The influence of thinning on tree stability in Sitka spruce (*Picea sitchensis* (Bong.) Carr.).

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Abstract

Wind is the most significant abiotic factor causing damage to forests in Ireland. Every year winter storms are experienced; once every 10-20 years severe storms occur. The strong winds associated with these storms result in the uprooting and breakage of trees, leading to negative economic consequences for forest owners. Empirical studies have identified a range of factors influencing windthrow risk; among these are the intensity and timing of thinning interventions. In this study the influence of these factors on the tree stability is explored.

A tree pulling experiment was undertaken in a Sitka spruce stand that had been planted in 1995 in the north-west of Ireland. Three thinning treatments were applied to three plots each in the stand in 2010: a light thinning; a medium thinning; and a heavy thinning (involving the removal of 20%, 32%, and 38% of the average stand volume respectively). A second thinning intervention took place in the nine plots in 2015. A further treatment which was assigned to three additional plots in 2013 represented a delayed medium thinning. There was also an unthinned control. Using a winch system, four trees of mean diameter at breast height were pulled in each of the 15 plots. The mode of failure was noted. The force and displacements were recorded and the critical turning moment for each tree was calculated. Additional characteristics of the pulled trees were recorded including stem, crown and root parameters. Some plot characteristics, such as basal area and stems per hectare and the water table depth, were also noted.

Of the 60 trees that were pulled, 36 uprooted and 24 snapped. A higher percentage of trees snapped in the unthinned and medium thinned plots compared to the heavy, light and medium delayed thinning treatments; however, these differences were not statistically significant. Maximum root depth and root plate height were the key variables influencing the mode of failure; trees that were more deeply rooted and had larger root plate heights were more likely to snap than to be uprooted. Trees in thinned plots had higher critical turning moments than trees in unthinned plots. Trees from the plots that had received a medium thinning also had higher critical turning moments than those from plots where the medium thinning had been delayed. However these differences were not statistically significant. Tree weight and root plate width were the key variables that influenced the critical turning moment of the trees.

Bending strength was recorded for the trees that snapped. This parameter was not influenced by the timing and intensity of thinning; additionally none of the tree variables were shown to be associated with this parameter.

Some differences in tree characteristics arising from the thinning treatments were also evident. Overall, trees in the plots that had received a medium or heavy thinning (not delayed) had on average greater diameters (at breast height, at 3 m and at 6 m) so lower height/dbh ratios; they also had wider and deeper crowns hence had lower centres of gravity than those from the unthinned plots. No significant differences were noted between the parameters of trees in plots where a delayed medium thinning had been applied and those where the medium (on time) thinning was used.

The findings confirm that even after only one thinning intervention thinning is already having an impact on some tree parameters that ultimately will affect tree stability. The trends in the data also suggest that thinning (and increasing intensity thereof) is increasing critical turning moment. However, this impact is not yet sufficient or consistent enough to be reliable. Further testing is recommended following future thinning interventions to see if these initial trends hold true.

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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”.

Gonzalo González Fernández

1 Introduction

1.1 Background

At the beginning of the 20th century, approximately 1% of the land area of Ireland was forest. Arising from a series of afforestation programmes, the percentage forest cover has increased to 10.5% (Forest Service, 2013), with 47% of the forest area in private ownership. The main species used in this afforestation process was Sitka spruce (*Picea sitchensis* (Bong.) Carr.). The species originates from the north-west Pacific coast of North America and it is suited to the soil and climatic conditions of Ireland (Savill *et al*., 1997). Originally Sitka spruce was planted in mixture in Ireland with other species such as larch (*Larix spp.)*, western red cedar (*Thuja plicata* Donn ex D. Don), pine species (*Pinus sylvestris* L. and *Pinus contorta* Douglas ex Louden) and Norway spruce (*Picea abies* (L.) Karst); from the 1950's it was planted in monoculture. O'Flanagan and Bulfin (1970) estimated that by the end of the 1950's the area covered by Sitka spruce was 22,471 ha (22.5% of the total forest area). By the late 1970's, this had increased to 110,753 ha (49% of the forest area) (Purcell, 1977), making Sitka spruce the most common tree species in Ireland.

Until the 1970's Sitka spruce was most commonly planted on peatlands reflecting the quality of land that was available for afforestation by the State. However, during the 1980's, as private sector afforestation developed, incentivised by the availability of EU co-funded subsidies, the range of soil types in which the species was planted increased to include gley soils. This type of soil, although more fertile than peatlands, has poor drainage which leads to waterlogging.

The tendency to plant Sitka spruce in a wider range of soils continued in the following years, helped by new afforestation schemes and the fact that it had been shown to grow well on a wide range of soils and site conditions in the country (Farrelly *et al.,* 2009). Sitka spruce continues to be the most important commercially grown tree species in the Republic of Ireland accounting for 52.3% of the forest estate (Forest Service, 2013).

1.2 Windthrow problem in Ireland

Atlantic depressions pass over Ireland and Britain every year resulting in these countries experiencing a more severe wind climate than their neighbours (Cook, 1985). The depressions, which move eastwards, often bring heavy rainfall. On the south and west coasts of Ireland, 25 gale days (i.e. days with at least one occurrence of a 10 minute wind reaching 17.2 ms^{-1} (Keane and Sheridan, 2004)), on average, are recorded annually, while inland counties in Leinster experience, on average, 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.

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. The most obvious manifestations of this damage are uprooting (referred to as windthrow) or breakage of stems (windsnap), the former being more common than the latter (Quine *et al*., 1995). From a management perspective two main categories of windthrow are recognised: catastrophic windthrow and endemic windthrow. Catastrophic windthrow occurs as a result of storm conditions of unusual severity (Miller, 1985). Historical climate records indicate that severe storm conditions can be expected at 10-15 year intervals in Ireland (McInerney *et al*., 2016). Such storms can cause damage in both unstable forests and forests planted in well-drained soils with good root anchorage, with stem breakage being more common in the latter (Miller, 1985). Endemic windthrow occurs more regularly and although it happens on a smaller scale (Stathers *et al.,* 1994), it has a greater impact on the forest as it spreads progressively over several years, threatening the entire forest (Quine and Bell, 1998).

