The development and validation of a windthrow probability model for Sitka spruce in Ireland

Áine Ní Dhubháin[a], Michael Bulfin[b], Michael Keane[c], Paul Mills[d] and Jonathon Walshe[e]

Abstract

An empirical windthrow probability model for Sitka spruce (*Picea sitchensis*) in Ireland was developed and validated. Data were collected from a range of Sitka spruce stands on different sites. Logistic regression was used to determine which site, stand and silvicultural factors significantly influenced the probability of windthrow. Top height, top height squared, the regional location of the stand, soil type, and altitude significantly influenced the occurrence of windthrow in Sitka spruce. Whether or not the stand had been thinned was also important. A model to predict the probability of windthrow occurring in a forest stand was developed. A validation exercise indicated that only 6% of the stands for which the model predicted the probability of windthrow to be less than 1% actually experienced windthrow.

Keywords

probabilistic model, windthrow, Sitka spruce, thinning

Introduction

Windthrow is a major constraint to economic forestry in Ireland. Over the period 1971 to 1993, 85,000 cubic metres of roundwood were windthrown annually, which represents 9% of the volume sold by the state over the period. Windthrow is therefore a recurring problem in Irish forestry, with serious economic implications. Volume losses to windthrow are expected to increase as much of the afforestation programme (both Coillte and private) approaches a critical height in relation to windthrow.

Among the consequences of windthrow for the forest manager is increased harvesting cost on affected sites. More significantly, windthrow can lead to shortened rotations, resulting in stands being clearfelled well in advance of the economic rotation length.

A range of stand, site and silvicultural factors has been shown to influence the occurrence of windthrow, including soil type, elevation and slope (Savill 1983, Miller 1985). Silvicultural factors, such as ground preparation method (including drainage method), and thinning type, can also influence stand stability (Lynch 1985, Hendrick 1988).

Risk models have been developed in the United Kingdom, where windthrow is also a major constraint to forest management. This work commenced with the development

a Corresponding author: School of Biology and Environmental Science, University College Dublin, Belfield, Dublin 4, Ireland (aine.nidhubhain@ucd.ie).
b Teagasc, Malahide Road, Kinsealy, Dublin 17, Ireland.
c Coillte, Newtownmountkennedy, Co Wicklow, Ireland.
d Compass Informatics Limited, Block 8, Blackrock Business Park, Carysfort Avenue, Blackrock, Co Dublin, Ireland.
e Graduate student, School of Biology and Environmental Science, University College Dublin.

of the Forestry Commission's Windthrow Hazard Classification system in 1977 (Booth 1977), with the most recent development being FOREST GALES (Dunham et al. 2000), which calculates the probability of windthrow within a stand, based on a combination of site and stand factors. In Ireland, Hendrick (1988) developed a model to support forest managers in making decisions as to whether it was safe to thin forest stands. However, none of these models is routinely used in forest management in Ireland. Instead, subjective assessment of risk is used to guide decisions regarding thinning and rotation length.

This paper describes the development of a windthrow risk probability model for Sitka spruce in Ireland.

Materials and methods

Work was carried out in two phases.

Phase I

A sample of pure Sitka spruce stands was selected from five Coillte-owned forests. Based on Miller's wind zonation (Figure 1), three were selected in Co Clare, a relatively exposed part of the country (wind zone B), and two in Co Wexford, a relatively sheltered area (wind zone C). Another important factor for the selection of the two counties was that they had been covered under the National Soil survey (Gardiner and Ryan, Finch 1971).

To reduce costs a multi-stage sampling approach was used. Compartments satisfying the following criteria were selected at random from the five forests:

(a) Compartments must have at least two subcompartments comprised of pure Sitka spruce stands.

(b) These two or more subcompartments must be comprised of Sitka spruce stands < 5 years olds (reforestation only) or > 15 years at time of survey.

