The initial development of a windthrow risk model for Sitka spruce in Ireland

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Summary

Damage to trees by strong winds is one of the most important abiotic hazards in forestry in Ireland. A number of classification systems have been developed to assess the risk of wind damage to forests in Ireland and Great Britain. However, these models have tended to be deterministic, ranking the relative risk on different sites and/or from silvicultural treatments but not assigning a probability to the likelihood of damage. The main objective of the study described in this paper was to devise a windthrow risk model for Ireland which would yield estimates of the probability of windthrow for a combination of site and silvicultural factors. Data were collected for a range of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) stands growing on a variety of sites. These stands were selected in two regions of varying exposure. The modelling procedure examined the relationship between a range of site and silvicultural factors and the occurrence of windthrow. Out of the 15 factors examined, the following five were shown to contribute significantly to the risk of windthrow: top height, the regional location of the stand, the soil type on which the stand was established, as well as the compass bearing of the plough ribbons where the site had been ploughed. Whether or not the stand had been thinned was also important.

Introduction

At the beginning of the twentieth century only 1.4 per cent of the land area of Ireland was under forest (O'Carroll, 1984). An afforestation programme was launched in 1922 to increase the forest cover and by 1980 almost 375 000 ha were under forest. Most afforestation which took place in this 60-year period was on sub-marginal agricultural land such as peatland in the west of the country and upland areas elsewhere. This trend of afforesting marginal soils was also evident in private afforestation, which expanded rapidly following the introduction of EU grant-aid for afforestation in 1980. In recent years, better quality land is being afforested both by Coillte Teo (The Irish Forestry Board) and private owners. Currently, 9 per cent of the land area of the Republic of Ireland is afforested (i.e. 600 000 ha). The forest estate is dominated by exotic species, especially Sitka spruce (*Picea sitchensis* (Bong.) Carr.), which achieves average growth rates of 16m^3 ha^{-1} per year.

As a consequence of the type of sites afforested and the relatively windy climate of Ireland, windthrow is a major constraint to profitable forestry in Ireland. During the period 1971–93 an average of 85 000 m^3 of timber was windthrown annually. This equates with an annual average of 9 per cent of the volume sold. Windthrow is therefore a constant problem with serious financial implications in Irish forestry. Volume losses from windthrow are expected to increase during the next decade as much of the public and private afforestation programme approaches a height susceptible to windthrow.

Research has identified that a range of stand, site and silvicultural factors influence the occurrence of windthrow. These include the soil on which the crop is established as well as site elevation and slope (Savill, 1983; Miller, 1985). Silvicultural factors such as ground preparation techniques (including drainage methods), as well as thinning types have also been shown to play a role in the occurrence of windthrow (Lynch, 1985; Hendrick, 1988).

A number of models have been developed in Ireland and the United Kingdom to assess the risk of windthrow. The earliest of these was the Forestry Commission's Windthrow Hazard Classification system developed in 1977 (Booth, 1977) and later revised in 1985 (Miller, 1985) and in 1993 (Quine and White, 1993). In Ireland, limited work has been carried out on windthrow hazard classification. A windthrow risk model for thinning was produced by Hendrick (1988). This probabilistic model was designed as a guide in deciding whether or not to thin a stand as it approached the time or height of first thinning. The following eight site and crop factors were used in the model: presence of windthrown trees, yield class of the crop, stand exposure, ground preparation type, ground preparation direction relative to the contour, ground preparation bearing, soil type and method of timber extraction (to be) employed. More recently, Coillte developed a Land Acquisition Model as an aid to the decision-making process involved in purchasing land for forestry. It provides an indication of the rotation length that can be expected to be achieved in light of the risk of windthrow and therefore indicates the price that can be paid for land (Anon., 1993). It is based on five factors including soil type, slope, altitude, aspect and location, each of which is assigned a score. The scores and the weighting of the importance of the factors is subjective.

