 10 m mast and the 30 m mast suggest that the critical wind speed was not quite exceeded during either of the events. Nevertheless the wind speed distributions suggest that the critical wind speed of the stand is underestimated.

The mean gust factor measured for the nine experimental trees was 7.3. In contrast to the ForestGALES value, which predicts a value of 10.1 (a deviation of 28%). Setting the GF to 7.3 in the ForestGALES model results in a critical wind speed of 17.7 m s^{-1} . However, for the nine experimental trees the calculated gust

factors cover the range of 6.5 (ID: 37) to 8.2 (ID: 41), i.e. 89 % and 112 % of the mean value. This suggests that the gust factor cannot be assumed to be identical for all trees in the stand. At the same time the gust factor measurements for each tree show large scatter. All in all it seems as if the gust factor is very variable in time and difficult to estimate. Due to the way the gust factor is implemented into the ForestGALES model such deviations do have a significant impact on the predictions of the critical wind speed.

One of the major assumptions of the model is that all of the trees have the same properties and are therefore exposed to the same amount of drag. Gardiner (1995) measured very similar turning moments of three trees in a field experiment. The stand in his field study was 12 m tall (median) with the tallest tree around 15 m. For the Clocaenog stand these values are 24.5 m and 34.2 m, respectively. Due to the advanced maturation of the stand the differences in tree properties are much more pronounced compared to the Gardiner (1995) stand. The taller trees are more exposed to the wind. The diversity in tree properties impedes the validity of the roughness method. From a forest manager's point of view, the experimental stand might not look irregular. But in terms of shear partitioning, which is relevant for wind-tree interactions, it is rather variable.

The characteristics of tree 39 match almost perfectly those of the average tree in the stand for which ForestGALES performs its calculations. For the example calculations for the shear stress partitioning on the 24th of August the fraction of calculated and measured shear stress is unity, which indicates a perfect prediction. However, there is no obvious physical explanation for this and the agreement seems to be coincidental. In direct comparison with the other trees much less than the average shear stress is partitioned onto tree 39. In fact only tree 42 has a lower value. In terms of shear stress partitioning tree 39 is below average and does not act like the average tree. Reasons for this might be the sheltered position behind a dominant tree (80) for the prevailing wind direction.

Although the wind profile method was not fully tested, it seems as if it is not in any way superior to the roughness method. Finer adjustment of the parameters involved would probably increase the overall agreement of modelled and measured values. However, the much higher turning moments that tree 4 experiences in comparison to the other tall trees (37,43,80) cannot be explained just by differences in tree properties such as canopy area. It is more likely that the individual wind profiles for the group of trees differ. The fact that tree 4 is located next to an extraction track that creates a gap, points in this direction. Hence,

the profile method would need to be adapted in a way that allows adjustment of the wind profile for each individual tree.

2.5.2 Wind risk for experimental stand

As mentioned before ForestGALES calculates the critical wind speed for this experimental stand to be 14 m s^{-1} . The values for overturning and breaking are 15.2 m s^{-1} and 14.1 m s^{-1} . Those values change if we adjust the mean tree height to the true value, since the equation for calculating the mean height does not result in the correct value. By adjusting the values in the model the critical wind speed for overturning becomes 15.3 m s^{-1} and the one for breaking 14.4 m s^{-1} . The differences compared to the original values are rather small and do not explain the too pessimistic estimate of the model.

More significant changes are caused by adjusting the gust factor to 7.3 instead of 10.1. For this scenario the critical wind speeds are 17.7 m s^{-1} and 16.7 m s^{-1} . Those distinct differences emphasise the impact of the gust factor on the calculations of the critical wind speed. However, the wind speed distribution from the 10 m mast suggests that an hourly mean wind speed at the canopy top of 16.7 m s^{-1} (24.5 m s^{-1} at the 10 m mast) is still exceeded every year. Therefore it seems as if this value is still too pessimistic.

The adjustment of the mean height and the gust factor causes an increase of the critical wind speed value and seems to be more realistic.

2.6 Conclusions

This is the first time that several modules of the ForestGALES model have been validated independently using the data from a single field study. The results suggest that the stand is more stable than predicted by the ForestGALES model. Especially the modelled gust factor deviates from the field measurements. Its overestimation increases the wind induced turning moment in the model. The ForestGALES model was designed for even aged regular stands. Although the Clocaenog stand is even aged it is highly irregular from an aerodynamic point of view. The turning moment the nine experimental trees are exposed to differs by one order of magnitude. Therefore the model assumption that the atmospheric shear stress is distributed equally onto the individuals of the stand does not hold. In direct comparison the taller trees have to withstand significantly higher drag

than the smaller ones. Most of the momentum transfer takes place in the upper part of the canopy, so that smaller trees are exposed to much less drag.

The data analysis from the Clocaenog field experiment highlights the demand for modifications in the ForestGALES model to make it work with irregular stand structures as they occur under low impact silvicultural systems. The wind-tree interaction appears to be more complex than they are in regular stands. More field data are needed for a better understanding and parametrisation of the relevant processes.

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