Stands where the risk of windthrow is very high are often prematurely clearfelled. To ensure that the dataset used in this study included subcompartments with second rotation Sitka spruce stands <5 years old were also surveyed and data (including windthrow history) on the antecedent crop recorded. Stands 15 years or older were chosen as they were approaching the age of first thinning, when susceptibility to windthrow increases (Lynch 1985). Within the selected compartments, all accessible subcompartments satisfying the above criteria were surveyed, yielding 215 subcompartments in Clare and 59 in Wexford.

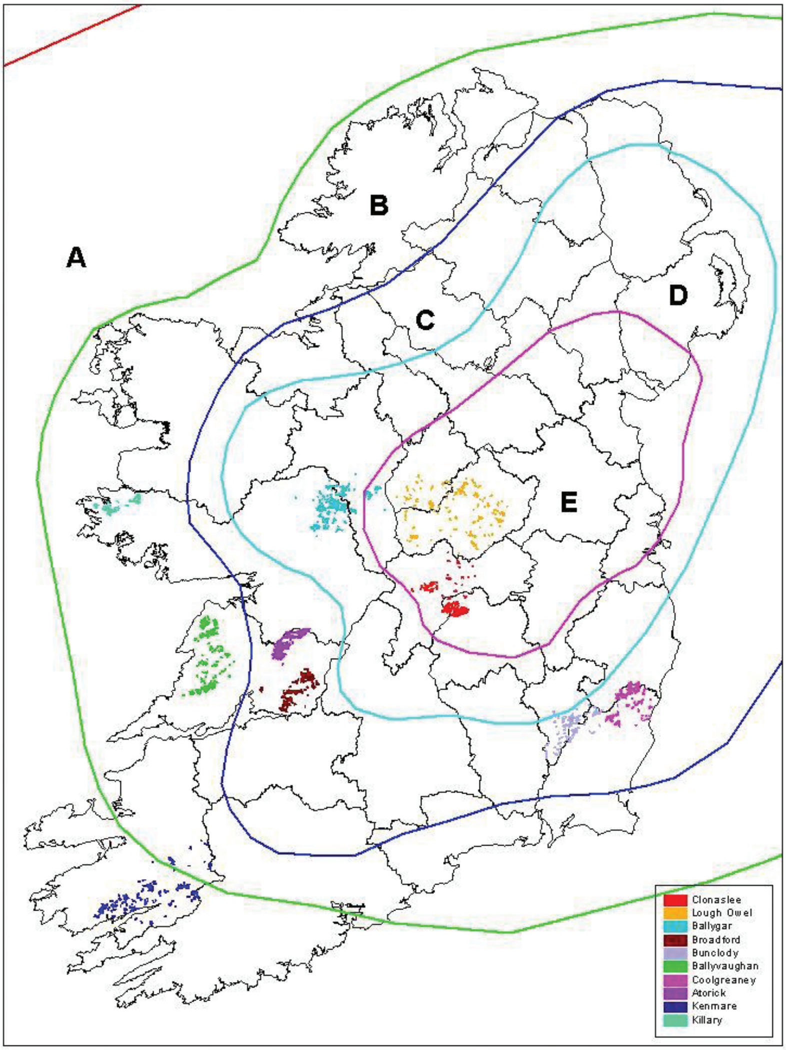

Figure 1: *Location of study forests overlain with Miller's (1986) wind zone map*.

At each subcompartment, a range of site and stand variables was determined (Table 1). Most of the data were collected from site visits and from Coillte's inventory database. The presence of windthrow was determined by site visit. Windthrow was assessed as having occurred where visual assessment indicated at least 3% of the stems were fallen or snapped.