None of the aforementioned models is currently used to assess the risk of windthrow in forest stands in Ireland. Instead subjective assessments of risk are used to guide decisions regarding thinning and rotation length. In addition, all but one of the models are deterministic. Quine (1995) considers a probabilistic model more appropriate to the phenomenon of windthrow. Examples of probabilistic models include one developed by Valinger and Fridman (1997) that predicts the probability of wind damage in *Pinus sylvestris* L. stands using tree characteristics. A PC-based software tool developed by Dunham *et al.* (2000) also calculates the probability of windthrow within a stand based on a combination of site and stand factors. Peltola *et al.* (1999), on the other hand, have developed a mechanistic model which assesses the risk of wind damage to single trees and stands by predicting critical wind speeds which will cause trees to be uprooted under a range of silvicultural conditions.

This paper describes the initial development of a windthrow risk probability model for Sitka spruce in Ireland. Where possible, use was made of GIS-based data, to make the model more convenient to use by forest managers.

Materials and methods

A sample of pure Sitka spruce stands was selected for study from five Coillte-owned forests. Three of these forests were located in Co. Clare, a relatively exposed part of the country, while two were in Co. Wexford, a relatively sheltered county (Figure 1). A major factor influencing the selection of these two counties was that a detailed soil survey had already been conducted for these areas (Gardiner and Ryan, 1964; Finch, 1971). To reduce the cost of the survey, a multi-stage sampling approach was used. Compartments satisfying the following two criteria were selected at random from the five forests: (1) compartments must have at least two subcompartments comprising pure Sitka spruce stands; and (2) these

