- *Wind is the most significant abiotic factor causing damage to forests in Ireland.*
- *Catastrophic windthrow occurs as a result of storms of unusual severity; endemic windthrow is the uprooting of trees in forests during normal winter storms.*
- *Windthrow risk increases with increasing crop height; conifers are at greater risk of windthrow than broadleaves.*
- *Forests planted in free draining soils such as brown earths are at lower risk of windthrow than those planted in gleyed and peat soils.*
- *Thinning late increases the risk of windthrow; thinning early can increase stability.*
- *The creation of new edges increases the risk of windthrow in the newly exposed stand.*

COFORD
Department of Agriculture, Food and the Marine, Agriculture House, Kildare Street, Dublin 2, Ireland.
Telephone: +353 1 607 2487
Email: fsd@agriculture.gov.ie
www.coford.ie

An Roinn Talmhaíochta, Bia agus Mara
Department of Agriculture, Food and the Marine

Understanding and managing windthrow

Authors: Dr. Áine Ní Dhubháin[1] and Dr. Niall Farrelly[2]

Introduction

Wind is the most significant abiotic factor causing damage to forests in Ireland. It results in the uprooting (windthrow/windblow) or breakage (windsnap) of trees leading to significant financial losses for forest owners (Moore et al., 2013). Wind is also a major disturbance factor at the wider European level where it accounts for more than half of all the damage to forests by volume (Gardiner, 2013).

Two main categories of windthrow are recognised: catastrophic and endemic. Catastrophic windthrow occurs as a result of storms of unusual severity. Over the past 40 years a number of such storms have caused considerable damage to forest stands in Ireland. In 1974, a storm classed as the most damaging of the 20th century, passed over Ireland, with the volume of windthrown material being equivalent to 50% more than the entire annual harvest at that time (Keane cited in Fitzpatrick, 2000). Towards the end of the 1990s two further 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. It was described as a 1 in 20 year storm event, during which areas in the south-west of Ireland experienced wind speeds (i.e. 120-160 kmh^{-1}) exceeding any other in living memory (McGrath, 2015). An estimated 8,000 ha of forest land was affected by this storm (McInerney et al., 2016). Endemic windthrow is the uprooting of trees in forests during normal winter storms. Once this type of windthrow begins it may extend rapidly and often results in the premature clearfell of entire stands of trees (Savill, 1983).

What are the consequences of storm damage in forests?

Damage to timber is one of the main consequences of storm damage. During the period 1971 to 1998 windthrown volumes accounted for 15.1% of the total volume sold during that period (Fitzpatrick, 2000). More recent statistics (covering the period between 1992 and 2015) from Coillte Teo indicate the annual average volume of windblown timber sold was 241,000 m^3 (Anon, 2016 cited in McInerney et al., 2016).

After major storms the price of timber often falls (Schuck and Schelhaas, 2013) arising from an oversupply of timber onto the market and/or a reduction in the quality of the timber salvaged (Schwarzhauer and Rauch, 2013). An increase in

1. Forestry Section, School of Agriculture and Food Science, University College Dublin
2. Teagasc, Agriculture and Food Development Authority

costs due to unscheduled thinning and clear-cutting operations, and problems associated with forestry planning and logistics are additional consequences of windthrow. Indirectly, windthrow can result in an increase in the incidence of disease outbreaks, as the affected areas are ideal breeding grounds for insects and fungi (Peltola, 2006).

What influences the occurrence of windthrow?

The occurrence of windthrow is influenced by weather, site and crop factors. Management factors also play a role.

Weather and site factors

Sustained mean wind speeds exceeding 25-29 $msec^{-1}$ can cause considerable damage to trees irrespective of soil type (Savill et al., 1997). Gusts of 22 to 27 $msec^{-1}$ can cause trees to be uprooted on soils where rooting is restricted (ibid). It is the gust speed that is most relevant as trees usually fail under the action of gusts rather than mean wind speeds (Brunet, 2013). Greater levels of exposure and higher wind speeds are experienced at higher elevations resulting in a greater risk of wind damage (Pasztor et al., 2015). Wind damage tends to occur more frequently in stands located on aspects that correspond to the prevailing wind direction (Scott and Mitchell, 2005); in Ireland the prevailing winds come from the south-west (Keane and Sheridan, 2004). Wind speeds can also vary greatly at local level and are influenced by landscape features and topography. In complex terrain, topography can alter the direction and speed of the wind; with wind being funneled through valleys and accelerating over hill-tops (Quine et al., 1995). The roughness of the terrain also influences wind speed; as it increases the mean wind speed decreases, while the maximum gust speed increases (Logue, 1989). Storms with mean speeds of 15 $msec^{-1}$ can result in gusts of up to 20 $msec^{-1}$ on flat land and 27 $msec^{-1}$ on wooded land (Keane and Sheridan, 2004).

Crop factors

The two key crop factors that influence the risk of damage occurring during storms are the height of the trees in a stand and the tree species (Albrecht et al., 2012). As tree height increases the force that is exerted on a tree, for a given wind speed, also increases; taller, slender trees are therefore vulnerable to windthrow. Windthrow risk is also associated with the ratio of tree height to tree diameter (H:D) and the H:D ratio is often used as an index of stability (Navratil, 1995, cited in Wang et al., 1998). Trees with a H:D ratio above 80 are most susceptible to damage by wind (Wonn and O'Hara, 2001).

Tree species differ in terms of their vulnerability to storm damage as a result of differences in canopy characteristics and the quality of root anchorage. Due to their stiffer foliage conifers exert a greater drag on the wind than broadleaves (Quine et al., 1995). Additionally broadleaves lose their 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). Among the conifers spruces appear to be the most vulnerable (Hanewinkel et al., 2013).