Table 1: *Site and stand variables assessed in the study and their source (Phase 1).*

Site	*Variable*	*Data source*
	Soil cultivation method, direction and bearing	Site visit
	Exposure	Site visit
	Aspect	Ordnance survey 1:50,000 Discovery Series
	Altitude (m)	Ordnance survey 1:50,000 Discovery Series
	Slope (°)	Ordnance survey 1:50,000 Discovery Series
	Wind zone	Miller's wind zone map
	Soil type	Teagasc GIS datasets
	Subcompartment area (ha)	Coillte inventory
	Topex	Ordnance survey 1:50,000 Discovery Series
Stand	Age	Coillte inventory
	Thinning delay	Coillte inventory
	Top height (m)	Site visit
	Presence of windthrow	Site visit
	Percentage windthrow	Site visit
	Thinned	Site visit
	Thinning system	Coillte inventory/site visit
	Thinning intensity	Site visit
	Method of extraction	Coillte inventory/site visit
	Mean height of fallen trees (m)	Site visit
	Initial crop spacing (stems ha^{-1})	Site visit
	Yield class ($m^3ha^{-1}a^{-1}$)	Coillte inventory/site visit

Topographic exposure (topex) was assessed by measuring the angle to the horizon at the eight cardinal compass points. Software tools were developed to derive topex, elevation, aspect and slope from a digital terrain model (DTM) of the sites (Mills and Cory 1998). The DTM was created using Ordnance Survey 1:50,000 (Discovery Series) contour data. It was divided into a 50 x 50 m grid, with aspect, slope, elevation and topex assigned to each grid cell. The DTM was then overlain with a digital subcompartment boundary map of the selected forests. Estimates of topex, elevation and slope for each of the subcompartments were obtained by taking the average of the grid values within a subcompartment. The most commonly occurring aspect for the grid cells within a subcompartment was determined.

A digitised soil map, added as a layer to the GIS database, was overlain with the digitised subcompartment map to determine the soil type which comprised most of the subcompartment. Where the digitised soil map indicated that soil complexes[a] represented most of the subcompartment area, the predominant soil type was assessed during the site visit.

Phase 2

Data were collected from an additional five forests, chosen from parts of the country which had not been covered in Phase 1, namely wind zones A, D and E. In addition, as only one forest from wind zone B had been represented in the original study, a second forest was chosen from this area. The five Coillte forests surveyed were Kenmare (wind zone A), Killary (wind zone B), Ballygar (wind zone D), Lough Owel (wind zone E) and Clonalsee (wind zone E) (Figure 1). In order to reduce costs, Coillte inventory staff collected site and stand variable data during scheduled forest inventory. Within each of the five forests, subcompartments which were 14 years or older were selected for survey (to coincide with the crop age at which Coillte undertakes its inventory), yielding a total of 193 stands.

The number of variables assessed in Phase 2 was less than in Phase 1. The main reason was that preliminary analysis of Phase 1 data indicated that a number of the stand and site variables did not significantly influence the occurrence of windthrow.

For each of the stands surveyed in Phase 2, estimates of topex, elevation, slope and aspect were obtained from DTMs using the method previously outlined. In addition, estimates of mean wind speed for the sites were obtained from Teagasc. These were derived from a combination of two sources. First the Meteorological Service provided mean annual wind speed data for the period 1960-1990 for 14 synoptic stations (Met Éireann 2002). Second, an Electricity Supply Board/Electrical Research Association survey in the 1950s (Golding and Stodhart 1952, Golding 1955, Munro 1953), reported in a paper by Haslett and Kennedy (1979), provided estimated mean annual wind speed for 26 hill-top sites.

In addition to the datasets assembled in Phases 1 and 2, an additional dataset was made available by Teagasc. It had been collected as part of an EU-funded study on the role of private forestry on highly productive sites in agriculturally disadvantaged areas (Bulfin 1987). In the study 1089 stands, on marginal agricultural soils throughout the country were surveyed in 1983-1985, and a range of stand and site variable data was recorded. In addition, the occurrence of windthrow was assessed. By combining these data with those collected in Phases 1 and 2, a larger sample was available for deriving the windthrow probability model.