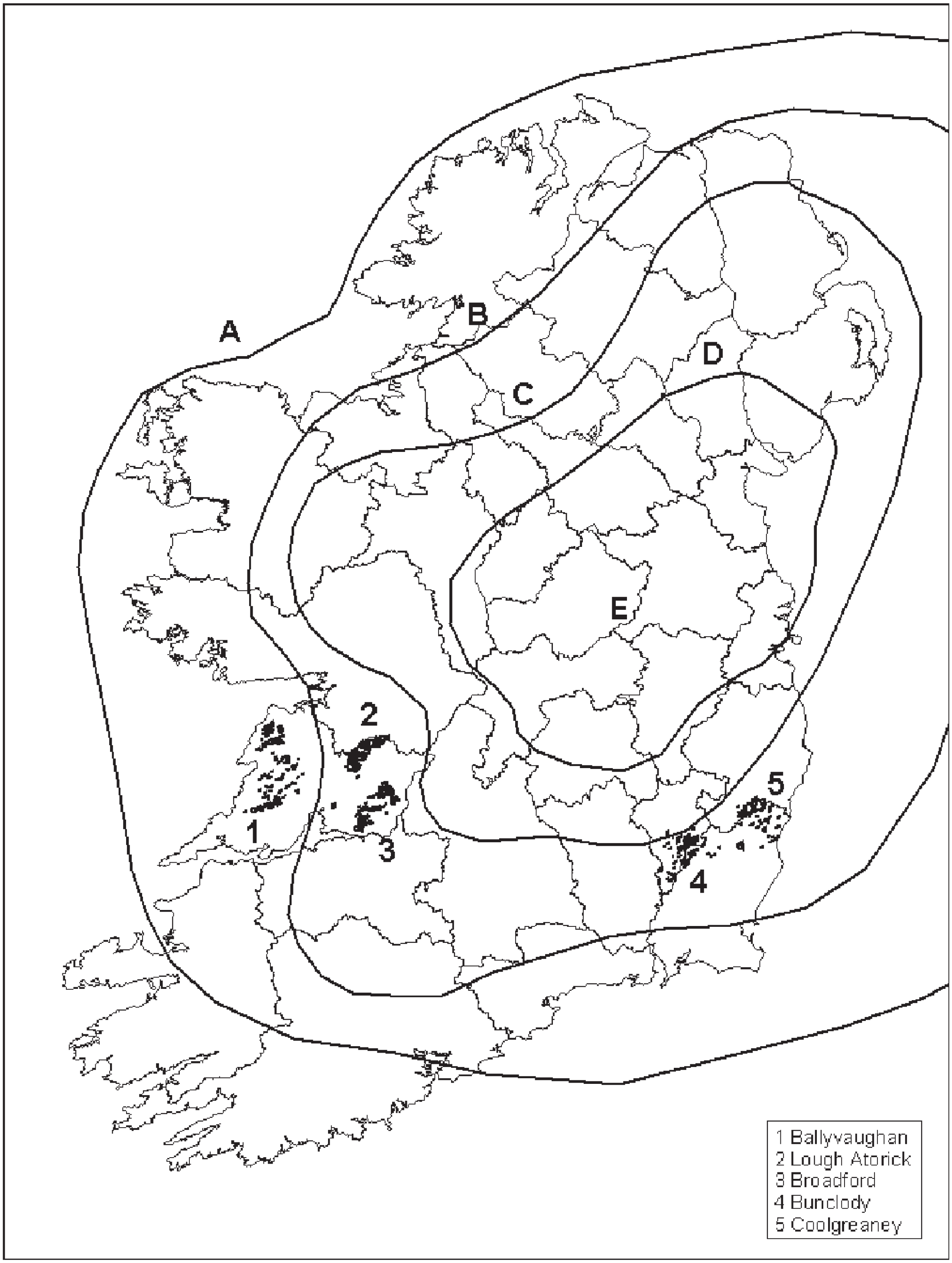

Figure 1. Map showing location of study forests overlain with Miller's (1986) wind zone map.

two or more subcompartments must comprise Sitka spruce stands <5 years old or >15 years of age at time of survey.

Reforested sites with stands <5 years old were sampled for the previous crop's history. These stands were included as the previous crop may have experienced windthrow and may have been prematurely clearfelled as a result. Thus any subcompartments with stands <5 years of age were included but the data recorded for these stands referred to the previous crop. Stands 15 years or older were chosen as they were approaching their age of first thinning and were susceptible to windthrow. Within the selected compartments, all accessible subcompartments satisfying the above criteria were surveyed, yielding a total of 215 subcompartments in Clare and 59 in Wexford.

For each of the subcompartments, site and stand parameters were recorded (Table 1). Most of these data were collected during site visits or from Coillte's Inventory database. The presence of windthrow was recorded for each of the subcompartments during these site visits. Windthrow was deemed to be present when a subjective visual assessment indicated at least 3 per cent of stems fallen or snapped.

Topographic exposure (topex) is assessed by measuring the angle to the horizon at eight cardinal compass points. In this study, software tools were developed to derive topex, elevation,

Table 1: Site and stand factors assessed in the study (according to the categories listed) and their source

Factor	Categories	Source of data
SITE		
Ground preparation method	Single mouldboard plough Double mouldboard plough Manual mounding Pit planting	Field survey
Ground preparation direction	90º to contour Parallel to contour Oblique to contour	Field survey
Ground preparation bearing	North-west/south-east North-east/south-west North/south East/west None (i.e. mound and pit plant)	Field survey
Aspect	Predominant aspect of stands	GIS datasets
Elevation	Metres	GIS datasets
Slope	Degrees	GIS datasets
Wind zone	Zones A, B, C, D, E	Wind zones of Ireland (Miller, 1986)
Soil type	As published soil survey (scale 1 : 126 720) except 'Complexes' where field survey data used	Published soil surveys (Finch, 1971; Gardiner and Ryan, 1964). Field survey
Area of subcompartment	Hectares	Coillte database
Topex		GIS datasets
STAND		
Age	Years	Coillte database
Thinning delay	Number of years thinning delayed from standard thinning year	Coillte database
Top height	Metres	Field survey
Presence of windthrow	Yes/No	Field survey
Initial crop spacing	Within row (m) × across row (m)	Field survey

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 then divided into a 50 m × 50 m grid. For each grid cell, aspect, slope, elevation and topex were assessed. The DTM was then overlain with a digital subcompartment boundary map of the selected forests. The estimates for topex, elevation and slope for each of the subcompartments were obtained by taking the average of the grid values within a subcompartment. The subcompartment areas ranged from 0.30 ha to 14.80 ha with an average size of 3.52 ha (Table 2). Thus the number of grid values for the subcompartments ranged from 1 to 54 with an average of 14. With regard to aspect, the most common aspect noted for the grid cells within a subcompartment was recorded.

A digitized soil map was added as a layer to the GIS database. This was overlain with the digitized subcompartment map and the soil type that made up the majority of the subcompartment area was determined. Where the digitized soil map indicated that 'complexes' represented the majority of the subcompartment area, the assessment of the predominant soil type made during the field survey was used.