Loss of timber is one of the main consequences of wind damage. Windthrow statistics for Ireland for the period 1971 to 1998 show that windthrown volumes accounted for 15.1% of the volume sold during that period (Table 1). More recent statistics from Coillte Teo.[1] indicate annual average invoicing levels for windthrown material of 241,000 m^3 between 1992 and 2015 (Anon, 2016 cited in McInerney *et al*., 2016). After major storms the price of timber falls (Schuck and Schelhaas, 2013). An increase in costs due to e.g. unscheduled thinning and clear-cutting, and problems associated with forestry planning are additional consequences of windthrow. Indirectly, windthrow can increase disease attacks, as the affected areas are ideal breeding grounds for insects and fungal outbreaks. The risk of fire or erosion increases as well while the landscape quality and the wildlife habitat decreases (Peltola, 2006).

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

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	7.0
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 Teoranta. 1991-1998

1.3 Research objective

The last major storm to hit Ireland was storm Darwin. It occurred on the 12th of February 2014. During that storm areas in the south-west of Ireland experienced wind speeds (i.e. 120-160 kmh^{-1}) exceeding any other in living memory (McGrath, 2015). It was estimated that 8000 ha of forest land was affected by this storm (McInerney *et al.*, 2016). Shortly after the extent of the damage was known the Department of Agriculture, Food and the Marine invited researchers to submit a research proposal to identify the factors that influence the risk of wind damage. The research described in this thesis was undertaken as part of the successful research proposal, i.e. WINDRISK.

Empirical studies have shown that a range of factors, including thinning practices, influence stand stability (e.g. Cremer *et al.,* 1982; Savill, 1983; Gardiner *et al.*, 1997). The objective of this research is to determine how thinning intensity and the timing of thinning influences individual tree stability.

2 Literature Review

Wind has a variety of impacts on trees and forests (Savill, 1983). This chapter focuses on literature relating to windsnap and windthrow. It begins by describing the mechanics of tree failure. It then describes the approaches that have been used to understand and model windthrow risk. An overview of the factors that this modelling work has identified as influencing windthrow and tree stability is then given. How one of these factors, i.e. thinning influences crop parameters is then reviewed. The chapter concludes with a brief review of research previously conducted in Ireland on windthrow and tree stability.

2.1 Mechanics of tree failure

Tree failure (i.e. uprooting or snapping) occurs when the horizontal forces on a tree are transmitted down the trunk to create a stress that exceeds the resistance to breaking or to turning of the root/soil system (Stathers *et al.,* 1994). When the resistive forces of the stem are exceeded, the tree will snap; and when the resistive forces of the soil or roots are exceeded, the tree will uproot. Peltola and Kellomaki (1993) described these forces in detail and show how the horizontal forces from wind on tree crowns and stems ($F_1(z)$) (N) and the displaced mass of the crown and stem ($F_2(z)$) (N) combine to cause a tree to fail where:

$$\boldsymbol{F_1(z) = \tfrac{1}{2} \cdot C_d \cdot \rho \cdot u\,(z) \cdot A(z) \cdot z} \quad \textbf{(Equation 1)}$$

and: C_d is the drag coefficient of the crown (dimensionless); ρ is the density of the air (kgm^{-3}); $u(z)$ is the mean wind speed (ms^{-1}); $A(z)$ is the projected area of the crown perpendicular to the direction of the wind (m^2) and z is the height of the stem (m).

$$\boldsymbol{F_2(z) = M(z) \cdot g} \quad \textbf{(Equation 2)}$$

where: $M(z)$ the mass of the height increment (kg) and g is the gravitational acceleration (ms^{-2}) (Peltola and Kellomaki, 1993; Stathers *et al.,* 1994; Peltola, 2006). Once both forces are transmitted down the stem they create a turning moment, also known as bending moment ($BM_{max}(z)$) (Nm) which can be represented as the sum of Equations 1 and 2, i.e.

$$\boldsymbol{BM_{max}(z) = F_1(z) \cdot z + F_2 \cdot x(z)} \quad \textbf{(Equation 3)}$$

where: z is the height on the stem (m) and x(z) is the horizontal displacement of the stem from the upright position (m), which is assumed to be directly proportional to the wind force acting on the tree and inversely proportional to the stiffness of the stem (Peltola and Kellomaki, 1993; Peltola, 2006).

2.2 Windthrow risk models

Damage to trees by strong winds threatens the productivity of managed forests (Quine, 1995) and the potential economic and ecological impacts of windthrow require that forestry advisors continually have updated information about windthrow risk factors (Schaetzl *et al.,* 1989). Numerous studies have been conducted to help provide such information. Often the output of these studies includes models that can be used by forest managers as decision support tools to minimise or avoid the risk of wind damage. These models can be classed as observational, empirical, mechanistic or hybrid mechanistic-empirical.

Booth (1977) and Miller (1985) developed an observational model, i.e. the windthrow hazard classification (WHC), for Great Britain. The WHC took into consideration four site features: the windiness of the regional climate; site elevation; topography; and soil conditions. This classification provided estimates of the height at which wind damage would be expected in thinned and unthinned stands. A criticism of this WHC system is that it considers the critical height of a stand, i.e. the height at which windthrow commences rather than terminal height which is the point the stand has experienced significant damage. It is also considered to be pessimistic and predicts damage to occur at a too low height (Quine, 1995). The WHC was based on expert judgement and the contributions of the factors to risk were based on a subjective assessment.