Adjustments were made to make the three datasets as compatible as possible. Variables assessed in Phases 1 and 2 that were not included in the Teagasc dataset were the compass bearing of the planting lines and the cultivation direction relative to the contour. Topex was also excluded as the approach used by Teagasc to determine

a A soil complex is a mapping unit which represents contiguous soils which can be distinguished in the field, but which are arranged in a pattern that is too complex to represent at the current scale of mapping (Hammond and Brennan 2003, p.29).

it differed from the approach used in Phases 1 and 2. In addition, topex was found not to be a significant variable in explaining windthrow probability in the preliminary analysis (Ni Dhubháin et al. 2001). Although the datasets were collected at different times, it was felt that this would have little impact on the wind climate. Thus, the final dataset comprised data from 1152 stands and included the following variables: stand thinned (yes/no), cultivation method, soil type, top height, altitude, slope, wind zone, aspect and wind speed. Independent data from a further 175 stands were retained for the model validation process.

Statistical analysis
A windthrow probability model was derived from the data using stepwise logistic regression. Initially, all stand and site variables were tested individually to determine which ones significantly influenced (at the 5% level) windthrow probability. An intermediate model was then fitted with all significant variables included; and the impact of the stepwise removal of each variable examined. Only those variables, whose exclusion from the intermediate model was significant, were included in the final model. The final model had the general form:

$$p_i=\exp(ß_0+ ß_1x_1+ ß_2x_2+......+ ß_nx_n)/(1+\exp(ß_0+ ß_1x_1+ß_2x_2+......+ß_nx_n)$$

where
p_i: probability of windthrow in subcompartment i
$x_1, x_2 \ldots x_n$: independent variables
$ß_{0,1,n}$: parameters estimated.

Results

Six factors were found to influence the probability of windthrow in Sitka spruce: top height, top height squared, soil type, thinning, wind zone, altitude and the interaction between top height and soil type (Table 2).

Table 2: *Logistic regression parameter estimates for variables in Sitka spruce windthrow probability model.*

Variable		*Parameter estimate*	*Standard error*	*t-value*	*Significance*
Intercept		-10.5100	2.2400	-4.69	<0.001
Top height (m)		0.6280	0.2350	2.67	0.008
Top height (m^2)		-0.0156	0.0061	-2.54	0.011
Soil type	*1. Brown earth/ Brown podzolic/Podzol*	0.0000			
	2. Raised bog	-2.6800	1.6900	-1.59	0.112
	3. Blanket peat/Gley	-3.2600	1.2300	-2.66	0.008
Thinned	*0. Not thinned*	0.0000			
	1. Thinned	1.3720	0.2020	6.78	<0.001
Altitude (m)		0.0096	0.0014	7.05	<0.001
Wind zone	*E*	0.0000			
	D/C	1.1190	0.3930	2.85	0.004
	B	2.3920	0.4180	5.72	<0.001
Top height soil type 1*		0.0000			
Top height soil type 2*		0.1680	0.1060	1.58	0.114
Top height soil type 3*		0.2677	0.0742	3.61	<0.001

Windthrow probability increased with top height but the effect was not constant across soil types (Figure 2).

