# Factors influencing the occurrence of windthrow in forest stands during Storm Darwin

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# Table of Contents

# Table of Tables

# Table of Figures

## Abstract

Ireland is subject to “normal” winter storms every year; once every 10-20 years severe storms are experienced. The strong winds associated with these storms result in the uprooting and breakage of trees, leading to negative economic consequences for forest owners. In February 2014, a severe storm, Storm Darwin, was responsible for damage to over 8000 ha of forests in Ireland. The aim of this study is to determine the factors that influenced whether forests experienced damage during this Storm.

The region of the country that suffered most damage, i.e. Counties Cork, Kerry, Limerick, Galway and Clare in the south-west, was selected for study. Within this area, all forest stands were stratified according to site elevation and soil type. A stratified random sample of 118 stands was selected for field study. Within each of these stands site (i.e. elevation, soil type, location, wind speed, topex, slope, drainage, land class surrounding the forest), stand (i.e. dbh, top height, H:D, tree species, basal area, stem density, yield class), and silvicultural factors (i.e. features of the ground preparation method, thinning) were recorded. Whether or not windthrow had occurred was also recorded.

Wind damage was noted in 36 of the 118 stands. In all cases damage was in the form of uprooting. Univariate analysis was used to determine the marginal influence of the various site, stand and silvicultural factors on windthrow occurrence. The drainage status (i.e. the extent of waterlogging) and the method of ground preparation had significant marginal influences on windthrow occurrence. Significant effects were also noted for top height, mean dbh, yield class, age and basal area. The land class to the south and east of stands was also important. Many of these variables were correlated. A stepwise logistic regression identified that there were two key predictor variables for windthrow occurrence, i.e. top height and drainage status. The odds ratio for top height was 1.366, hence for every 1 metre increase in top height, the probability of windthrow occurrence increased by 1.36. Further, the odds of windthrow occurring on poorly drained sites was just over 12 times as high as they were on sites where drainage was very good; on sites where drainage was either very poor or good, the odds of windthrow occurring were almost three times that on sites where drainage was very good.

The findings confirm what other studies have noted in relation to wind damage during catastrophic storms, i.e. that silvicultural and management factors have a limited influence on the occurrence of windthrow when extreme wind speeds are recorded.

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## Statement of Original Authorship

“I hereby certify that the submitted work is my own work, was completed while registered as a candidate for the degree stated on the Title Page, and I have not obtained a degree elsewhere on the basis of the research presented in this submitted work”.

Cian Gallagher

# 1 Introduction

This chapter provides the context to the body of research that is presented in this thesis. It begins with a brief overview of the history of forestry development in Ireland. A short description of the climate of Ireland is then given, followed by a review of the historical occurrence of windthrow in Ireland. The chapter ends with an outline of the objectives of the research work presented in this thesis.

## 1.1 Brief overview of Irish forestry

Ireland's forest cover was negligible at the beginning of the 20th century (Neeson, 1991). An afforestation programme was launched to address this deficit and planting took place initially on poor quality, high elevation, land. On such poor sites, Sitka spruce (*Picea sitchensis* (Bong.) Carr.), a non-native conifer, proved to be very productive and the species has dominated the Irish afforestation programme since then. In the 1980s, the introduction of EU-funded financial subsidies acted as the catalyst for private sector involvement in afforestation. Initially private afforestation mirrored that conducted by the State and took place on marginal agricultural land with Sitka spruce the species of choice. A re-targeting of the subsidies to encourage the planting of broadleaves in the 1990s resulted in private landowners (mostly farmers) afforesting better quality, lower elevation sites, with broadleaves (Upton *et al.,* 2012).

Today the forest area of Ireland is estimated to be 731,650 ha (i.e. 10.5% of the total land area); 54% of which is public forest[1] (Forest Service, 2013). Conifers dominate, accounting for 75% of the area. Reflecting the upsurge in afforestation since the 1980s, just over half (56%) of the estate is less than 20 years of age. The legacy of the early State planting on lands marginal for agriculture means that currently 75% of the entire estate is located above 100 m and 44% is on peat soils (Forest Service, 2013). Gley soils are the most common mineral soil afforested (Forest Service, 2013). Growth rates in Irish forests are among the highest in Europe. O'Carroll (1984) noted

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[1] Public forests are primarily managed by Coillte Teo. (The Irish Forestry Board). This is a semi-state company established in 1989 which is responsible for the management of State forests.

that conifer growth rates are over four to five times those in Scandinavia. The current average yield class is 11.5 $m^3$/ha/year (Forest Service, 2013); however, for Sitka spruce it is estimated to be 17 $m^3$/ha/year (Farrelly *et al*., 2009).

## 1.2 Wind and forests in Ireland

Ireland has a maritime climate and experiences mean annual wind speeds of 4-5 $ms^{-1}$ in flat inland regions, while coastal regions experience 6 $ms^{-1}$ and regions along the north-western coastline experience mean wind speeds of 7 $ms^{-1}$ (Nolan *et al.,* 2012). Frequent Atlantic depressions pass over the country during the winter months bringing strong windy conditions (Nieuwenhuis and Fitzpatrick, 2002). These depressions, which move eastwards, also bring heavy rainfall. The south and west coasts experience 25 gale days annually, while inland counties in Leinster experience 2 gale days per year (Sweeney, 2014). Highest wind speeds are recorded along the north and west coasts with gales of up to 49 $ms^{-1}$ in winter months. Occasionally, Ireland is affected by severe cyclonic storms which originate in the tropics. These cyclones result in extreme levels of rainfall and strong gale force winds (McGrath, 2015).

Given the climate and historical trends in planting it is not surprising that the most significant abiotic factor causing damage to forests in Ireland is wind. Approximately 85,000 $m^3$ of Irish commercial timber were damaged by wind annually during the period 1971-1993 (Ní Dhubháin *et al*., 2001). Damage caused by “normal” winter storms is referred to as endemic damage, such damage usually results in the uprooting of a small proportion of stems (Miller, 1985; Nieuwenhuis and Fitzpatrick, 2002); if not managed correctly this damage can spread leaving the remaining forest more susceptible to windthrow (Quine, 1995). Endemic damage can result in serious financial and ecological implications for the forest industry with annual damage accounting for approximately 9% of the total timber sales in Ireland (Ní Dhubháin *et al.,* 2001). Severe storms with associated strong gusts can cause significant damage to forests, this type of damage is referred to as catastrophic damage (Nieuwenhuis and Fitzpatrick, 2002). During storm events trees can be uprooted (i.e. windthrow or windblow) or they can snap. The former is the most common class of wind damage in Ireland.

Windthrow statistics for Ireland for the period 1971 to 1998[2] are shown in Table 1. During that period windthrown volumes accounted for 15.1% of the volume sold. Also evident is that the total volume sold increased during this period reflecting the expansion and maturing of the forest estate.  The windthrow statistics also show that on a number of occasions large volumes were windthrow. These large losses were associated with a number of major storms that hit the country between 1971 and 1998. For example, in 1974, a major storm passed over the country which was classed as the most damaging of the 20th century in Ireland with the volume of blown material representing 50% more than the annual harvest at that time (Keane cited in Fitzpatrick, 2000) (Table 1). Towards the end of the 1990s a further two major storms hit the country one year after the other leading to substantial amounts of damage. Most recently, in 2014, Storm Darwin passed over Ireland. According to extended metrological reports, Storm Darwin was a 1 in 20 year storm event, during which areas in the south west of Ireland experienced wind speeds (i.e. 120-160 km/h) exceeding any other in living memory (McGrath, 2015). It was estimated that 8000 ha of forest land was affected by this storm.

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[2] Annual windthrow statistics for Ireland have not been published since 1998.

**Table 1: Historical occurrence of windthrow in the Republic of Ireland.**

| Year | Annual volume sold 000's m$^3$ | Windthrown volume 000's m$^3$ | Percentage |
|---|---|---|---|
| 1971 | 308 | 0.6 | 0.2 |
| 1972 | 380 | 1.4 | 0.4 |
| 1973 | 317 | 46 | 14.5 |
| 1974 | 240 | 374 | 155.8 |
| 1975 | 287 | 106 | 36.9 |
| 1976 | 483 | 134 | 27.7 |
| 1977 | 388 | 38 | 9.8 |
| 1978 | 450 | 43 | 9.6 |
| 1979 | 317 | 13 | 4.1 |
| 1980 | 529 | 6.8 | 1.3 |
| 1981 | 771 | 10 | 1.3 |
| 1982 | 999 | 61 | 6.1 |
| 1983 | 1000 | 53 | 5.3 |
| 1984 | 1013 | 141 | 13.9 |
| 1985 | 1218 | 95 | 7.8 |
| 1986 | 1263 | 74 | 5.9 |
| 1987 | 1380 | 84 | 6.1 |
| 1988 | 1450 | 101 | 7 |
| 1989 | 1503 | 111 | 7.4 |
| 1990 | 1444 | 167 | 11.6 |
| 1991 | 1537 | 80 | 5.2 |
| 1992 | 1840 | 125 | 6.8 |
| 1993 | 1854 | 92 | 6.8 |
| 1994 | 2044 | 235 | 11.5 |
| 1995 | 2129 | 183 | 8.6 |
| 1996 | 2192 | 92 | 4.2 |
| 1997 | 2062 | 500 | 24.2 |
| 1998 | 2364 | 1600 | 67.7 |
| Total | 31761 | 4792.8 | 15.1 |

Source: Forest Service data from 1971-1990; Coillte Teo. 1991-1998

## 1.3 Research objective

Storm Darwin caused considerable damage to forests. In response to this the Department of Agriculture, Food and the Marine invited researchers to submit a research proposal which would, *inter alia*, identify key factors that may render “some forests and potential forest land as higher windblow risk in light of extreme weather events”. The research described in this thesis was undertaken as part of the successful research proposal, i.e. WINDRISK. The objective of this research was to identify the factors that influenced the occurrence of windthrow in forest stands during Storm Darwin.