The rooting system of a tree is governed by the characteristics of the soil in which it is planted; hence soil type plays an important role in determining the overall tree stability (Sutton, 1969). On free draining soils such as brown earths, deep rooting can occur; whereas on gleyed and peat soils rooting depth is often restricted by impeded drainage. The occurrence of windthrow in Sitka spruce stands established in gleyed and peat soils was found to be higher than in those planted in brown earths (Ní Dhubháin et al., 2001). In general, the waterlogging of soils can affect the rooting characteristics of trees and negatively affect the stability of forest stands.

Management/silviculture factors

Thinning disrupts the canopy of a stand, increasing its roughness which temporarily destabilises the stand (Albrecht et al., 2012). It also allows wind to penetrate the stand, exposing trees, that relied on mutual support from neighbouring trees, to higher wind forces (Locatelli et al., 2016). However, if carried out at an early stand age, thinning can increase the stability of trees (Albrecht et al., 2012). This has been attributed to the increased growing space for trees promoted through thinning which improves the development of structural roots and thus anchorage and stem stability (Hanewinkel et al., 2013). A thinned stand does regain stability but the length of time this takes depends on the growth rate and the age of the stand at the time of thinning (Cremer et al., 1982), and can vary from 5 to 10 years (Peltola et al., 2013). A no-thinning regime is often adopted in exposed areas; however in such stands trees develop very large H:D ratios with short crowns which are highly susceptible to wind damage and the loss of the entire stand can occur (Cameron, 2002). Mason and Valinger (2013) conclude that in the long-term a series of thinning operations that commence early in the life of a stand can lead to sturdier and better anchored trees leading to a reduction in vulnerability to wind damage.

Another silvicultural factor that can influence the stability of trees is the method of ground preparation used. In Ireland, ploughing was the most common method of site preparation until the 1980s (Hendrick, 1999). Trees planted in ploughed sites were unstable (MacKenzie, 1976) as the roots were often confined to the plough ribbon and their spread restricted on the side of the plough furrow (Hendrick, 1989). 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).

Trees growing at the edge of a stand adapt to the increased levels of exposure experienced there; they tend to be less tall but have greater diameters (i.e. have a lower H:D ratio) than stems further in and thus are more stable. These edge trees often withstand wind speeds that cause damage a few tree heights in. The removal of these trees and the creation of new edges, sometimes referred to as brown edges, exposes trees which have not been adapted to deal with the increased level of exposure. These trees become especially vulnerable during stormy condition (Forsell et al., 2011).

What can be done to minimise windthrow risk?

The previous section outlined how a number of factors influence windthrow risk. However, the influence of these factors varies over time as forest stands grow and develop; the factors also interact to influence windthrow risk. This is important to bear in mind when considering how to manage stands to minimise windthrow risk. Also some of the factors can be controlled by management, others not. Nevertheless, the following is a list of some actions that can be taken to reduce the risk of windthrow occurring:

- Avoid exposing tree/stands by creating a new edge; fell to an established edge (such as a road, ride-line or a very young stand);
- Removal of green edges for timber stacking should be discouraged as this increases windthrow risk;
- Break an iron-pan using ripping;
- Consider using mole ploughing on suitable sites (e.g. surface water gleys with adequate slope);
- Drain wet hollows (Mason and Valinger, 2013);
- Avoid delayed thinning; thin on time or early if possible;
- The orientation of planting lines should be the same as that of the prevailing wind;
- Create a transition zone 30-50 m on the windward edge of a stand with a mixture of species and spacing so that the wind is gradually filtered through the trees rather than being forced upwards (Mason and Valinger, 2013);
- Minimise damage to roots when undertaking harvesting and extraction operations during thinning (Quine et al., 1995);
- Serious consideration should be given to leaving areas unplanted in the afforestation programme for the purposes of road construction as this will alleviate risk.

Research conducted in Ireland

In Ireland, research on the topic of wind damage in forest stands has employed both mechanistic and empirical approaches. The mechanistic work has been in the form of tree pulling experiments carried out to assess individual tree stability. Both Hendrick (1989) and Rodgers et al. (2006) evaluated the effect of different cultivation methods on the stability of Sitka spruce using monotonic testing. They found that the mean overturning moment of trees on mole drained plots was significantly higher than that on sites where furrow ploughing had been applied. Most recently, González Fernández (2017) explored how thinning intensity and the timing of thinning influenced the critical overturning moments of Sitka spruce trees.

The empirical work on windthrow in Ireland has focused 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. Ní Dhubháin et al. (2001) developed a model using empirical data to predict the probability of windthrow occurrence in Sitka spruce stands in Ireland. This model was updated some years later (Ní Dhubháin et al., 2009) when additional data became available; the model includes the following factors: top height, the regional location of the stand, whether the stand had been thinned or not; the soil type, and site elevation. Most recently Gallagher (2017) identified that the key factors that influenced the occurrence of windthrow in forest stands during Storm Darwin were the top height of stands and the extent of waterlogging in the soils.

Conclusion

Increases in extreme wind speeds (Nolan et al., 2012) are predicted for Ireland and the winters are projected to become wetter (Steele-Dunne et al., 2012). These changing climate conditions combined with a developing forest estate may result in greater amounts of storm damage. Research suggests changing management practices according to the recommendations given above will increase the resilience of a forest to normal winter storms. However, the influence of forest management (e.g. thinning intensity and timing) is less relevant for forests that lie in the track of an extreme storm (Schutz et al., 2006). In these circumstances reducing rotation lengths may help alleviate windthrow risk, however the financial implications of adopting such an approach would need to be fully investigated.

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