Statistical analysis

A windthrow risk model was derived from the data collected from the 274 subcompartments sampled using stepwise logistic regression. GENSTAT was the statistical software package used.

To model the probability of a stand experiencing windthrow, all the stand and site factors measured were included as independent variables. For each of the categorical factors, for example soil type, each category was represented by a separate independent variable. The first step involved identifying those factors which significantly (i.e. at the 5 per cent level) influenced windthrow risk, when modelled individually. A model (model 2) was then fitted with all these 'significant' factors included, and the impact of removing each of these significant factors from the model tested. Only those factors, whose exclusion from model 2 was significant, were included in the final model. This final model had the general form:

$$p_i = \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n) / (1 + \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n) \quad (1)$$

where p_i = probability of windthrow in subcompartment i, x_1,x_2, x_n = independent variables for subcompartment i, and $\beta_{0,1,n}$ = parameters.

Results

The final regression model included six factors and an intercept (Table 3). The residual element of this model was not statistically significant, indicating no significant lack of fit. The six factors were, top height, soil type, ground preparation bearing, wind zone and thinning status as well as the square of the value for top height (Table 4).

By applying the parameter estimates to equation 1 the probability of windthrow occurring in a subcompartment was estimated.

The model shows the probability of windthrow to be greatest on gleyed and peaty soils (parameter values 2.390 and 2.160, respectively)

Table 2: Summary of quantitative input data

Factor	Minimum	Maximum	Mean
Area (ha)	0.30	14.80	3.52
Age (years)	15.00	56.00	29.34
Top height (m)	4.50	29.50	16.11
Thinning delay (years)	0.00	15.00	2.35
Elevation (m)	37.90	343.60	183.90
Slope (degrees)	0.27	18.69	4.69
Topex	–0.05	63.54	17.04

Table 3: Summary of logistic regression analysis of five crop and site factors on occurrence of windthrow

Response variate: windthrow
Fitted terms: constant, top height, top height², thinned, ground preparation bearing, windzone, soil type
Summary of analysis:

	d.f.	Deviance	Mean deviance	Deviance ratio
Regression	12	141.9	11.8222	11.82
Residual	261	235.9	0.9037	
Total	273	377.7	1.3837	

while the least risk was associated with brown podzolics (Figure 2). Increasing top height results in a significant increase in the probability of windthrow across all soil types found in this study (Figure 2). The analysis showed this relationship to be curvilinear with windthrow risk increasing at an exponential rate up to certain top heights and then levelling off.

The analysis also showed that following thinning, the probability of windthrow increases on all soil types (Figure 3 vs Figure 2).

Wind zone C (Miller, 1986) is a more sheltered part of the country than wind zone B and the probability of windthrow is greater on all soil types in the latter wind zone. Figure 4 illustrates this finding for podzolic soils.

Ground preparation bearing is the final factor in the model, indicating that the orientation of ploughing on ploughed sites significantly influences the probability of windthrow occurring. An examination of the parameter estimates in Table 4 shows that aligning the ribbons in a north-west/south-east direction resulted in the greatest risk of windthrow.