Empirical models based on previous damage data have also been used to predict future wind damage (Hale *et al.,* 2015). Such models are typically based on regression equations that relate windthrow occurrence (yes/no) and/or severity (percentage stand damage) to site, stand and/or tree attributes. However empirical models need a large amount of data and might only be useful for the region where the data were collected (*ibid*).

Mechanistic models analyse the mechanics involved in stem breakage and/or uprooting of trees. The output of such models is usually an estimate of the critical wind speed, i.e. the speed at which the tree will snap/overturn (Gardiner *et al*., 2008). Mechanistic risk modelling then uses this information in conjunction with information on local wind climatology to estimate the probability of wind damage (Hanewinkel *et al*., 2011). Static-pulling, tree swaying or wind tunnel experiments are typically used in mechanical modelling (Gardiner *et al*., 2008), Critical wind speeds are derived from loading and resistance models determined in wind tunnel experiments, while tree resistance to wind forces on stems and crowns is determined by using static pulling tests.

Hybrid models have also been developed, e.g. HWIND (Peltola *et al.,* 1999), FOREOLE (Ancelin *et al.,* 2004) and GALES (Gardiner *et al.,* 2000). These hybrid models combine mechanistic approaches and empirical correlations to calculate the critical wind speed that can cause damage to the trees (Hale *et al.,* 2015).

2.3 Mechanical stability of trees based on static-pulling tests

Pulling tests are used as a means of simulating wind load forces on trees. In these tests the stability of a tree (or its anchorage) is represented as the critical resistive turning moment at the stem base during overturning (Nicoll *et al.,* 2006). The tests are conducted by pulling on a cable or rope (pulling line), attached to the trunk of a tree with a pulling device. A measuring device positioned in-line of the pulling records the amount of force that is exerted on the tree during the test. Pulling devices vary from experiment to experiment, but pulling with a tractor or winch and pulley systems are the most common. The height from ground level to where the pulling line attaches to the trunk also differs among experiments depending on the nature of the research: Cucchi *et al.* (2004) attached the line at a point located at 10-50% of the tree height; Moore (2000) and Peltola *et al.* (2000) used 33%, while Milne and Blackburn (1989) attached their pulling line to a point situated at 70% of tree height. However, typically the height at the centre of mass is used. Pulling a tree first produces a deflection of the stem that involves a horizontal displacement of its centre of gravity. As a consequence a second force, one that depends on the stem and crown mass, acts. In turn the resistance to uprooting and the resistance to stem breakage are generated. If the uprooting moment exceeds the resistive bending moment at a certain angle of deflection, the tree will continue deflecting until it is uprooted. At this point the breakage of the stem may happen as well (Peltola, 2006).

Forestry researchers first pioneered pulling tests on trees. Today pulling tests are generally considered an acceptable means for testing the stability of trees. The advantage of pulling tests is that they allow researchers to place a known controlled load on a tree to examine its particular response. A disadvantage of pulling tests is that they use a static load to simulate dynamic forces, potentially oversimplifying wind force loading (Eckstein and Gilman, 2008).

2.4 Factors influencing tree stability

Both mechanistic and empirical studies have identified factors that influence tree stability. Some of these factors influence the force that wind exerts on the tree; others influence the tree's resistive forces. The force that the wind exerts on a tree is influenced by characteristics of the wind climate (e.g. wind speed, duration, and gustiness) as well as characteristics of the trees (Figure 1).

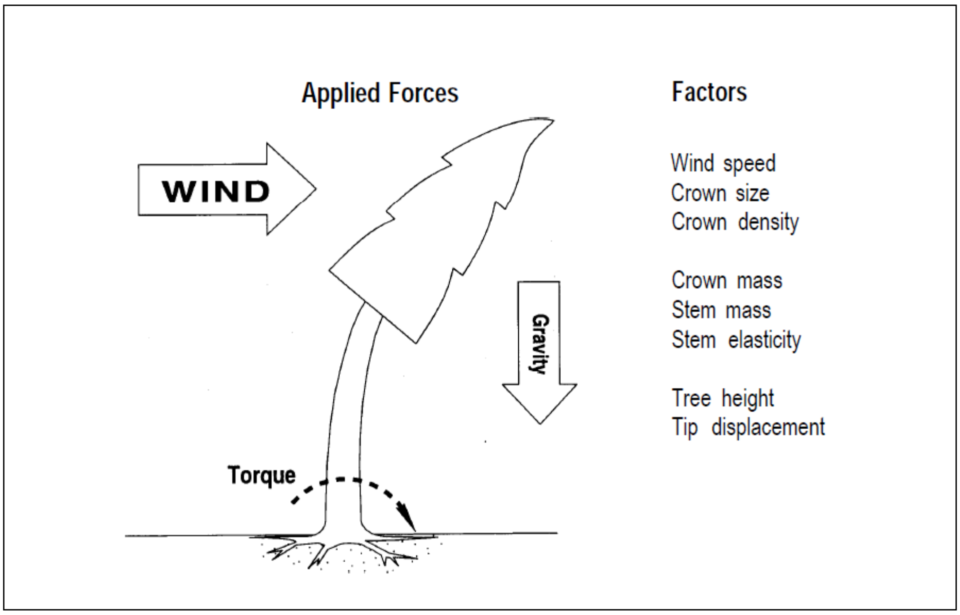

Figure 1: Factors affecting wind and gravitational forces acting on a tree.
Source: Stathers *et al.* (1994)

Wood properties, such as stem thickness, wood strength and elasticity; as well as root properties (i.e. root strength and weight of the root plate) contribute to a tree's resistance to failure (Kerzenmacher and Gardiner, 1998) (Figure 2).