# 2 Literature Review

Wind had a variety of impacts on trees and forests. This chapter focuses on literature relating to windthrow (and windsnap). It begins by describing how trees overturn or snap. It then describes the approaches that have been used to model windthrow risk. An overview of the factors that have been shown to influence windthrow in forest stands is then given. The chapter concludes with a brief review of research previously conducted in Ireland on windthrow.

## 2.1 Mechanics of windthrow and windsnap

Windthrow occurs when aerodynamic forces on the stem and canopy create a tipping moment which exceeds the resistance forces of the root system, the tipping moment is referred to as the tree's critical break point (Woods, 1995). The most significant factor determining the overturning moment is the strength of the wind and its loading distribution on a tree. The aerodynamic forces may be influenced by the drag effect created by the crown, with larger crowns generating more drag (Kerr, 1973; Cremer *et al*., 1977; Foster, 1988). As the tree matures the tipping moment increases. The effect of wind loading on a tree is related to height, as the tree grows taller greater wind pressure is exerted upon it, increasing the likelihood of wind damage. Dominant trees evolve to compensate for their height with thicker stems and well established rooting systems, suppressed trees of similar height with slender stems and poor rooting are most vulnerable (Quine *et al*., 1995).

Windsnap occurs when the resistive strength of the rooting system is greater than the strength of the bole (Mergen, 1954). Putz *et al.* (1983) reported that tree species that had characteristics such as tall stems, with low wood density tended to snap rather than uproot. The authors also suggest that there is a higher level of snapping in species with larger buttresses. Dunham and Cameron (2000) noted that taller trees with the greatest diameters tended to snap more frequently than others.

## 2.2 Wind Risk Modelling

In an effort to predict and hopefully mitigate the influence of storms on forest stands, models have been developed to help understand how various characteristics interact to influence windthrow risk (e.g Schmidt *et al*., 2010; Albrecht *et al*., 2012, Pasztor *et al.,* 2015; Moore and Watt, 2015; Pukkala *et al.,* 2016). Some of these models have been used as decision support tools to help forest managers understand the impact of their silvicultural decision-making on stand stability. Wind risk models can be divided into two main categories, mechanistic and empirical; additionally combinations of both types have been developed to form hybrid models.

Empirical models can be used to assess the probability of damage occurring on a particular site based on stand and site variables. These models are typically based on inventories of past damage and are suitable for stands and areas similar to those on which the models are based (Hale *et al*., 2015). The sampling units are either stands of trees or individual trees. Stand-level empirical models can be used to generate coarse-resolution windthrow risk maps for operational planning, while models based on individual trees can be used to estimate windthrow risk for individual trees within a stand (Scott and Mitchell, 2005).

Mechanistic modelling examines the tree level mechanics involved in the uprooting or stem breakage of a tree. It uses the results of tree winching and wind tunnel studies to predict critical wind speeds (CWS) (Gardiner *et al*., 2008), which is the point at which stem snapping or uprooting occurs. A mechanistic model can also be used to calculate the probability of damage at a specific location in the event of CWS (Gardiner *et al.*, 2008).

Hybrids of mechanistic and empirical models have been developed e.g. HWIND (Peltola *et al*., 1999), FOREOLE (Ancelin *et al*., 2004) and GALES (Gardiner *et al*., 2000).

### *2.2.1 Empirical Models*

A range of statistical approaches has been used in empirical modelling of windthrow risk. These include logistic regression (e.g. Lanquaye-Opoku and Mitchell, 2005); neural networks (Hanewinkel *et al.,* 2004), and classification and regression trees (e.g. Dobbertin, 2002). Some have used more than one approach. For example, Schindler *et al.* (2009) applied the weights of evidence methodology and a logistic regression model to calculate the wind damage probability and compared the results produced from both methods.

Interlinked with the statistical approaches used is the choice of response/dependent variable. Damage is often recorded as binary, i.e. damage present or not (e.g. Mitchell *et al.,* 2001); or extent of damage (e.g. Schütz *et al.,* 2006; Martín-Alcón *et al*., 2010). Pasztor *et al*. (2015) used binomial generalized linear mixed models to quantify the probability of damage events and also used linear mixed models to explain damage intensity.

Empirical models have been derived from data collated following a single catastrophic event (e.g. Cucchi and Bert, 2003); others have used data derived from disturbances occurring over a period of time (e.g. Ní Dhubháin *et al*., 2001). The data sources vary from large-scale inventory data (e.g. Schmidt *et al*., 2010) to case study data (e.g. Martín-Alcón *et al*., 2010). More recently, remote sensing and GIS tools have been used to identify areas damaged and site factors associated with such damage (Schindler *et al.,* 2009).

In the following section the factors that have been identified in the empirical models as influencing the risk of windthrow are described.

## 2.3 Characteristics influencing windthrow risk

### *2.3.1 Wind speed*

The occurrence of windthrow is a function of forest characteristics and weather characteristics. However, very often wind speed data are not available or are available at too coarse a level to capture between-stand differences (Scott and Mitchell, 2005). Wind speed can vary greatly at local level, small changes in landscape features can influence the velocity of wind. Changes occur as land turns from open bog or aquatic zones to enclosed farmland with high hedgerows, to very rough surfaces such as forests. As the terrain roughness increases the mean wind speed decreases, while the maximum gust speed increases (Logue, 1989).

Wind speed varies depending on topographic characteristics (Peterson and Pickett, 1991). Finnigan and Brunet (1995) found that wind velocity changes according to the steepness and rigidity of land. Undulating hills allow for airflow to pass over or around without any significant change in velocity, while steep ridges and jagged peaks act as a barrier causing rapid changes to wind velocity. Air decelerates at the foot of these ridges and gradually accelerates as the gradient rises until maximum velocity is reached at the summit, this is followed by a sudden decrease in velocity on the leeward side of the ridge (Figure 1). Lower wind speeds are recorded on low lying land such as sheltered valleys. These differences in wind speed are found due to topographic variation and are referred to as the "*topographic effect*".

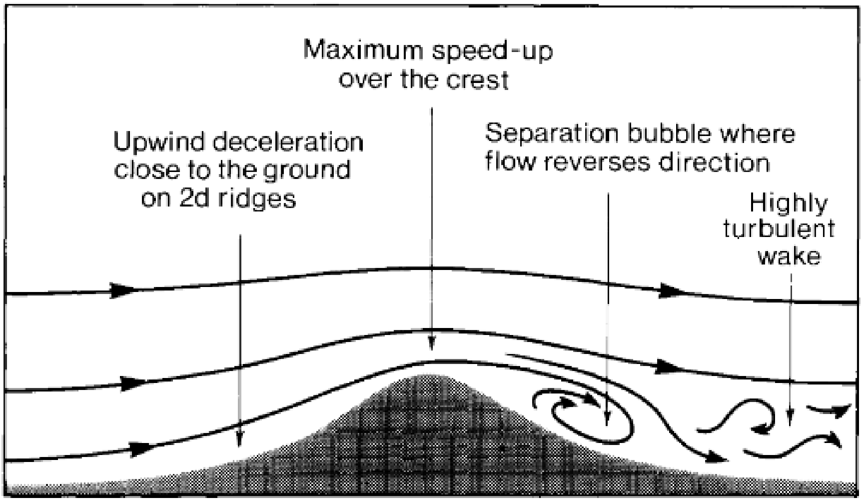

**Figure 1. Schematic diagram of the key elements of neutrally stratified windflow over a hill. (Source: Finnigan and Brunet, 1995)**

In the absence of local wind speed data the topographic exposure of forest stands using indices such as topex is often recorded. Topex is the sum of the angles to the skyline in the eight cardinal directions, with negative angles recorded as zero (Wilson, 1984). Modifications to this index have been used. For example, Schmidt *et al*. (2010) calculated the level of exposure using a 25 x 25 m resolution digital elevation model (DEM). They employed an adapted version of Scott and Mitchell's (2005) Topex-to Distance index by accounting for wind direction and measured the terrain angles for 36 different directions. They found a higher level of risk for stands exposed to south westerly winds (the direction from which the storm they were studying, i.e. Lothar, came), and along steep south east/west ridges. Scott and Mitchell (2005) found windthrow was greatest in locations with the lowest and highest topex score, which they attributed to a funneling effect along valley bottoms.

### *2.3.2 Aspect, slope and elevation*

Aspect, slope and elevation are all relief factors that have been shown to influence windthrow risk. Scott and Mitchell (2005) found wind damage most frequently occurred on south and west aspects (68%), this corresponded with the south westerly prevailing wind experienced in the region.

Schutz *et al.* (2006) was one of the few to study the influence of steepness of slope. They found a decrease in the likelihood of damage as slope increased. Their study categorised slopes as: gentle (<20%), steep (20-49%) and very steep (>49%) with results showing the ratio of damage in the aforementioned categories to be 6:3:1. respectively.

Greater levels of exposure and higher wind speeds are recorded at higher elevations leading to a greater risk of wind damage (Pasztor *et al*., 2015). Scott and Mitchell (2005) also found a significant increase in damage at elevations over 200 m. In contrast, Lanquaye-Opoku and Mitchell (2005) observed that while an increase in elevation did correlate with changes in parameters such as slope and tree height, it did not have any significant effect on the rate of windthrow. Albrecht *et al.* (2013) found a negative relationship between elevation and storm damage, a finding they attributed to the adaptive growth of trees in windy locations.