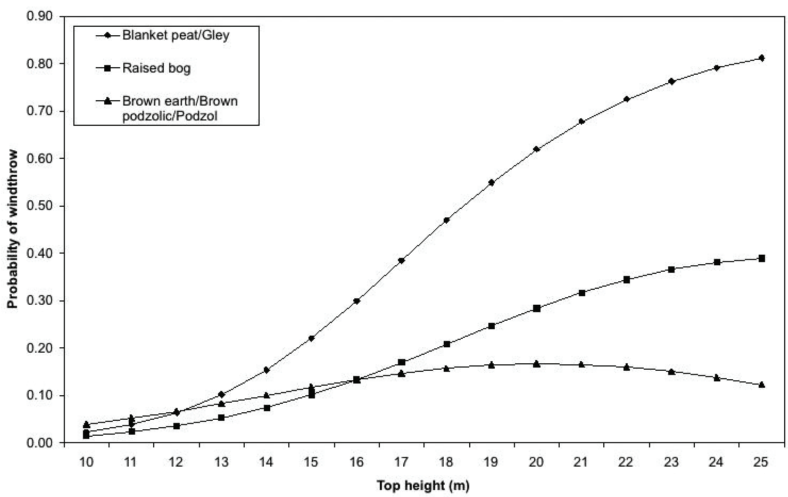

Figure 2: *Effect of top height on the probability of windthrow occurrence in unthinned Sitka spruce stands on a range of soil types (wind zone C; altitude 150 m).*

Following thinning, the probability of windthrow occurring increased on all soil types (Figure 3).

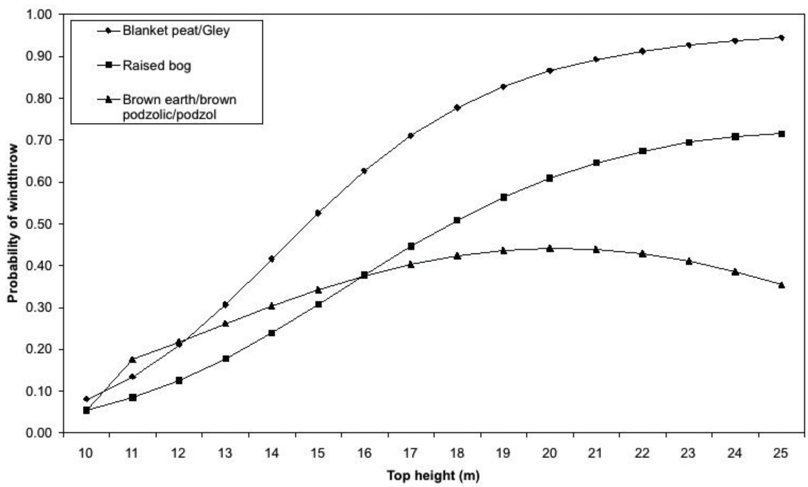

Figure 3: *Effect of top height on the probability of windthrow occurrence in thinned Sitka spruce stands on a range of soil types (wind zone C; altitude 150 m).*

Altitude also had a significant effect on the probability of windthrow occurring in Sitka spruce (Figure 4).

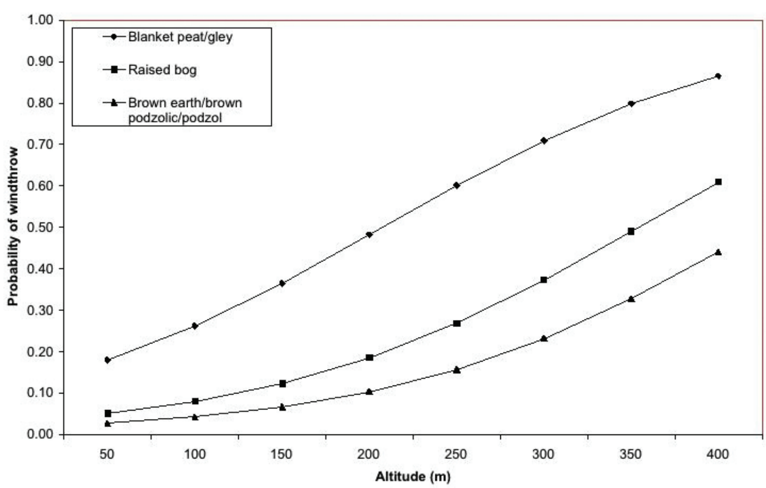

Figure 4: *Effect of altitude on the probability of windthrow occurrence in unthinned Sitka spruce stands on a range of soil types (wind zone C; top height 20 m).*

Model validation

The estimates of windthrow probability provided by the model were tested in a sample of 168 stands. Only 6% of the stands where the model predicted the probability of windthrow to be less than 1% actually experienced windthrow (Table 3). Fifty percent of the stands where the predicted probability of windthrow was greater than 50% had experienced windthrow.