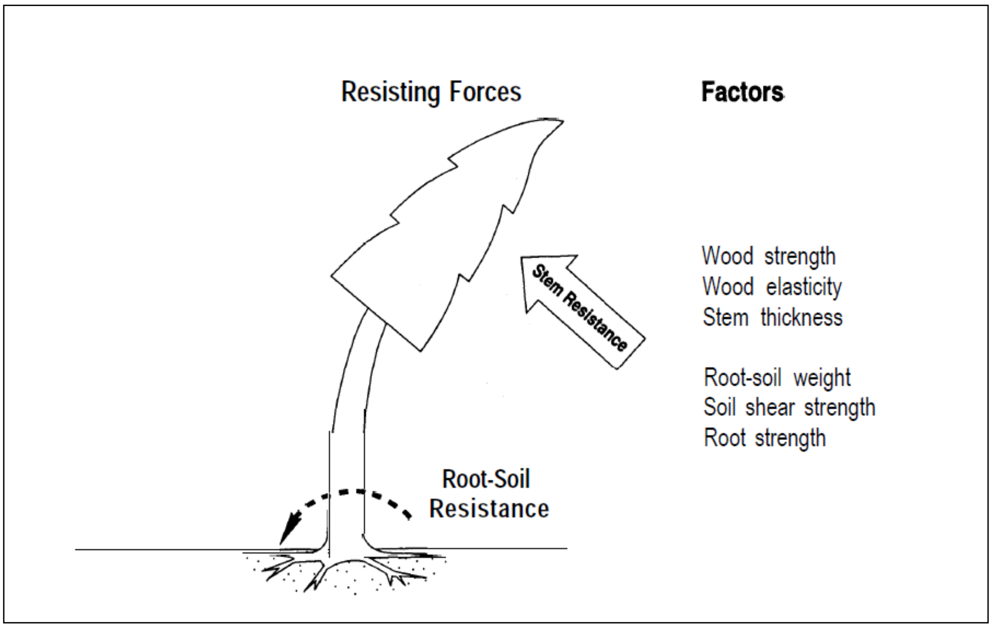

Figure 2: Factors affecting the resistance to wind and gravitational forces acting on a tree.
Source: Stathers *et al.* (1994)

The following is a brief overview of the key findings from previous studies on stability in coniferous species, focussing on those that include Sitka spruce as the main species of study.

Most tree pulling studies have found that critical turning moment is most strongly related to stem parameters. Fraser (1962) and Fraser and Gardiner (1967) found a significant linear relationship between critical turning moment and stem mass in Sitka spruce in the UK. Bergeron *et al.* (2009), Lundstrom *et al.* (2007) and Achim *et al*. (2005) similarly found stem mass to be a key factor influencing critical turning moment in various tree species. In addition to stem mass, other stem factors such as tree height (e.g. Moore, 2000; Peltola *et al.,* 2000) and stem volume (Moore, 2000) have been shown to be positively related to critical turning moment. The tree dbh (e.g. Moore, 2000; Peltola *et al.,* 2000; Lundstrom *et al.,* 2007) or some function of dbh (e.g. Peltola *et al.,* 2000; Lundstrom *et al.,* 2007) were also found to be positively associated with critical turning moment. The relationship between height and diameter, i.e. the h/dbh ratio, is also important with critical turning moment declining with increasing h/dbh ratio (Peltola and Kellomaki, 1993). Often interactions between the variables outlined above with respect to their influence on critical turning moments have been noted. For example, Peltola *et al.* (2000) found tree height multiplied by dbh squared to be the most important predictor of maximum resistive bending moment.

Empirical studies have similarly found tree height to be the most important factor influencing stability (e.g. Valinger and Fridman, 2011; Albrecht *et al*. 2012). Scott and

Mitchell (2005) and Albrecht *et al*. (2012) also noted that greater h/dbh ratios lead to reduced tree stability.

Another group of factors that influence the resistance to overturning include those related to soil anchorage. Coutts (1986) was one of the first to examine the mechanics of root anchorage in Sitka spruce. He found that soil resistance was the major component of anchorage during the early stages of the uprooting process; thereafter the windward roots and the weight of the root plate and hinge play the major role in anchorage. Ray and Nicoll (1998) found that root-soil plate rigidity to be the major factor influencing soil resistance to overturning. Nicoll *et al.* (2006) and Nicoll *et al.* (2008) explored how soil group and root depth influenced the stability of Sitka spruce. Their results show that for trees growing on soils that allow deeper rooting, the resistance to overturning is greatest. Building on these studies, Achim and Nicoll (2009) found that for a given soil type and depth, tree anchorage can be modelled as being proportional to the square of the root-soil plate spread. Nicoll *et al.* (2005) also compared the anchorage of 40 year old Sitka spruce trees growing on a steep slope to that of Sitka spruce trees growing on an adjacent horizontal area. They found no difference in anchorage between the two sets of trees but did note that for the trees on the slope those being pulled upslope exhibited greater resistance to overturning for a given stem mass than those pulled downslope.

A number of studies have explored tree stability in more than one species (e.g. Peltola *et al.,* 2000; Achim *et al*., 2005; Lundstrom *et al.,* 2007, Bergeron *et al.,* 2009), but one of the most extensive works on species stability was produced by Nicoll *et al.* (2006). Their database covers the UK and includes data on 12 different conifer species[2] planted in a wide range of soils. It showed that only grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.) and Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) exhibited greater anchorage than Sitka spruce.