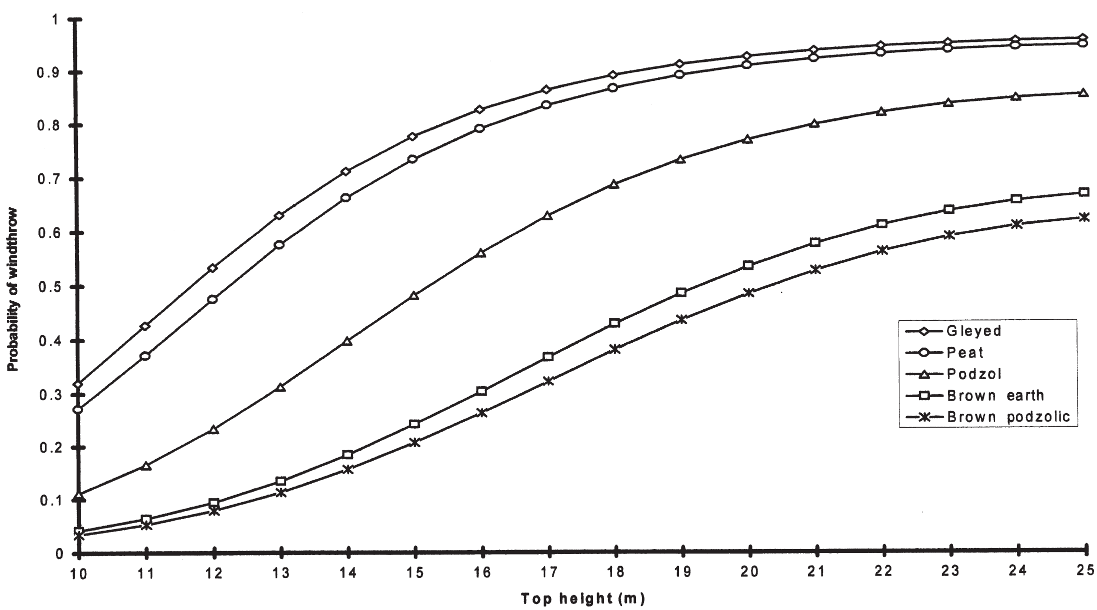

Figure 2. Effect of top height on the probability of windthrow in unthinned stands for a range of soil types (assuming stands in wind zone C and plough ribbons aligned north-west/south-east).

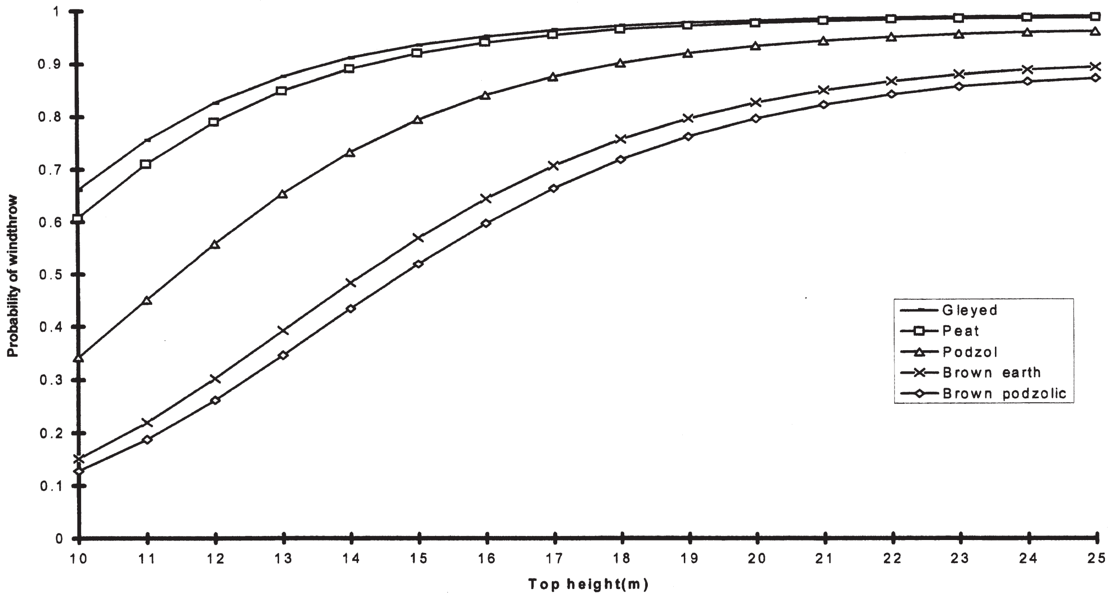

Figure 3. Effect of top height on the probability of windthrow in thinned stands for a range of soil types (assuming stands in wind zone C and plough ribbons aligned north-west/south-east).