### *2.3.3 Stand height*

Albrecht *et al.* (2012) found that stand height is one of two (the other being tree species) most important storm risk factors. As tree height increases the force that a given wind speed exerts on a tree increases; taller, slender trees are therefore vulnerable to windthrow. The stability of a tree is expressed as the maximum turning moment at the base of the stem during overturning. The turning moment is a function of force multiplied by length, in this case wind velocity multiplied by tree height (Nicoll *et al*., 2006). Schmidt *et al.* (2010) found that tree height proved to be one of the most important variables influencing the risk of windthrow. Dobbertin (2002) similarly found that taller stands were more likely to suffer storm damage. One of the few studies that did not find tree height to be a significant predictor of wind damage was conducted by Schutz *et al.* (2006). They noted that very high wind speeds are extremely variable in their characteristics, such as direction and velocity, this makes the correlation of key variables and wind damage very difficult to represent, especially when considering stand level damage. They conclude that with such high wind speeds (45 $ms^{-1}$, Storm Lothar) an attempt to interpolate data based on localised wind predictors may not yield accurate results.

Some studies use stand age when stand height is not available. Pasztor *et al.* (2015) found stand age to be a key predictor of wind damage, with damage probability increasing with increasing age. They attributed their finding to the fact that increasing age represents the positive effect of tree height on damage probability. There appears to be a plateau/threshold to this effect with Quine (1995) noting that beyond certain heights a levelling off of the risk of damage occurs.

### *2.3.4 Dbh, H:D ratio, basal area*

The influence of the diameter characteristics of stands is rarely considered in isolation. One of the few such studies to include mean dbh (diameter at breast height, i.e. 1.3 m) as a potential predictor variable for the occurrence of wind damage was conducted by Valinger and Fridman (2011). They indicated that the mean dbh of the Norway spruce (*Picea abies* L. Karst.) trees in stands significantly influenced the probability of damage from wind. They did not, however, highlight the direction of the relationship. Martín-Alcón *et al*. (2010) did investigate the relationship between the coefficient of variation of dbhs in plots and damage in those plots, however, they used this as a proxy for the stand’s vertical structure. Most commonly, it is the relationship or ratio between the height of a tree and its diameter (H:D) that is used in windrisk studies. This so-called slenderness coefficient is defined as the ratio of total height of a tree to its diameter at 1.3 m above ground (Wang *et al*., 1998) and it is often used as an index of stability (Navratil, 1995, cited in Wang *et al*., 1998). At tree level greater H:D ratios lead to a greater risk of windthrow (Scott and Mitchell, 2005; Albrecht *et al.* 2012). At stand or plot level the H:D ratio is less useful with Valinger and Fridman (2011) finding no significant influence of mean H:D ratio on windthrow risk. Schutz *et al.* (2006) also found that the H:D ratio was not a significant predictor of stand damage.

Occasionally the role of basal area is addressed in windrisk studies, although its influence is often considered in the context of thinning. Conflicting trends have been noted. For example, Jane (1986) found no significant influence of basal area on windthrow occurrence; the basal area of the windthrown stands he observed ranged from 70 $m^2$/ha to 20 $m^2$/ha. However, the same author points out that at very high basal areas there is heightened competition between trees and restricted development. The author suggests that these competitively induced stresses reduce the tree's ability to deal with threats such as disease, resulting in a weakening of the tree's physical characteristics culminating in significant levels of damage during catastrophic wind events.

### *2.3.5 Soils*

Soil characteristics are frequently shown to significantly influence windthrow risk. This is because the rooting system of a tree plays a vital role in determining the overall stability of a tree (Sutton, 1969). Rooting depth and overall morphology are all dependent on the composition of the soil in which the forest is growing. Soils are characterised by a variety of different elements (Duerr, 1975). The key soil characteristics associated with stability are depth of soil, soil texture and water table level.

In some empirical models soil type is included as a predictor variable. For example, Ní Dhubháin *et al.* (2001) found that the probability of stands of Sitka spruce experiencing windthrow was lowest in those established on brown earths or brown podzolic soils and highest on gleys and peats. Quine *et al.* (1995) suggest that a tree's ability to withstand wind damage can be directly related to the mass of the soil associated with the roots of the tree. The mass of a poorly drained soil, such as peat, will have a density of approximately 1.0 mg $m^{-3}$, whereas a well-drained soil, such as a brown earth, will have a density closer to 2.0 mg $m^{-3}$.

Schmidt *et al*. (2010) accounted for soils by categorising them into three classes according to the extent to which they were waterlogged. They noted an increase in the predicted probability of wind damage as the degree of waterlogging increased. Scott and Mitchell (2005) examined the role of permeable soil depth, soil moisture and nutrient regime; among these they found that windthrow decreased as permeable soil depth increased. Dobbertin (2002) used a combination of soil characteristics, and found that sites with higher soil depth, less stone content, and less water permeability or water logging were associated with an increased probability of damage.

### *2.3.6 Silvicultural factors*

Interventions such as thinning and clearcutting increase the exposure of residual trees (e.g. Ruel, 1995). Albrecht *et al.* (2012) found that past timber removals and selective thinning appeared to be more important for explaining storm damage risk than stand density, soil and site conditions or topographic features. Crown contact plays an important role in the stability of a tree and closely spaced trees can pass energy on to their neighbours resulting in a dampening effect. After thinning has taken place, the distance between crowns increases leaving the trees more susceptible to windthrow. Dobbertin (2002) found that prior thinning was associated with a doubling of the observed proportions of damaged stands, which he attributed to increased wind loading.

The increase in risk associated with thinning depends on its timing, intensity, and type (Quine *et al*., 1995). Thinning performed at an early stand age can increase the stability of trees (Albrecht *et al.,* 2012); Hamilton (1980) found that delayed thinning increases the extent of windthrow and removing large amounts of timber at a time can cause large amounts of damage. Greene *et al.* (1992) found that high intensity thinning contributed to severe wind damage. Thinnings that remove dominant trees may destabilise stands more as they may play a role in forming a “skeleton” or “scaffold” for the less stable trees in the stand (Albrecht *et al.* 2012, p. 241). Nevertheless, Cremer *et al.* (1977) suggests that stands with a long history of thinning have a degree of preconditioning allowing them to withstand very windy conditions.

Schutz *et al.* (2006) observed that as wind speeds increase to extreme velocities the role that forest management plays, such as thinning intensity and timing, becomes less relevant when considering the potential of windthrow.

Another silvicultural factor that can influence the stability of trees is the method of ground preparation. In Ireland, given the soil types that were available for afforestation, ploughing was the most common method of site preparation used until the 1980s. As early as 1976 however, MacKenzie (1976) had noted that ploughing can restrict the rooting system and therefore make trees less stable. Later, Savill (1983) outlined that while ploughing can reduce the amount of waterlogging on a site, it is very much at the expense of root development and anchorage. Hendrick's (1989) study into the growth and root anchorage in Sitka spruce suggested that alternatives to ploughing may be more beneficial from a stability perspective.

In a previous study of factors influencing windthrow risk in Ireland, stands on ploughed sites exhibited the greatest risk of windthrow, with the lowest risk noted on mounded or pit planted sites. The same study concluded that ploughing orientation should be the same as that of the prevailing wind to minimise damage (Ní Dhubháin *et al*., 2001).

### *2.3.7 Species*

Many studies have found that the risk of wind damage varies significantly according to species (e.g. Schmidt *et al*., 2010), with Albrecht *et al.* (2012) noting that species was the most important storm risk factor (along with stand height). The latter authors attributed the effect of tree species in part to differences between them in terms of canopy characteristics and quality of root anchorage. More pressure is exerted upon trees with large dense canopies, this is due to an increase in the drag coefficient or lateral force. Species such as Sitka spruce have a larger drag coefficient due to large dense foliage and branches, whereas broadleaves, such as birch, have a lower drag coefficient due to the larger spacing of the branches and the loss of foliage during winter months, when wind speeds are highest (Savill, 1983). Hence many studies have noted a greater risk of wind damage among conifers than among broadleaves (e.g. Dobbertin, 2002).

The type of damage caused by wind may vary between species, some may be more susceptible to stem breakage while others are more susceptible to uprooting. Putz *et al.* (1983) reported that damage in species that had characteristics such as thick, short stems, with high wood density tended to be in the form of uprooting rather than snapping. The authors also suggest that there is a higher level of snapping in species with larger buttresses. Trees species that are known to be at high risk to pathogenic contamination are said to have poorer structural properties and perhaps are more prone to windthrow (Landis and Evans,1974).

### *2.3.8 Neighbourhood effect*

A change in boundary or tree exposure to wind after harvesting is important as it influences the wind damage risk to remaining or neighbouring stands. This is sometimes referred to as the neighbourhood or edge effect. Scott and Mitchell (2005) attempted to capture the effect of post-harvest wind exposure on windthrow risk using fetch indices. They found that as the length of opening continuous to a plot increased (accounting for the effect of aspect or cardinal direction) the odds of windthrow occurring increased.

The design of the forest influences the wind speed and turbulence that the trees within that forest stand experience. Ruck *et al*. (2010) suggest that the composition of the forest edge on the upwind side of the stand can play a significant role in the path the wind takes over or through the forest.

Trees planted along the edge of a plantation evolve to withstand wind damage; their thick stems are better suited to handle wind loading. The creation of new edges due to clearfelling in neighbouring stands exposes trees which have not been adapted to deal with the increased level of exposure, instead they often have tall slender characteristics. These trees become especially vulnerable during stormy condition (Zeng *et al*., 2007; Forsell *et al*., 2011).

## 2.4 Research on wind and forests in Ireland

In Ireland, limited work has been carried out on the topic of wind damage in forest stands. One of the earliest assessments of the extent of windthrow that was occurring in Irish forests was conducted by Gallagher (1974). He examined historical trends in windthrow occurrence and explored some of the factors that potentially may have influenced these trends. However, he did not use empirical data. A number of tree pulling experiments have also been conducted to evaluate the effect of different cultivation methods on the stability of Sitka spruce (Hendrick, 1989; Rodgers *et al*., 2006). In addition, a number of studies have explored the financial impact of catastrophic storms (Nieuwenhius and O'Connor, 2001; Nieuwenhuis and Fitzpatrick, 2002).