The influence of silvicultural practices on windthrow risk has often been explored with empirical data. Numerous studies have found that thinning practices influence stand stability (e.g. Cremer *et al.,* 1982; Savill, 1983; Gardiner *et al*., 1997). Thinning disrupts the canopy, increasing its roughness which temporarily destabilises the stand (Albrecht *et al*., 2012). The creation of a new edge after a thinning intervention usually leads to an increased probability of damage as thinning allows wind to penetrate the stand, exposing trees that relied on mutual support from neighbouring trees (and hence did not grow acclimated to such wind action) to higher wind forces (Locatelli *et al.,* 2016). A thinned

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[2] Corsican pine (*Pinus nigra* subsp. *laricio* (Poir.) Maire; Douglas fir; European larch (*Larix decidua* Mill.); Grand fir; Japanese larch (*Larix kaempfer* (Lindl.) Carr.); Lodgepole pine; Noble fir (*Abies procera* Rehd.); Norway spruce; Scots pine; Sitka spruce; Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.); Western red cedar.

stand does regain stability but the length of time this takes depends on the growth rate and the age and the state of the stand at the time of thinning (Cremer *et al.,* 1982).

Empirical studies have identified that the probability of wind damage is associated with the timing and intensity of the thinning interventions (Quine, 1995). Delaying thinning increases the risk of damage (Pollanschutz, 1991 cited in Cameron, 2002) and can be catastrophic in stands with high h/dbh ratios (Wonn and O'Hara, 2001). Cameron (2002) also found that delaying the first thinning to improve average tree size and volume output greatly increases instability. For stands subject to high wind risk there are advantages to an early start to thinning to develop more stable trees (Kerr and Haufe, 2011). Thinning at an early age encourages stem movement and the gradual development of stability features to improve resistance to wind damage. The intensity of the thinning also influences the risk of wind damage; the heavier the thinning the greater the risk of windthrow (Booth, 1974). Greene *et al*. (1992) similarly noted that high intensity thinning contributed to severe wind damage.

The influence of silvicultural practices on stability has rarely been explored in mechanistic modelling. Among the few studies that have been conducted is that by Blackburn (1986) who investigated the influence of spacing on critical turning moment in Sitka spruce in Scotland. He concluded that critical turning moment was not greatly influenced by spacing. Achim *et al*. (2005) compared the stability of trees immediately after a thinning intervention involving the removal of 30% of the basal area in a balsam fir (*Abies balsamea* (L.) Mill.) stand. Their results showed that the critical wind speed was reduced by approximately 4 ms^{-1} after the intervention. A more recent study focused on how different stand densities in Sitka spruce affected tree stability (Nicoll *et al.,* 2009). It found that trees growing at wider spacing exhibited greater critical turning moments than those more closely spaced; however lower critical wind speeds were found to uproot the former. In addition, a higher critical wind speed was required to snap trees in the widely spaced stands compared to densely spaced stands (*ibid*).

2.5 Thinning and crop parameters

Thinning clearly plays an important role in tree stability. In the following section a brief overview of how thinning influences a range of crop parameters is given.

2.5.1 Stem

Mitchell (2000) found that Sitka spruce and Douglas fir trees responded to thinning by reducing their height increment during the first years after the intervention with a gradual increase in the radial growth. Similar results were recorded by Rees and Grace (1980a, b) in lodgepole pine (although in that case radial growth was not affected), by Valinger (1992) in Scots pine plantations; and in a range of species by Telewski (1995). A reallocation of resources was noted by Mitchell (2000) and Kozlowski and Pallardy (1997) and it suggests a period of acclimative growth following thinning interventions in forest stands with high initial densities.

Trees in thinned stands have high growth rates for longer periods of time compared with unthinned stands; consequently they will be more tapered and have larger branches which remain alive further down the stem (Evert, 1971). Deans and Milne (1999) similarly found that stem taper declined progressively as the number of trees per hectare increased, suggesting that wider spaced trees should have centres of gravity closer to the ground than trees growing at closer spacing.

A decrease in the strength of timber with increasing thinning intensity has been observed; a finding Moore *et al.* (2009) attributed to larger knot sizes. Early thinnings, i.e. pre-commercial thinnings, usually lead to a larger juvenile core that contains wood of low strength and stiffness (*ibid*).

2.5.2 Crown

In comparison to other species, Sitka spruce holds many branches (Cannell, 1974) and often responds to thinning and pruning treatments with the production of numerous epicormic branches (Deal *et al.,* 2003; Quine, 2004). Thinning leads to an increase in branch diameter and also lowers the height at which branches die (Achim *et al.,* 2006). Auty *et al.* (2012) found maximum branch diameters in Sitka spruce to be 10–15% larger following a heavy respacing compared to a light respacing; in the lower crown, the branches were as much as 120% larger.

A few studies have explored the effects of thinning or respacing on crown foliage in coniferous trees. Heavily thinned Monterey Pine (*Pinus radiata* D. Don) trees had a greater proportion of foliage in lower sections of the crown than lighter thinned trees due to greater branch size and number (Siemon *et al.,* 1980). An improvement in light conditions in the lower crowns of 24-year-old Douglas fir after thinning resulted in an increase in the foliage area of the lower crown whorls 7 years later (Brix, 1981). Similarly, wider spacing induced a downward shift in relative foliage distribution in Douglas fir with the effect more pronounced with increasing tree dominance (Maguire and Bennett, 1996). However, some studies have found no difference in foliage distribution with thinning or stand density. Stephens (1969) found a normal distribution of foliage for red pine (*Pinus resinosa* (Ait.)) trees despite differences in their size, age, stand density and site quality.

Thinning does not influence the vertical distribution of foliage in loblolly pine (*Pinus taeda* L.) (Gillespie *et al.,* 1994).

Branch growth for two species studied by Kneeshaw *et al.* (2002) presented different growing patterns after thinning. Lodgepole pine branches grew less in the first post-harvest year after thinning than they did in the pre-thinning period, whereas Douglas fir branches responded immediately with increased growth.