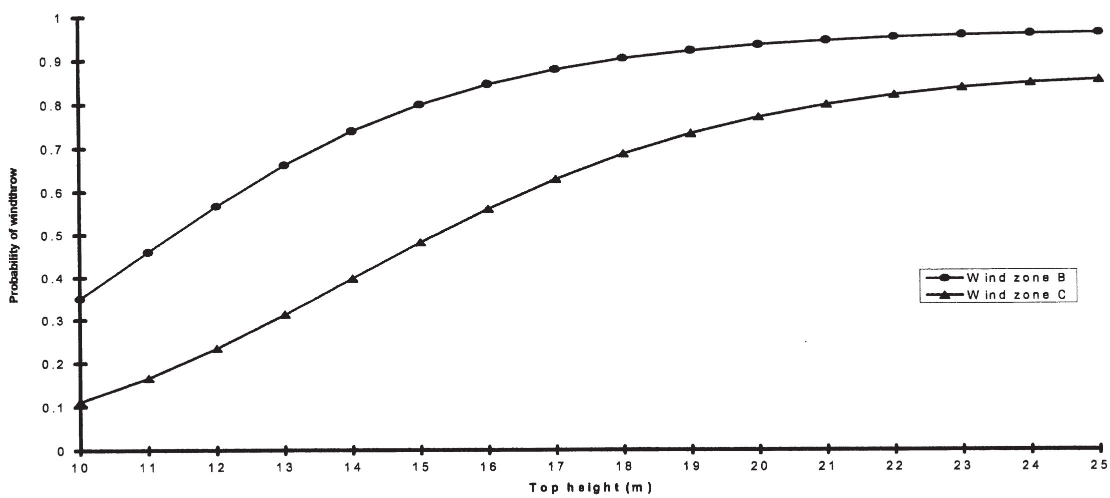

Figure 4. Effect of wind zone on the probability of windthrow in unthinned stands on podzolic soils (assuming plough ribbons aligned north-west/south-east).

Table 4: Parameter estimates for the variables included in the model of windthrow risk probability

Variable	Parameter estimate	Standard error	*t* value	Prob *t*
Intercept	–9.320	2.280	–4.09	<0.001
Top height (m)	0.762	0.241	3.16	0.002
Top height^2 (m)	–0.014	0.007	–2.13	0.033
Soil type				
Brown earth	0.000			
Brown podzolic	–0.200	1.110	–0.19	0.853
Gley	2.390	1.150	2.09	0.037
Peat	2.160	1.130	1.92	0.055
Podzol	1.070	1.160	0.92	0.356
Thinned				
No thin	0.000			
Thin	1.421	0.482	2.95	0.003
Ground preparation bearing				
Ploughing (single or double mould board), ribbons aligned north-west/south-east	0.000			
Ploughing (single or double mould board), ribbons aligned north-east/south-west	–1.822	0.614	–2.97	0.003
Ploughing (single or double mould board), ribbons aligned north/south	–1.649	0.597	–2.76	0.006
Ploughing (single or double mould board), ribbons aligned east/west	–1.377	0.663	–2.08	0.038
Mound and pit plant	–1.900	0.599	–3.17	0.002
Wind zone				
C (Miller, 1986)	0.000			
B (Miller, 1986)	1.456	0.469	3.10	0.002

Discussion

Selection of variables in model

This study showed that windthrow risk increased with top height with the increase levelling off beyond 27 m. Many others have found that windthrow risk increases with increasing top height (Quine and White, 1993; Quine *et al*., 1995). Quine (1995) also noted that beyond certain heights the increase in vulnerability of stands to windthrow levels off and attributed this in part to a decline in the height/diameter ratio leading to an increase in stability. It may, on the other hand, reflect some aspect of survivorship rather than a direct relationship between windthrow risk and top height. The stability of these taller stands may in fact be related to some genetic characteristic of the crop or it may be the result of silvicultural activities not accounted for in the model or local site conditions.

Opening up the canopy by roading or thinning increases the effective drag area (Quine *et al*., 1995) and consequently the risk of windthrow. Walshe and Fraser (1963) cited in Savill (1983) have shown that forces on trees in thinned stands can be doubled by removing adjacent trees. This study showed that the risk of windthrow increased when a stand was thinned. Other aspects of thinning such as thinning type, intensity and timing have also been shown to significantly influence crop vulnerability to windthrow (Lynch, 1985). However, the influence of thinning type was not examined in the current study as almost all selected stands, where thinned, had been subjected to the same rack and selective system.

It is well documented that silvicultural treatments at the establishment phase can influence windthrow risk (Lynch, 1985). Indeed, the occurrence of windthrow on many sites in Ireland has been linked to ground preparation techniques with root restriction being noted on sites that have been ploughed. In this study, three aspects of cultivation were recorded for the sites examined.