Aside from the work outlined above, much of the focus of the research in Ireland has been on assessing and developing models/systems for predicting windthrow risk. In 1988, a windthrow risk classification for thinning was produced by Hendrick (1988). It was designed as a guide to deciding whether or not to thin a stand as it approached time of first thinning. Lowe (1994) compared Hendrick's model with a number of windthrow risk classification systems from the UK and Northern Ireland, as well as a number of subjective classification systems that were used in State forests. He noted that all gave different assessments of risk and that none accurately predicted the occurrence of windthrow. Ní Dhubháin *et al.* (2001) developed a probabilistic model using empirical data to predict the probability of windthrow in Sitka spruce stands in Ireland. Five factors were included in this model: top height, the regional location of the stand, the soil type, the compass bearing of the plough ribbons where the site had been ploughed and thinning. This model was updated some years later (Ní Dhubháin *et al.,* 2009) when additional data became available and the model amended to include altitude and top height squared. The compass bearing element was removed.

## 2.5 Overview/conclusion

The review of the literature shows that the occurrence of windthrow is a function of the characteristics of the forest (i.e. species composition, dendrometric variables), its past silvicultural management and site variables. Windthrow occurrence is also influenced by weather characteristics; however the review of the literature indicates that accurate data on the winds experienced by forests are rarely available. Instead the effects of wind are often approximated by surrogates such as topex. Complicating the understanding of the phenomenon of windthrow and the identification of key influential factors, is that many potential predictor variables are not independent.

Studies on windthrow include those that have been conducted after catastrophic storms, as well those that relate to on-going or endemic windblow. Very often in the former, silvicultural/management variables are found not to be significant; a finding often attributed to the extreme wind speeds experienced during severe storms.

In Ireland, wind is the major abiotic threat to forests. Despite this, there has been limited research conducted to date on understanding the phenomenon. What has been done has not focussed on damage following a severe storm, but instead has looked at damage arising from normal winter storms. This is the research gap that this thesis aims to address.

# 3 Methods and Materials

## 3.1 Storm Darwin

In the winter of 2013/14 an extreme storm period was experienced in Ireland. Twelve separate severe weather warnings were issued between December 5th 2013 and 12th February 2014. Rainfall levels for the period reached a 60-year high, leading to flooding in lands that were already heavily saturated. This period of unsettled weather culminated on February 12th with a ‘’weather bomb’’ passing over Ireland, the so-called Storm Darwin (McGrath, 2015). To give an overview of key weather conditions on February 12th, hourly meteorological data on maximum gusts recorded in a 10 minute period from 15 weather stations were collated to form a heat map (Figure 2a). Additionally, rainfall data from the same weather stations for the period December 5th 2013 to February 12th, 2014 were also collated to generate a rainfall heatmap (Figure 2b). These show the south and west of Ireland, in particular the Counties of Cork, Kerry, Limerick, Galway and Clare, experienced the highest gusts and the greatest rainfall levels.

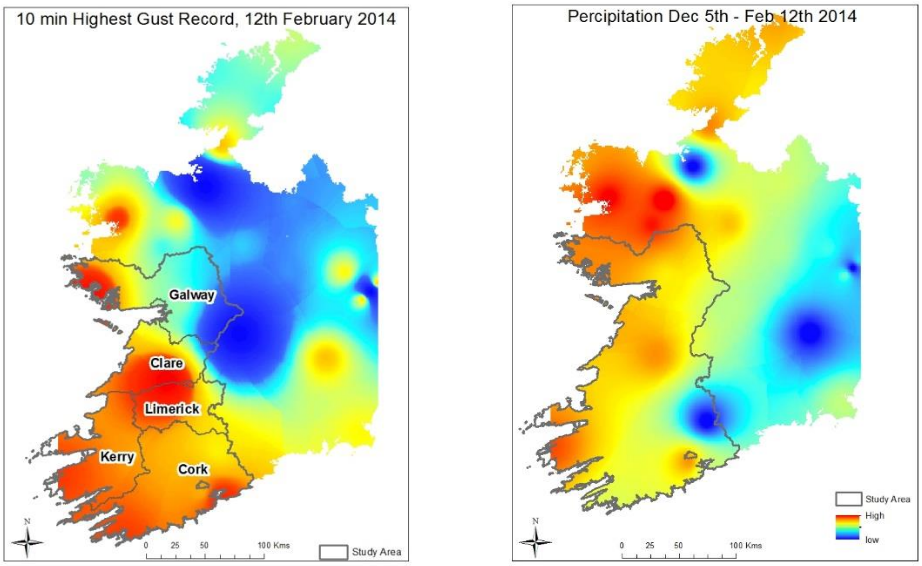

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**Figure 2: a) Interpolated 10 min highest gusts and b) Accumulative precipitation December 5th- February 12th 2014.**

In the aftermath of Storm Darwin, the Department of Agriculture, Food and the Marine and other forest industry players funded a project to assess the extent of wind damage that occurred during storm Darwin[3]. Rapid Eye imagery was used. This high-resolution imagery is derived from a German/Canadian satellite platform. The imagery was captured at a spatial resolution of 5 x 5 m, and each pixel was classified as damaged/no-damage. Pixels classified as damaged were converted to GIS shapefiles in the form of polygons for visual and quantitative assessment. The analysis of this imagery showed that the highest rates of windthrow were recorded in the aforementioned five counties[4].

## 3.2 Study area and sample selection

On the basis of the data on windthrow occurrence and wind speed information the study area, for the purpose of this research, was defined as the area comprising the following five counties: Cork, Kerry, Limerick, Galway and Clare. To facilitate the process of selecting stands from the population of stands within the study area, use was made of a number of spatial datasets. These included the Forestry 15 database, which is the latest version of the Forestry Inventory Planning System vector forest cover layer, which the Forest Service retains for the entire Irish forest estate. The dataset provides a spatial representation of each forest stand, along with attributes such as size, species, year of establishment, ownership category (i.e. public; private); each stand is assigned a unique ID. A soils GIS layer for the country was also used. This layer, which was provided by Teagasc, was derived from the General Soil Map of Ireland (Gardiner and Radford, 1980). The soil types in this layer were grouped into four broad categories as shown in Table 2.

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[3] (https://www.agriculture.gov.ie/forestservice/windblow/).

[4] (https://www.agriculture.gov.ie/media/migration/forestry/windblown/National%20Storm%20Damage%20Map.pdf).

**Table 2: Allocation of soil types to major soil groups.**

| Soil type | Soil group |
|---|---|
| Peaty podzol | Shallow Wel b bl |
| Minimal grey brown podzolic | Deep Well |
| Brown podzolic | Deep Well |
| Basin peat | Peat |
| Blanket peat (high level) | Peat |
| Blanket peat (low level) | Peat |
| Acid brown earth | Deep Well |
| Gley | Gley |
| Lithosol | Shallow Well |
| Peaty Gley | Gley |
| Lithosols and outcropping rock | Shallow Well |
| Redzina and outcropping rock | Shallow Well |
| Redzina | Shallow Well |
| Degraded brown podzolic | Deep Well |
| Urban | |
| Water | |
| Grey brown podzolic | Deep Well |
| Shallow brown earth with redzina | Shallow Well |
| Degraded grey brown podzolic | Deep Well |
| Acid brown earth (coarse texture) | Deep Well |

Within the study area the population of interest was all forest stands aged 10 years or older. This was an arbitrary cut-off age, representing a point after which stands would be approaching first thinning age and a potentially critical height with respect to windthrow. Within the selected counties a list of all forest stands aged 10 years or older was compiled using the Forestry 15 database. A stratified random sample was chosen from this list, as previous Irish studies on windthrow risk had shown elevation and soils to influence its occurrence (Ní Dhubháin *et al*., 2001; Ní Dhubháin *et al*., 2009). Hence, to ensure that a range of soil types and elevation classes were represented, all forest stands within the five counties chosen were stratified according to the four soil groups shown in Table 2 and the following four elevations classes: i.e. < 100 m; 100 < 200 m; 200 < 300 m; . > 300 m.

Within each of the 16 strata, six Coillte stands were randomly selected. Private forests were stratified into 12 groups; the 300+ category was excluded as only a very small number of private stands are found at this elevation. Two private stands were randomly selected from each of the 12 strata, yielding a total of 24 private stands. Fewer stands were selected from the private sector reflecting the lower number of private stands that experienced windthrow damage during storm Darwin.

### 3.3 Data collection

A total of 118 stands were visited between October 2015 and May 2016. Within each stand, sample plots were randomly located using GIS software (random point generator). Larger plots of 0.04 ha (20 x 20 m) were used in stands with low stem density, while smaller plots of 0.01 ha (10 x 10 m) were used in younger, denser, unthinned stands.

Each forest stand was thoroughly inspected for forest damage along forest edges and throughout the stand. Where stands displayed significant levels of damage, the random plot location was changed to be positioned in a location that represented the damaged trees. In each plot the proportion of the stems that were damaged (both blown and snapped), if any, was recorded.

Within each of the 118 stands, data were recorded on a range of stand, site and silvicultural factors. Although the Teagasc soil dataset provided the most accurate and up to date source of information for the forest estate and was used as a principal parameter in the stratification of the forest stands, there were some issues identified once field work commenced. Some of the soil types observed in the field differed from that recorded within the Teagasc dataset, this is to be expected when using a large scale low resolution dataset to identify soil type at stand level. However, the dataset was able to provide an accurate soil type in the majority of cases. Where observed soil types differed from the Teagasc record the stand was reclassified into the correct stratum.