2.5.3 Root-soil plate

Root growth changes have been observed in different coniferous species as a consequence of thinning practices. Kneeshaw *et al.* (2002) and Ruel *et al.* (2003) observed significant root radial growth in balsam fir between 2 and 4 years after a thinning intervention. Interestingly, some studies (e.g. Ruel *et al.,* 2003; Vincent *et al.,* 2009) have found that growth increment in roots was stronger in the first years following an intervention than in the stem for various coniferous species including white spruce (*Picea glauca* (Moench) Voss). Thinning generally does not influence root depth (Fraser and Gardiner, 1967).

2.6 Previous studies on windthrow in Ireland

In Ireland, limited work has been carried out on windthrow. Hendrick (1988) produced a windthrow risk classification for thinning to be used as a guide as to whether a stand was suitable for thinning. The classification was based primarily on soil parameters (i.e. soil preparation type, soil preparation direction relative to the contour, soil preparation bearing and soil type) and the method of timber extraction employed. Ní Dhubháin *et al*. (2001) developed a windthrow risk model where the stand top height, thinning (yes/no), the location of the stand, the soil type and the altitude were shown to contribute significantly to the risk of windthrow. Ní Dhubháin *et al*. (2009) revisited that model when additional data became available. This revised model included stand top height, top height squared, soil type, thinning, wind zone and altitude. The study additionally confirmed that Sitka spruce stands planted in gley and peat soils have a greater probability of suffering windthrow than those planted in brown earths or podzols.

A small number of tree pulling tests have been carried out in Irish forests. All of them compared the anchorage of Sitka spruce trees on sites in which different cultivation methods were used. Hendrick (1989) was the first to employ such a procedure in Ireland. He 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. Rodgers *et al.* (1995) carried out an investigation that explored the effects of dynamic loading on Sitka spruce and also investigated the stiffness values and Young's moduli of the stems by using a monotonic pulling test. Their results showed that Sitka spruce stems exhibited stiffness values ranging between 5.17-7.81 kNm^{-1} and Young's moduli of between 5.26-5.92 Gpa. Mulqueen *et al.* (1999) compared the stability of Sitka spruce trees established on a surface water gley soil that had been mole drained with that of trees established on a ploughed section of the same site. Their results showed that trees growing on sites that had been mole drained were more stable than those growing on sites that had been prepared using mouldboard ploughing or had had no cultivation. They attributed their findings to the root system, which seemed to be more symmetric and deeper in mole drained areas. Rodgers *et al.* (2006) compared the overturning moment of trees established on sites that had been cultivated using a double mouldboard plough with those that had been mole drained. Their monotonic tree pulling tests showed that trees on the mole drained plots exhibited the greatest overturning moment.

2.7 Overview/conclusion/implications for the study

The review of the literature shows that tree stability is influenced by both aboveground and belowground characteristics of a tree. It in turn shows that many of these characteristics are influenced by thinning. Furthermore, empirical studies on windthrow occurrence have identified that thinning practice plays an important role in determining whether forest stands experience windthrow or not.

In Ireland, wind is the major abiotic threat to forests. Despite this, there has been limited research conducted to date on understanding the phenomenon. Tree pulling experiments conducted previously in Ireland have focused on the influence of ground cultivation techniques on stability. The influence of thinning (intensity and timing) on individual tree stability has not been addressed to date in Ireland. It is this research gap that this study primarily aims to address.

3 Methods

3.1 Study site

The study site is located approximately 5 km north-east of Frenchpark in Co. Roscommon (8°21' W, 53°52' N) at an elevation of 70 m above sea level. The soil is a surface water gley of mixed sandstone and limestone glacial till. The soil is characterised by a dark top soil (A Horizon), silty loam in texture, 20-25 cm thick, which is underlain by a gleyed B horizon to a depth of 100 cm to the C horizon. There is a slight slope of 2 degrees and the aspect is north-south. The site was mounded with mound drains at 12 m centres in a north-south direction and mounds were placed between drains at 2 x 2 m intervals and planted with Sitka spruce in 1995. The site was previously an agricultural field. The average yield class of the crop is 24 $m^3ha^{-1}yr^{-1}$.

Long term (1981-2010) weather data from Knock airport, the closest meteorological station to the site, show annual precipitation averages of 1350 mm. The wettest month is January with 140 mm and the driest month is April with 95 mm of rain (Figure 3). The mean annual temperature is 8.5 °C, with the warmest temperatures occurring in July, (averaging 13.9 °C) and the coldest temperatures occurring in January (averaging 4 °C). The mean annual wind speed is 4.5 ms^{-1} (Met Eireann, 1981-2010).