Table 3: *Predicted and actual occurrence of windthrow, using windthrow probability.*

Actual occurrence of windthrow	*Predicted probability of windthrow occurrence*				
	≤ 0.01	0.01-0.05	0.05-0.10	0.10-0.50	>0.50
	Number and percentage of stands				
No	77(94%)	34(65%)	6(35%)	4(44%)	4(50%)
Yes	5(6%)	18(35%)	11(65%)	5(55%)	4(50%)

User-friendly software

In 2007, a user-friendly interface to the model was developed in conjunction with PTR Ltd and placed on www.coford.ie. The interface is linked to yield models, making it possible to examine how windthrow probability changes with increasing top height, once the yield class of the stand is known.

Discussion

Six of the nine site and stand variables examined were shown to contribute significantly to the probability of windthrow: top height, top height squared, soil type, thinning, wind zone and altitude. The relationship between soil type and windthrow probability was not consistent over the range of top heights examined; thus an interaction term (top height x soil type) was included in the model. In Ní Dhubháin et al. (2001) the impact of top height and thinning on windthrow probability was discussed, thus this discussion concentrates on soil type, wind speed and windthrow probability.

Many researchers have identified the key contribution of soil type in determining stand vulnerability to windthrow (Savill 1983, Lynch 1985). This study confirmed that Sitka spruce stands on gleys and peats had the greatest probability of windthrow occurrence. The least probability was associated with brown earths, brown podzolics and podzols. Raised peats had an intermediate probability. These findings generally coincide with those of Miller (1985). However, a greater range of soils was represented in his classification compared with the five in this study.

A number of factors influence the wind load that stands experience. Gusts, the severity of wind speeds and their frequency of occurrence play a major role in determining the risk of windthrow occurring. Unlike the Forestry Commission, where work on this component of windthrow risk has been ongoing for many years, the collection of wind speed data in Ireland has been largely undertaken by Met Éireann. The usefulness of these data in estimating wind speeds in forests is limited.

The Forestry Commission, on the other hand, has a long history and experience of estimating relative exposure using flag tatter. The use of such tatter flags has been limited in Ireland. While the recent interest in establishing wind farms has, and is expected to continue to, provide wind speed data from more remote locations, enquiries made during this study were unable to locate additional data for the study sites. Thus, the wind climate element of the windthrow prediction equation is addressed simply by using Miller's (1986) wind zone map for Ireland. He acknowledges the limited scientific basis of this map, which was based on some tatter flag data from Northern Ireland, which were extrapolated across the whole of Ireland, taking account of regional variation in mean wind speed. Nevertheless the model developed in the study showed the significant difference in the probability of windthrow between stands established in more exposed locations (wind zone B) compared to those in more sheltered locations (wind zone E). Stands located in wind zones C and D were associated with an intermediate probability. The analysis found no difference in the probability of windthrow occurrence in stands in these two wind zones.

The validation exercise indicated that the model worked reasonably well. In 94% of stands where windthrow had not occurred the model estimated the probability of windthrow was less 10%. However, in stands where windthrow had occurred, estimates of windthrow probability were quite varied. The small number of stands with windthrow in this validation dataset (43) may partly explain this finding. Users of the model can use both the validation results, as well as the confidence interval associated with the estimate (see www.coford.ie) to assess whether the precision of the model is acceptable for particular uses. These can vary from assessing the potential impact of thinning on windthrow probability, to estimating its probability over the lifetime of a stand.

Conclusions and recommendations

To gain a fuller understanding of windthrow, site and stand monitoring over time is essential. In this way the progression of windthrow can be examined. Such a process has been ongoing in Britain since 1987, where eight monitoring sites have been established (Quine and Bell 1998). Aerial photography is used to monitor progression. A similar process should be started in a selection of forests in Ireland.

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