The following is a summary of the stand, site and silvicultural variables recorded for each of the stands. Summary statistics for the continuous predictor variables are shown in Table 3.

### *3.3.1 Stand factors*

The DBHs (diameter at 1.3 m above ground level) of all trees in the plot were recorded and the quadratic mean DBH calculated. The height of the tree of largest dbh was recorded to give top height. The H:D ratio was then determined, by dividing the height of the tree of largest dbh in a plot by its dbh. This is somewhat similar to the dominant strata slenderness ratio calculated by Martín-Alcón *et al*. (2010); although they divide the height of the dominant trees in a plot by the quadratic mean diameter of the trees. The number of stems per plot was counted and used to estimate the number of stems per hectare, i.e. stem density. The yield class ($m^3ha^{-1}an^{-1}$) for the stand was taken from the Forestry 15 database.

The tree species in the stand was available from the Forestry 15 database; this was validated during the field visit. The proportions of the stand that the various species comprised were also available from the Forestry 15 database; species 1 was the species that made up more than 50% of the stand area. If the stand was comprised more than one species it was classed as mixed.

### *3.3.2 Site factors*

Information on a number of site factors was available from spatial layers. A topex (topographic exposure) map of Ireland produced by Teagasc provided topex scores for each stand. This topex map was developed using a DEM, made available from Ordnance Survey Ireland, resized from 20 m to 100 m resolution in the x-y plane, with 1 m vertical resolution (Farrelly, pers coms). Using this DEM Farrelly (pers com) calculated a restricted distance topex value (i.e. to 0.5 km) as per Quine and White (1998). In addition, a field based topex assessment was made, by recording the angle of elevation (using a clinometer) to the visible skyline at each of the eight cardinal compass directions. The sum of these eight values yielded the field-based topex score.

A GIS layer of mean annual wind speed (SEAI, 2003) was used to provide mean wind speed values for each stand. Additionally, the windzone in which each of the 118 stands was located was recorded. This windzone value was taken from Miller’s (1986) windzone map of Ireland, which divided the country into five zones, A to E, reflecting declining windiness. Miller’s (1986) zonation was based on tatter flag data from Northern Ireland, which were extrapolated across the whole of Ireland, taking account of regional variation in mean wind speeds.

The slope of the plot was also recorded during the field visit (using a clinometer), as was the elevation (using a GPS). The elevation data were verified using a DEM.

The soil type for each site was available from the Teagasc soil dataset. This was verified on site and updated if necessary. Based on this soil type, the site was assigned to one of the four soils classes shown in Table 2. In addition, a subjective assessment of the degree of waterlogging on the sites was made. This was based on a visual inspection of the extent of water underfoot and four drainage/waterlogging classes were identified: 1. Very poor; 2. Poor; 3. Good; and 4. Very Good.

The predominant land class/vegetation type to the south, east, north and west of each stand was recorded. The classes included: coniferous forest, recently clearfelled stands, water, urban, shrub, pasture, heath, and mixed forestry.

### *3.3.3 Silvicultural factors*

The ground preparation method that had been used on the site was determined by visual inspection. The methods encountered were: Pit planting, Mounding, and Ploughing. In some instances it was not possible to identify the method that had been used due to extensive undergrowth. The bearing of the mounds or plough ribbons relative to the contour was recorded as either parallel, perpendicular or oblique to the contour. The cardinal direction of tree lines was also recorded and classes included: SW/NE; S/N; E/W; and SE/NW.

A note was made as to whether the stand had been thinned or not during the field visit.

**Table 3: Summary statistics for continuous predictor variables.**

| Variable | Units | N | Mean | Standard Deviation | Minimum | Maximum |
|---|---|---|---:|---:|---:|---:|
| Slope | Degrees | 118 | 7.7 | 6.5 | 0.0 | 33.0 |
| Elevation | m | 118 | 189.2 | 104.7 | 2.0 | 384.0 |
| Stem density | # per ha | 117 | 1697.4 | 577.9 | 300.0 | 2700.0 |
| Basal Area | $m^2ha^{-1}$ | 117 | 49.2 | 21.2 | 4.0 | 111.5 |
| Yield Class | $m^3ha^{-1}an^{-1}$ | 109 | 15.9 | 4.7 | 6.0 | 26.0 |
| Wind Speed | $msec^{-1}$ | 118 | 7.9 | 1.2 | 0.0 | 9.8 |
| Top height | m | 118 | 15.1 | 4.4 | 6.0 | 28.0 |
| H:D ratio |  | 118 | 57.1 | 12.5 | 19.0 | 83.8 |
| DEM topex | Score | 118 | 6.9 | 6.6 | 0.0 | 34.0 |
| Field topex | Score | 118 | 7.1 | 6.2 | 0.0 | 29.1 |
| Mean dbh | cm | 118 | 19.8 | 5.5 | 8.0 | 35.0 |

### 3.4 Analytical procedures

The first step in the analysis was to investigate the marginal influence of each of the site, stand and silvicultural factors on the occurrence of windthrow by conducting univariate analysis. Two-way contingency tables were generated, for windthrow occurrence (yes/no) and each of the categorical variables, to determine whether the occurrence of windthrow was independent of each of those variables using the $\chi^2$ statistic. The PROC FREQ option on SAS was used to conduct these tests. Logistic regression (PROC LOGISTIC) on SAS, was used to explore the marginal relationships between the continuous variables and windthrow occurrence.

A correlation matrix for the continuous predictor variables was also generated using the PROC CORR option on SAS.

Stepwise logistic regression was then used to determine which of the predictor variables were the most important in a multi-factor model. In the stepwise process, a significance level of 0.3 was the required level to allow a variable into the model; a significance level of 0.35 was required to allow a variable to stay. The goodness-of-fit of the models tested was assessed using the Hosmer and Lemeshow test.

All predictor variables were included in the selection set for the stepwise procedure; two-way interactions between all these variables and quadratic terms for continuous variables were also allowed.

Based on the results of the stepwise selection process, those variables which were shown to be significant (i.e ($P<0.05$) were fitted in one model and odd ratios were generated for each of the significant factors. Odd ratios, in this instance, show the odds of windthrow occurring in one set of conditions versus another. SAS was the statistical software package used.

The final model had the general form:

$$p_i=\exp(\beta_0+\beta_1x_1+\beta_2x_2+......+\beta_nx_n)/(1+\exp(\beta_0+\beta_1x_1+\beta_2x_2+......+\beta_nx_n)) \text{ (Equation 1)}$$

where
$p_i$=probability of windthrow in stand i
$x_{1,}$ $x_2$ $x_n$ =independent variables for stand i
$\beta_{0,1,n}$ = parameters

# 4 Results

The primary goal of this research was to identify the factors that influenced the occurrence of wind damage in forests in the south-west of Ireland during Storm Darwin. Data collected in 118 stands were analysed. In this chapter the results of the univariate analysis, which investigated the marginal influence of each of the site, stand and silvicultural factors on the occurrence of windthrow are presented. The results of the correlation analysis are then presented. The chapter concludes with the results of the stepwise regression.

## 4.1 Univariate analysis

Wind damage was noted in 36 of the 118 stands. In all cases damage was in the form of uprooting, with trees either completely overturned, with root systems fully exposed or partially uprooted, often leaning on neighbouring trees. The marginal influence of the various factors recorded on the occurrence of windthrow is shown below.

### *4.1.1 Site factors*

The site factors investigated included soil group, elevation, wind speed, windzone, drainage, topex and slope.

*Soil Group*

Damage occurred most frequently within the peat and gley soils (Table 4). Nevertheless, the occurrence of windthrow was independent of soil group ($\chi^2$=6.895; P=0.075).

**Table 4: Windthrow occurrence by soil group.**

| **Windthrow** | **Soil group** | | | |
|---|---|---|---|---|
| | Gley | Peat | Shallow | Deep |
| No | 60% | 58% | 77% | 84% |
| Yes | 40% | 42% | 23% | 16% |
| # of sites | 35 | 26 | 26 | 31 |

*Elevation*

Stands located at altitudes above 300 m+ experienced damage more frequently that those situated at altitudes lower than 100 m (Table 5). The occurrence of windthrow was found, however, to be independent of elevation class. The absence of a relationship between the probability of windthrow occurring and elevation (expressed as the actual elevation of the sites rather than assigned a category) was also noted ($\chi^2$= 1.003; p=0.172).

**Table 5: Windthrow occurrence by elevation.**

| **Windthrow** | **Elevation (m)** | | | |
|---|---|---|---|---|
| | 0-100 | 101-200 | 201-300 | 301-400 |
| No | 83% | 56% | 75% | 64% |
| Yes | 17% | 44% | 25% | 36% |
| # of sites | 29 | 32 | 32 | 25 |

*Wind speed and windzone*

No significant relationship was found between the probability of windthrow occurring and wind speed when explored using logistic regression (P=0.666). When the effect of wind was investigated in the context of location, i.e. windzone, the results showed that stands located in the windier part of the country, i.e. the south west (Windzone A) experienced damage more frequently that stands located further east (in windzone D) (Table 6). Nevertheless, the occurrence of damage was independent of windzone (Table 4; $\chi^2$=3.646; P=0.302).

**Table 6: Windthrow occurrence by windzone**

| **Windthrow** | **Windzone** | | | |
|---|---|---|---|---|
| | A | B | C | D |
| No | 59% | 77% | 65% | 100% |
| Yes | 41% | 23% | 35% | 0% |
| # of sites | 17 | 48 | 51 | 2 |

*Drainage*

The extent of waterlogging in the sites was represented by four drainage categories ranging from very good to poor. Windthrow occurrence was not independent of the extent of waterlogging; windthrow was recorded on sites where drainage was very poor or poor, more frequently that it was on better drained sites (Table 7; $\chi^2$=13.324; P=0.004).