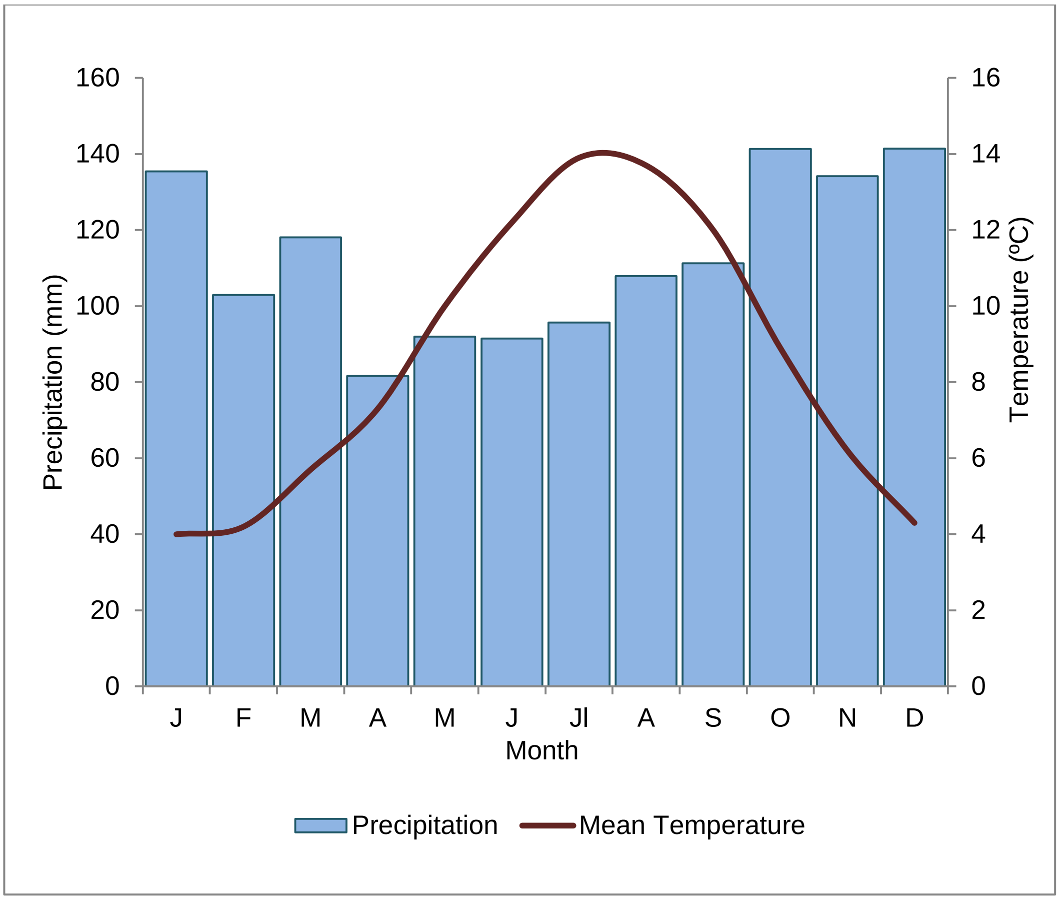

Figure 3: Average temperature and precipitation from Knock Airport for the period 1981-2010

Source: Met Eireann (1981-2010).

3.2 Sitka spruce thinning trial

A thinning trial was established on the site in 2010 by Teagasc (The Irish Agricultural and Food Development Authority) to observe the effect of different thinning intensities on volume production in the Sitka spruce crop. When the trial was established, the crop had a top height of 11 m and mean dbh of 16.4 cm, with an average volume of 200 m^3ha^{-1}. Three different thinning treatments were assigned to the crop; light, medium and heavy thinning. Sections were left unthinned as a control. Thinning followed a systematic and selective procedure removing 1 line in 7 to form extraction racks, with a low selection conducted between the racks involving the removal of supressed trees and competing co-dominants. All trees were marked for selection by Dr Niall Farrelly of Teagasc. The volume removed in the first thinning conducted in 2010 was as follows; light thinning (20% of the average stand volume), medium thinning (32% of the average stand volume), and heavy thinning (38% of the average stand volume) (Table 2). A further treatment was assigned in 2013 which represented a delayed medium thinning. This took place in an unthinned section of the stand and involved the removal of 32% of the volume of the control plots in 2012. A further thinning took place in all plots in 2015. As previously, in the light thinning plots the volume removed was 20% of the volume (in 2015) in the control plots; in the medium thinning plots (delayed and not delayed) it was 32%, while in the heavy thinning plots it was 38%. Summary data at the end of 2015 are presented in Table 3.

In total fifteen plots formed the experiment representing three replications each of the four thinning treatments (light, medium, heavy and medium delay) and an unthinned control.

Table 2: Mean parameters in the different thinning treatments after the first thinning.

Treatment	N° of plots	Age * (years)	Top Height (m)	Trees/ha	Mean dbh (cm)	BA/ha (m^2ha^{-1})	Mean volume (m^3)	Volume/ha (m^3ha^{-1})	Volume removed (m^3ha^{-1})
Unthinned	3	15	11.8	2133	16.2	44	0.10	211	0
Light	3	15	11.4	1500	17.2	35	0.11	168	51
Medium	3	15	10.5	1230	17.7	30	0.12	148	62
Heavy	3	15	11.3	1015	18.5	27	0.13	134	73
Medium delayed	3	18	13.4	1237	19.6	37	0.15	187	77

*Age of the trees when the first thinning intervention was applied.

Table 3: Mean parameters in the different thinning treatments after the second thinning.

Treatment	N° of plots	Age* (years)	Top Height (m)	Trees/ha	Mean dbh (cm)	BA/ha ($m^2 ha^{-1}$)	Mean volume (m^3)	Volume/ha (m^3ha^{-1})	Volume removed (m^3ha^{-1})
Unthinned	3	21	17.1	1990	19.9	62	0.23	452	0
Light	3	21	16.7	1163	23.2	49	0.34	368	40
Medium	3	21	16.2	938	23.9	42	0.36	388	61
Heavy	3	21	16.9	791	24.9	38	0.40	311	62
Medium delayed	3	21	16.5	1058	22.6	42	0.31	329	47

*Age of the trees when the second thinning intervention was applied.

3.3 Tree pulling experiments

A winching test was undertaken during the month of November 2015. Within each of the 15 plots 4 trees were selected for winching. The trees selected were those with:

- a dbh equivalent (or as close as possible) to the mean dbh of the trees in the respective plot in 2015;
- single straight stems;
- no crown or pathological damage.

Trees close to the edge of the stand were not selected as there would not have been any tree to use as an anchor tree outside the plantation. Two of the four trees selected within the plots were located next to the mound drains while the other two were randomly located within the plots but at least two lines away from the drains. This allowed the role (if any) of proximity to the drains on tree stability to be determined.

The mean dbh of the selected trees ranged from 19 cm for those selected in the control, i.e. unthinned plots to 23.5 cm in the heavy thinning plots. The mean dbh of the selected trees in the light, medium and 3 years delayed medium thinning plots were 20.5 cm, 22 cm and 21 cm respectively. The heights of the selected trees varied from 13 m to 17 m across all the plots.