These included the method of ground preparation, the direction of ground preparation as well as the ground preparation bearing. Of these, only ground preparation bearing was included in the final model and the analysis showed the risk of windthrow to be greatest on sites where the ribbons are aligned in a north-west/south-east direction. This result agrees with the findings of Hendrick (1988) and can be attributed to a combination of two factors. First, the prevailing wind direction in Ireland is from the south-west and second, root growth is restricted on plough ribbons. Thus if plough ribbons are aligned the north-west/south-east direction, the rows of trees are planted perpendicular to the prevailing wind with roots restricted on both the lee and windward sides. Not surprisingly stands established in this way would be at greater risk from windthrow than if rows were planted parallel to the direction of the prevailing wind.

The study showed that regional location as defined by wind zone significantly influenced the probability of windthrow occurring. It is acknowledged that the map from which these wind zones were taken has a limited scientific basis, as it was based on tatter flag data from Northern Ireland which were extrapolated across the whole of Ireland, taking account of regional variations in mean wind speed. However, data on wind speeds in forests are not commonly available in Ireland and there has been limited use of tatter flags to estimate exposure. Thus the wind zone map provided the best available estimate of the relative windiness of the sites surveyed. In addition, the trends noted in the wind zone map broadly agree with those noted by Troen and Petersen (1989) and Lowe (1994). Coincidently, the model showed that the increase in the risk of windthrow attributed to changing wind zone was almost identical to that which follows thinning (parameter estimate of 1.456 and 1.421, respectively).

Practical developments

In line with most other windthrow risk classification systems, the model produced in this study should not be considered as giving a precise estimate of windthrow risk in a given subcompartment. It should instead be viewed as a decision support tool for forest planners and managers. For example, the model could be used to aid managers in making decisions regarding rotation lengths and thinning on a subcompartment basis. In Ireland, these decisions currently involve a subjective estimate of windthrow risk. A spreadsheet-based version of the model could be linked to a GIS and updated estimates of the probability of windthrow produced as the crop develops. Those stands in which the risk of windthrow had reached a certain level could be highlighted to the forest manager. To facilitate this, the model needs to be linked to yield tables. The model could also be used to determine the potential impact of certain silvicultural treatments such as thinning or aspects of ground preparation on windthrow risk. It could identify those stands where thinning would increase the risk of windthrow to unacceptable levels.

One of the deterrents to using windthrow models in the past has been the cost and difficulty associated with collating stand and site factors and the consequent need for costly field surveys. In this project the role that digital terrain models can play in providing site data was illustrated. Using a DTM of the study area, aspect, elevation and topographical exposure were assessed. The topex scores derived from the DTM were compared with a sample derived in the field and were shown not to differ significantly. However, information gaps remain. The lack of soils data for a number of counties remains a major difficulty. Similarly, the lack of computerized records on forest operations means that information on silvicultural activities often needs to be gathered in the field or from detailed discussions with forest managers. Indeed, one of the potential limitations to the use of the model derived in this project is that one of the factors, i.e. ground preparation bearing, is not currently included in any database. Linking a database on silvicultural operations with an inventory database would make data that are relevant to windthrow easily available.

Limitations of the model

Changes to cultivation practices in the late 1980s have meant that the majority of stands established since that time are on sites that have been either mechanically mounded or ripped. Thus it is likely that this component of the model might be redundant in the future. However, while it is anticipated that trees established on mounded sites will be more wind-firm than those on ploughed sites, there has been limited scientific evidence to support this to date.

Other approaches to modelling windthrow risk, such as mechanistic modelling, need to be investigated. One of the limitations to the approach used in this study is that it uses historical data on the occurrence of windthrow to predict future occurrences of windthrow. However, changes in afforestation trends and silvicultural practices as well as climate change, will all influence the future occurrence of windthrow (Ni Dhubhain, 1998). Thus the model described in this paper may need to be reviewed on a regular basis to accommodate these changes.

Conclusions

This study has developed the first GIS-based windthrow risk model for Irish forests. It also confirms the usefulness of digital terrain models in providing data for these models. However, this study was based on a relatively small sample of subcompartments representing only two wind zones. It is intended therefore to sample more subcompartments in areas of the country not currently represented in the model. On the basis of this additional work, the model may be updated. Validating the final model will also form a key part of this new study.

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