**Table 7: Windthrow occurrence by drainage**

| Windthrow | Drainage | | | |
|---|---|---|---|---|
| | Very Poor | Poor | Good | Very good |
| No | 63% | 47% | 74% | 84% |
| Yes | 37% | 53% | 26% | 16% |
| # of sites | 8 | 34 | 31 | 45 |

*Topex and slope*

The topex (either site based or DEM based) and slope recorded for stands had no significant influence on the probability of windthrow occurring (Table 8).

**Table 8: Windthrow occurrence by topex and slope.**

| Parameter | Odds ratio | Significance |
|---|---|---|
| Topex (site-based) | 0.988 | 0.716 |
| Topex (DEM) | 1.0273 | 0.352 |
| Slope | 0.9970 | 0.918 |

*Surrounding land class*

The surrounding land class, if any, may have an influence on the stability of adjacent stands. Results show that the land class surrounding the south and east of a forest stand to be important when considering wind damage. Stands where the predominant vegetation to the south (P=0.004) and east (P=0.010) was classed as shrub exhibited windthrow more frequently than stands with any other land class in this direction (Table 9). Occurrence of damage was independent of northern (P=0.227) and western (P=0.379) land classes.

**Table 9: Windthrow occurrence by surrounding land class.**

| **Windthrow** | **Land class surrounding southern edge** | | | |
|---|---|---|---|---|
| | Clearfell | Pasture | Shrub | Forestry |
| No | 100% | 76% | 31% | 75% |
| Yes | 0% | 24% | 69% | 25% |
| # of sites | 1 | 46 | 16 | 55 |
| **Windthrow** | **Land class surrounding northern edge** | | | |
| | Clearfell | Pasture | Shrub | Forestry |
| No | 0% | 77% | 76% | 62% |
| Yes | 0% | 23% | 24% | 38% |
| # of sites | 0 | 43 | 17 | 58 |
| **Windthrow** | **Land class surrounding eastern edge** | | | |
| | Clearfell | Pasture | Shrub | Forestry |
| No | 50% | 91% | 61% | 60% |
| Yes | 50% | 9% | 39% | 40% |
| # of sites | 2 | 35 | 23 | 58 |
| **Windthrow** | **Land class surrounding western edge** | | | |
| | Clearfell | Pasture | Shrub | Forestry |
| No | 67% | 78% | 57% | 67% |
| Yes | 33% | 22% | 43% | 33% |
| # of sites | 3 | 45 | 21 | 49 |

### *4.1.2 Stand factors*

The stand factors investigated included species, age, top height, mean dbh, yield class, stem spacing and height/diameter ratio.

*Species*

Stands comprising of conifers other than Sitka spruce were most frequently damaged, with broadleaved stands rarely exhibiting damage. The occurrence of windthrow was independent of species class (Table 10; $\chi^2$ =2.990; P= 0.224). Grouping all conifers together and comparing the frequency of windthrow occurrence by broadleaf/conifer did not change the trend ($\chi^2$ =1.729; P= 0.1885).

**Table 10: Windthrow occurrence by species.**

| **Windthrow** | **Species** | | |
|---|---|---|---|
| | Broadleaf | Sitka spruce | Other conifers* |
| No | 89% | 71% | 59% |
| Yes | 11% | 29% | 41% |
| # of sites | 9 | 27 | 82 |

* Other conifers included: Larch, Norway spruce, Lodgepole Pine, Western hemlock, Pine Contorta, Scots pine

The role of species in windthrow risk was also explored by classing stands as either mixed or single species. Wind damage was noted more frequently in homogenous stands than mixed stands, albeit not to a significant extent (Table 11; $\chi^2$ 2.990; P= 0.224).

**Table 11: Windthrow occurrence by mixed species.**

| Windthrow | Mixed species | |
|---|---|---|
| | No | Yes |
| No | 62% | 77% |
| Yes | 38% | 23% |
| # of sites | 60 | 58 |

*Crop parameters*

The age, top height, mean dbh and yield class of stands each significantly influenced the probability of windthrow occurring (Table 12).

**Table 12: Odd ratios for windthrow occurrence for crop parameters.**

| Parameter | Odds ratio | Significance |
|---|---|---|
| Age | 1.0692 | 0.001 |
| Top height | 1.32313 | 0.0014 |
| Mean dbh | 1.18412 | 0.001 |
| Yield class | 0.8860 | 0.01 |
| Basal area | 1.049 | < 0.001 |
| H:D | 1.004 | 0.823 |
| Stem Density | 0.9990 | 0.052 |

An increase in the stand age by a single year results in an increase in the odds of wind damage occurring by 1.0692. Similarly a one metre increase in top height enhances the odds of windthrow occurrence by 1.3231 and a one centimetre increase in mean dbh increases the odds of windthrow occurring by 1.1841. Windthrow risk also increases with increasing basal area. An increase in yield class by a single unit reduces the odds of wind damage.

### *4.1.3 Silvicultural factors*

The silvicultural factors investigated included ground preparation method, ground preparation bearing, ground preparation direction and thinning.

*Ground preparation method*

Three forms of ground preparation were encountered in the stands visited; ploughing, pit planting and mounding. Ploughed sites exhibited wind damage more frequently than sites prepared using mounding or pit planting (Table 13; $\chi^2$=12.130; P=0.002).

**Table 13: Windthrow occurrence by ground preparation method.**

| **Windthrow** | **Ground preparation method** | | |
|---|---|---|---|
| | Mounding | Pit | Ploughing |
| No | 72% | 67% | 40% |
| Yes | 23% | 33% | 60% |
| # of sites* | 79 | 6 | 25 |

* In 8 sites the group preparation method could not be identified

*Ground preparation direction*

The occurrence of windthrow was independent of the direction trees were planted in relation to the contour/slope of the stand (Table 14; $\chi^2$=0.717; P=0.699).

**Table 14: Windthrow occurrence by ground preparation direction.**

| Windthrow | Ground preparation direction | | |
|---|---|---|---|
| | 90 | Oblique | Parallel |
| No | 70% | 56% | 68% |
| Yes | 30% | 44% | 32% |
| # of sites* | 69 | 9 | 28 |

* In 12 sites the group preparation method could not be identified

*Ground preparation bearing*

Stands where trees had been planted in either a south-west/north-east bearing or west/east bearing, exhibited damage more frequently than those where trees had been planted at a different bearing. However, occurrence of windthrow was found to be independent of ground preparation bearing (Table 15; $\chi^2$=3.291; P=0.349).

**Table 15: Windthrow occurrence by ground preparation bearing.**

| Windthrow | Ground preparation bearing | | | |
|---|---|---|---|---|
| | SW/NE | W/E | NW/SE | N/S |
| No | 58% | 59% | 80% | 74% |
| Yes | 42% | 41% | 20% | 26% |
| # of sites* | 12 | 31 | 15 | 49 |

* In 11 sites the group preparation method could not be identified

*Thinned*

Half of the stands that had been thinned exhibited windthrow; however, windthrow occurrence was shown to be independent of thinning history at the 5% significance level (Table 16; $\chi^2$=3.317; P=0.069).

**Table 16: Windthrow occurrence by thinning.**

| **Windthrow** | **Thinned** | |
|---|---|---|
| | No | Yes |
| No | 73% | 50% |
| Yes | 27% | 50% |
| # of sites | 92 | 16 |

## 4.2 Correlation analysis

Several continuous variables had moderate to high levels of correlation (Table 17). As anticipated slope and topex, elevation and topex, age and top height all displayed moderate levels of correlation, while top height and mean DBH had the highest level of correlation, 0.74.

**Table 17: Pearson correlation coefficients for continuous predictor variables.**

| | **Slope** | **Elevation** | **Stem Density** | **Basal Area** | **Yield Class** | **Wind Speed** | **Top Height** | **H/D ratio** | **Teagasc Topex** | **Topex** | **MDBH** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Age** | 0.30421 | _NS_* | -0.45419 | 0.36428 | -0.51135 | *NS* | 0.56857 | *NS* | *NS* | *NS* | 0.656 |
| **Slope** | | 0.27224 | NS | 0.21926 | -0.20615 | *NS* | 0.24625 | *NS* | 0.43996 | 0.56459 | 0.35137 |
| **Elevation** | | | *NS* | *NS* | -0.50397 | *NS* | NS | *NS* | 0.39056 | 0.32616 | *NS* |
| **Stem Density** | | | | 0.1923 | 0.26018 | *NS* | -0.25558 | 0.284 | *NS* | *NS* | -0.50709 |
| **Basal Area** | | | | | *NS* | *NS* | 0.64047 | *NS* | 0.24288 | *NS* | 0.67212 |
| **Yield Class** | | | | | | *NS* | -0.19231 | *NS* | *NS* | *NS* | -0.21819 |
| **Wind Speed** | | | | | | | *NS* | *NS* | *NS* | *NS* | *NS* |
| **Top Height** | | | | | | | | 0.38042 | 0.27699 | *NS* | 0.74274 |
| **H/D ratio** | | | | | | | | | *NS* | *NS* | *NS* |
| **Teagasc Topex** | | | | | | | | | | 0.70127 | 0.2505 |
| **Topex** | | | | | | | | | | | *NS* |

**NS-Not significant.*

## 4.3 Regression analysis

The stepwise regression procedure was used to explore the influence of the predictor variables and the interactions between them. This stepwise process ultimately identified that only two predictor variables had a significant influence on the probability of windthrow occurring, i.e. the top height of the stand (i.e. $p < 0.05$) and the drainage class of the site (i.e. $p < 0.05$) (Table 18). The Wald Chi-square statistic was highest for top height, suggesting that this factor had the most important influence on the probability of damage. The Hosmer and Lemeshow value of 10.1669 indicated no significant lack of fit ($P = 0.2535$) for this two-factor model.

**Table 18: Analysis of effects of key predictor variables.**

| Effect | DF | Wald Chi-Square | Pr > ChiSq |
|---|---|---|---|
| Drainage | 3 | 14.2479 | 0.0026 |
| Top height | 1 | 20.3849 | < 0.0001 |

There were four drainage classes. The results suggest that the probability of windthrow is significantly higher on sites with poor drainage compared to all other drainage classes (Table 19).

**Table 19: Analysis of maximum likelihood estimates.**

| Parameter | | DF | Estimate | Standard Error | Wald Chi-Square | Pr > ChiSq |
|---|---|---|---|---|---|---|
| Intercept | | 1 | -6.9840 | 1.3350 | 27.3683 | <.0001 |
| Drainage | Very Poor (1) | 1 | 1.1958 | 0.8981 | 1.7728 | 0.1830 |
| Drainage | Poor (2) | 1 | 2.4926 | 0.6637 | 14.1065 | 0.0002 |
| Drainage | Good (3) | 1 | 1.1959 | 0.6796 | 3.0963 | 0.0785 |
| Top height | | 1 | 0.3118 | 0.0691 | 20.3849 | <.0001 |

Using the model shown in Table 19 and equation 1 from section 3.4 the probability of windthrow occurring can be plotted (Figure 3). As the estimates associated with the very poorly drained sites and sites where drainage is good were similar, the lines representing these are not distinguishable.

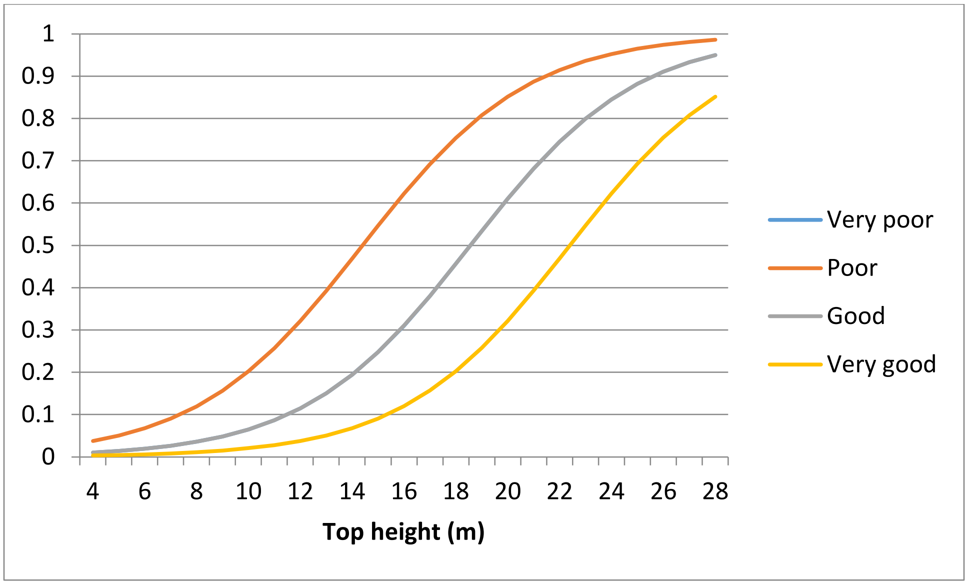

**Figure 3: Probability of windthrow occurring as a function of top height (m) and drainage class**

In this best fit model the odds of windthrow occurring increased with increasing top height (Table 20), with each one metre increase in top height increasing the odds of windthrow occurring by 1.366. Further, the odds of windthrow occurring on poorly drained sites was just over 12 times as high as it was on sites were drainage was very good; on sites where drainage was either very poor or good, the odds of windthrow occurring were almost three times that on sites where drainage was very good.

**Table 20: Odds ratio estimates.**

| Effect | Point Estimate | 95% Wald Confidence Limits | |
|---|---|---|---|
| Drainage 1 vs 4 | 3.306 | 0.569 | 19.222 |
| Drainage 2 vs 4 | 12.093 | 3.293 | 44.407 |
| Drainage 3 vs 4 | 3.307 | 0.873 | 12.527 |
| Top height | 1.366 | 1.193 | 1.564 |

# 5 Discussion

This study set out to identify the key factors that influenced the occurrence of storm damage in forest stands in the southwest of Ireland, following a series of winter storms culminating in Storm Darwin on 12 February 2014. Previous work on the topic of windthrow in Ireland has focused on a series of damage events, i.e. endemic windthrow, whereas the aim of this study was to explore what makes certain forest stands vulnerable to damage during a catastrophic event. In this discussion chapter what the findings reveal about the influence of the potential predictor variables is discussed.

## 5.1 Tree height and other stand variables

Analysis of damage from many past storm events has shown tree height to be the most consistent factor contributing to wind damage in forests (Hanewinkel *et al*., 2011), with taller (older) trees experiencing greater levels of damage than smaller (younger) trees (e.g. Pasztor *et al*., 2015; Moore and Watt, 2015; Pukkala *et al*., 2016). In the storm event studied here, top height was identified as the key influential factor; increasing top height was associated with an increasing risk of wind damage. This suggests that as the trees mature the levels of exposure increase, with greater forces being applied upon individual trees during storm events.

A number of the crop variables, i.e. basal area and mean dbh, which had significant marginal effects on windthrow, were not shown to be significant predictor variables. However, as both these variables were shown to be significantly correlated with top height, it is likely that their significant marginal influence was a reflection of the effect of top height on windrisk.

## 5.2 Drainage and soils

The second key factor identified as influencing whether a forest stand experienced windthrow was the drainage/waterlogging status of the site. Analysis from many storm events has shown soil type and their associated water levels to be important factors contributing to wind damage in forestry (Quine *et al*., 1995; Schmidt *et al*. 2010). In the storm event analysed in this study, the extent of waterlogging in the sites (as reflected in the drainage variable), rather than soil type, emerged as the key factor influencing the probability of storm damage. Soil types are characterised by a variety of different elements including moisture, aeration and physical characteristics (Duerr, 1975). The results of this study suggest that the key characteristic was the ability (or inability) of soils to channel water away from the site, particularly after an extended period of wet weather. The fact that soil group, *per se,* was not a significant factor suggests that a prolonged deluge of rain will lead to poor drainage and an accumulation of surface water, regardless of specific soil characteristics. This finding agrees with that noted by Schmidt *et al.* (2010), who found that the probability of wind damage occurring increased significantly on a variety of soil types as the degree of waterlogging increased. Quine *et al.* (2005) and Dobbertin (2002) attribute the probability of wind damage to several soil characteristics including mass of the soil associated with the roots of the tree, soil depth and stone content, which may all be good indicators of the probability of endemic wind damage. However, in the case of catastrophic wind damage resulting from extreme levels of precipitation and very high winds over a short period, it would seem that these variables become less relevant.

While a general trend of increasing windrisk as drainage dis-improved (and waterlogging increased) was noted, an anomaly with respect to the trends in very poorly drained compared to poorly drained sites was noted, with windthrow occurring more frequently in the former rather than the latter. There is no obvious explanation for this. The assessment of drainage class and extent of waterlogging was subjective and hence distinctions between these two classes may be blurred, especially as the field work was often conducted during very wet weather. Perhaps a more accurate representation of drainage could have been obtained if the record was taken during a period that represents mean precipitation for the time of year, if possible.

## 5.3 Species

Previous wind risk studies suggest that coniferous species are at greater risk than broadleaves due to their higher drag coefficient, caused by their large dense evergreen foliage (Dobbertin, 2002). The findings of this study are in agreement, with the frequency of damage within the coniferous stands greater than in broadleaf stands, albeit not to a statistically significant extent. However, it is important to note the small number of stands classed as broadleaf included in the sample (i.e. 7 sites, 6% of cases). Broadleaf forests accounts for 26% of the area of the national forest estate; but only account for 17% of the Coillte estate (Forest Service, 2013). Coillte forests accounted for the vast majority of sites visited. Furthermore, broadleaf forests are more likely to be found on better quality sites than those represented within the study area. The sampling approach used in the study, where the population was stratified according to soil type and elevation and with an over emphasis on Coillte stands, all help explain the relatively low incidence of broadleaf stands in the sample.

Previous studies have found that mixed stands i.e. stands containing more than one species, have different structural dynamics than that of a homogenous stand, making them more tolerant to high wind speeds. Such a trend was noted in the data collected in this study although not to a statistically significant extent.

## 5.4 Thinning

Previous studies have documented the importance of silvicultural operations in influencing windthrow risk. Amongst the operations most commonly examined is thinning, with research showing that the timing, type and intensity of thinning all significantly influence the probability of wind damage (e.g. Quine *et al*., 1995). However, capturing information on these aspects of thinning is challenging and requires detailed silvicultural records to be available. In this study only information on whether thinning had occurred or not (at least once) was available. The trend, in the univariate analysis, was that a greater proportion of thinned stands exhibited windthrow than unthinned stands. However, in the modelling process, the occurrence of thinning was found not to be a significant predictor of windthrow. This would suggest that thinning was associated with one (or more) of the key predictor variables, such as top height or drainage. An examination of the mean top height of thinned versus unthinned stands confirmed that unthinned stands on average had a mean top height of 14 m, while the thinned stands had a mean top height of 19 m ($P < 0.001$), while no significant association was found between drainage and thinning. This finding suggests that the significant marginal effect of thinning was in fact an indicator of the influence of greater top height rather than a direct reflection of the effect of thinning on canopy smoothness etc. This finding concurs with that of Schutz *et al*. (2006), who observed that as wind speeds increase to extreme velocities, the role that forest management plays, such as thinning occurrence, intensity and timing, becomes less relevant when considering the potential of windthrow.

## 5.5 Ground Preparation

The method used to cultivate the ground in advance of tree planting (i.e. ground preparation method) has not commonly been examined in windrisk studies, nevertheless in the small number of Irish studies that have previously been conducted, it has been considered. This is because windthrow in Ireland has been linked with ground preparation methods, such as ploughing; alternatives were introduced in the 1980s and were expected to lead to greater stability (Hendrick, 1989). This study provided the first opportunity to test this assumption, as the stands established on mounded sites were reaching a critical height in relation to windthrow at the time Storm Darwin occurred. The results from the univariate analysis showed that the ground preparation method had a significant marginal influence on the occurrence of damage. Stands on ploughed sites were less stable and experienced damage more frequently than stands on sites prepared with other methods. However, similar to the trend noted with thinning, ground preparation was not a key predictor of risk. This finding can be explained by the fact that stands on ploughed sites were generally taller than those on mounded sites (16.5 m vs 14.5 m), reflecting the relatively recent introduction of the latter method of ground preparation. Additionally, the ground preparation method was not independent of drainage ($P < 0.001$), with the majority of ploughed sites being associated with poor or moderate drainage, while the opposite was true for mounded and pit planted sites.

### 5.6 Neighbouring effect

Studies suggest that the surroundings of a forest on the upwind side can play a significant role in the path the wind takes over or through the forest and hence can potentially influence windthrow risk (Gardiner *et al.,* 1997; Marcolla *et al.,* 2003; Dupont and Brunet, 2008, Queck and Bernhofer, 2010). Scott and Mitchell (2005) expanded the investigation into the role of surrounding vegetation by taking into account the distance between the forest edge and the area of land surrounding it. In this study an effort was made to evaluate the neighbouring effect, in a simplistic way, by noting the land classes in the four cardinal directions surrounding a forest. The univariate results suggested that the land classes found in the south and east were associated with occurrence of windthrow. For example, in the case of the vegetation to the south of the forest stands, forests surrounded by shrub were more likely to experience windthrow in comparison to those surrounded by other vegetation types. However, further investigation of these findings found that once again they were in fact a reflection of differences in top height, with the mean top height in shrub surrounded stands that experienced windthrow much higher than the mean top height in the shrub surrounded stands that did not.

### 5.7 Wind speed, elevation, topex, slope, windzone

The characteristics of the wind that a forest experiences will, along with the characteristics of the forests, combine to determine windthrow occurrence. In this study the only wind data available were the mean wind speed values from the Wind Atlas of Ireland. Additionally, data on a number of site characteristics, which would act as potential indicators for the winds experienced by the stand, were recorded. Windthrow risk was found to be independent of mean wind speed. This finding agrees with those from other windrisk studies, which suggest that broad scale mean wind speed data are uninformative when trying to understand the phenomenon of windthrow (Scott and Mitchell, 2005). Information on gusts would have been more informative, however this was not available. No significant relationship between windzone and windthrow occurrence was noted although stands in zone A, the most south westerly zone of the country, experienced damage more frequently. Again the wind zone map is based on mean wind speed data along with some tatter flag data from Northern Ireland which were extrapolated across the whole of Ireland (Miller, 1986). This represents broad scale data which, as highlighted above, can be uninformative when explaining windthrow.

No significant relationship between windthrow occurrence and elevation, topex, or slope was found. There have been conflicting findings in relation to elevation and windthrow risk, with some finding a positive relationship, others a negative relation and finally some have found no relationship with windthrow occurrence. The high correlation between elevation and topex would suggest that stands become more exposed as elevation rises, however topex was shown to have no significant effect on the occurrence of windthrow. Previous studies suggest trees that are planted in highly exposed areas adapt, with thicker stems able to support increased levels of wind loading (Zeng *et al*., 2007, Forsell *et al*., 2011). This may suggest that during catastrophic wind events, highly exposed stands on steeper slopes with large topex values are able to tolerate wind loading, to a degree, while stands in more sheltered, flatter land have not been adapted to withstand extreme winds and are therefore more susceptible to wind damage.

## 5.8 Considerations and limitations associated with the methodology

Large scale storm damage analyses usually have a limited range of information on the forest and management attributes; in contrast a case study approach, such as that conducted here, provides that opportunity. However, a limitation often associated with the latter approach is its “restricted spatial representativeness” (Albrecht *et al*., 2012, p. 230). The rationale for using a case study approach in this study was that it enabled the influence of stand and silvicultural factors, in particular thinning, to be investigated. Selecting a relatively large case study area and adopting a stratified random sampling approach went some way to addressing any potential restricted spatial representativeness.

One of the primary limitations of this study was that it was not possible to confirm whether the windthrow, recorded in the study, occurred during Storm Darwin. The timing of field work, along with the lack of pre-storm data on the stands contributed to this limitation. Field work commenced in October 2015, 20 months after Storm Darwin. Ideally, field work would have commenced as soon after the event as possible, but for a number of reasons, not least because funding to carry out the research was only made available one year after the Storm, this was not possible. As a result, some clearance of windblown areas was already underway. Nevertheless, it was possible to record the number of uprooted stumps left on the site where this occurred, hence the estimate of the extent of damage is considered reliable. Furthermore, as the modelling process used the occurrence of damage (rather than the percentage damage) as the dependent variable, the lack of precision in estimating the extent of damage is not so important.

Another factor that delayed the field work was the difficulty gaining access to the forest stands. In the case of Coillte stands access could be granted quickly by contacting regional managers prior to site visits, often permission to access 20 or more sites could be granted in a single phone call. Access to private stands however, proved to be challenging. The names of the owners were not available from the database; only the location of the stand was given. Due to Data Protection laws, the Forest Service was not permitted to release the names of the owners without their permission. Rather than wait for this to take place and run the risk of some owners refusing to allow access to their stands, foresters operating the area where the private forests were located were contacted to see if they could identify the owners. This inevitably took some time.

The use of the RapidEye dataset to verify whether the windthrow that was observed in the field had occurred during Storm Darwin was limited. First, the time gap between the capturing of the RapidEye data and Storm Darwin was approximately four months. Furthermore, while this dataset had proved useful for classifying the scale of damage caused by Storm Darwin at a national level, at individual stand level it was less accurate. In small and medium sized stands, particularly in the fragmented private forest estate, Rapideye data were often inaccurate, in some cases overestimating the extent of damage, while in other cases classifying stands as damaged when no evidence of damage could be observed in the field. It had been intended that in the

WINDRISK project, in which the study outlined in this thesis is part of, an analysis of large scale storm damage provided by the RapidEye would be conducted. However, the inaccuracies noted with the stand level data provided by this imagery raises questions about suitability of these data for further investigation.

There continues to be gaps in the data available on a number of variables that potentially influence windthrow risk. As outlined above, the case study approach was used in order to facilitate the investigation of the influence of silvicultural variables, such as thinning practice and ground preparation. However, records on silvicultural activities within stands are rarely kept (as is the case in private stands) or are kept in different databases to that of inventory data (as occurs in Coillte), which makes interrogation of these datasets challenging. While all forest owners must obtain a felling licence if they wish to thin their stands, and the Forest Service retains records on these applications, there is no follow-up check that in fact thinning did occur and no record is kept of the precise timing of the thinning.  The latter consideration has shown to be very important in previous windrisk studies. Along with a lack of silvicultural data, there continues to be a lack of stand level wind speed data and in this study only coarse resolution data were available. This challenge is not unique to Ireland, but it remains one the key constraints to understanding the phenomenon of windthrow.

While the primary aim of this thesis was to identify the key factors influencing the risk of windthrow following a catastrophic storm, the two-factor model generated could potentially be used by forest managers to provide an indication of the probability of windthrow. To use it they would require information on the top height of the stand and an assessment of the extent of waterlogging on the sites. While the latter data are potentially available from databases, the former would require an on-site assessment which would limit the potential use of the model. Alongside these limitations, given the time involved in the field work, only a limited number of stands could be visited. This meant that it was not possible to have an adequate number of stands to allow a splitting of the dataset into a model building dataset and a model testing dataset. Thus it was not possible to validate the two-factor model produced.

# 6 Conclusion

The study presented investigates how stand, site and silvicultural factors influenced the occurrence of windthrow in Irish forests following a catastrophic storm. The study identified that two factors; top height and drainage, were the most significant parameters influencing windthrow occurrence. The study also found that the occurrence of windthrow was not influenced by stand management factors such as species selection, thinning and ground preparation. This would suggest that during catastrophic storms such as Storm Darwin, windthrow is inevitable once trees reach a critical height in poorly drained stands.

In light of the above findings it is difficult to provide forestry stakeholders in Ireland with guidance as how the minimise the risk of storm damage. Many studies suggest that thinning at an earlier stage may allow trees to adapt to windy environments (Quine, 1995), while other indicate that maintaining a high stocking density allows the stand to withstand high winds (Greene *et al.,* 1992). Indeed it seemed that in this study a cautious approach to forest management was already being implemented, with many stands not been thinned on high elevation sites.

Meteorological advances allow for extended forecasts, which enable local authorities to limit damage where possible. Such forecasts are of little use to the forestry industry, even with advanced warning it seems little can be done to limit damage to established stands which have reached a critical height, in the face of catastrophic storms.

The lack of prior research conducted in Ireland means that it is not possible to compare the findings of this study with any of the previous catastrophic storms experienced in Ireland. Although Storm Darwin brought severe wind speeds, exceeding any other in living memory, the high levels of rainfall leading up to this period influenced the amount of damage, with this studying finding that waterlogging significantly increased the potential of windthrow. Perhaps the degree of damage may have been different if the weather had been dry and settled, leading up to Storm Darwin.

Research conducted throughout Europe suggests that these types of catastrophic storms are likely to become more frequent in the future (Haarsma *et al.,* 2013). This study should provide a good platform from which repeat studies may be conducted, allowing for a better understanding of windthrow occurrence during severe winds.

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