All selected trees were truncated at 6 m height. For safety reasons, a notch was made almost at the top of the truncated stem to be used as a cable attachment point (Figure 4). The anchor tree was always selected in the north-east direction as the prevailing wind in the area is south-west, and all trees were pulled in the direction of the prevailing wind. The distance to the anchor tree was always at least twice the height of the truncated stem for safety reasons. Neighbouring trees were pruned to avoid obstruction or pull interference.

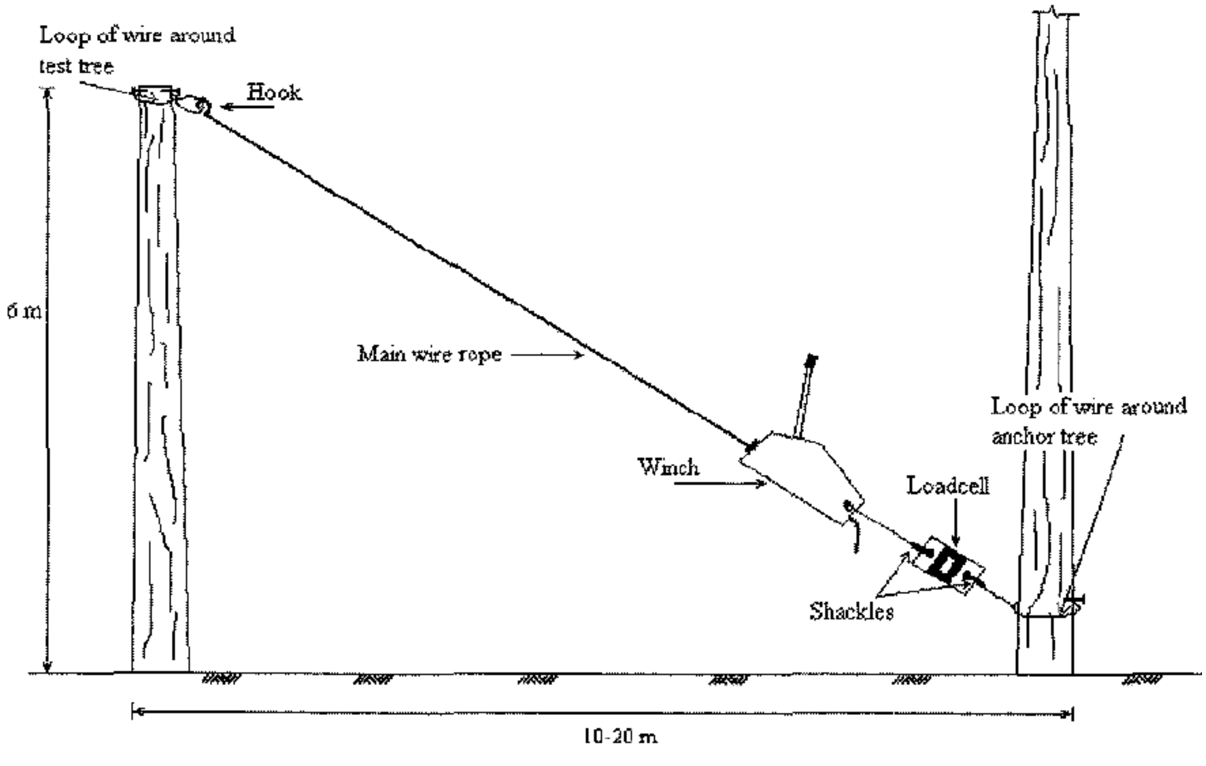

Figure 4: Winch system arrangement.
Source: Rodgers *et al.* (2006)

The webslings, wire ropes, load cell and winch were attached to the selected tree (Figure 4). One end of the wire rope was attached to the top of the truncated tree using a websling and the other end to the winch. The load cell was connected in between the winch and the websling that was around the anchor tree. A manual winch (model TIRFOR^{TM} 3.2 tonne) was used to winch the tree to complete failure or stem breakage. Generally, the winching or monotonic testing took less than 10 minutes.

3.4 Data collection

Before each selected tree was truncated its total height and the height to the start of the live crown (CH) were measured. The length (CL) and the width of the crown (CW) were recorded once the crown was laid on the ground. The crown width was measured at metre intervals from the first green branch and the maximum value was recorded. Following truncation, the distance to the anchor tree and the bearing to the anchor tree were also recorded.

The horizontal and vertical displacements at maximum load, i.e. the force applied at the point of failure of the tested trees, were recorded. Tree level measurements such as the diameter at different heights (i.e. diameter at stump height (Ø at 5 cm), diameter at breast height (dbh), at 3 m height (Ø at 3 m) and at 6 m height (Ø at 6 m)) were recorded on the 6 m log. The h/dbh ratio of every tested tree was calculated using the total height and the dbh of that tree.

Modes of failure were recorded for each tree: these included uprooting and stem breakage; no tree exhibited root collar breakage. If a stem snapped during pulling, the height at the point of rupture was recorded. Because an accurate measurement of the diameter at this point was often impossible to obtain it was estimated from diameters measured at both sides of the breakage point.

Attributes of the soil and root plate were also recorded following the methodology described by Nicoll *et al.* (2005). The dimensions of the root plate were measured as shown in Figure 5: root plate width (w), distance from the top edge of the plate to the tree centre (d_1), distance from the tree centre to the hinge (d_2), and root depth at 3 points in a line across the plate at 0.5 × d_1. An average of the depths of these 3 points yielded root depth for the tree. Maximum root depth was the value of the largest measurement. The root plate area and volume were estimated from these measurements, assuming a half-ellipse shape for the area above the stem centre, and a rectangular shape below the stem centre and using the root depth value.

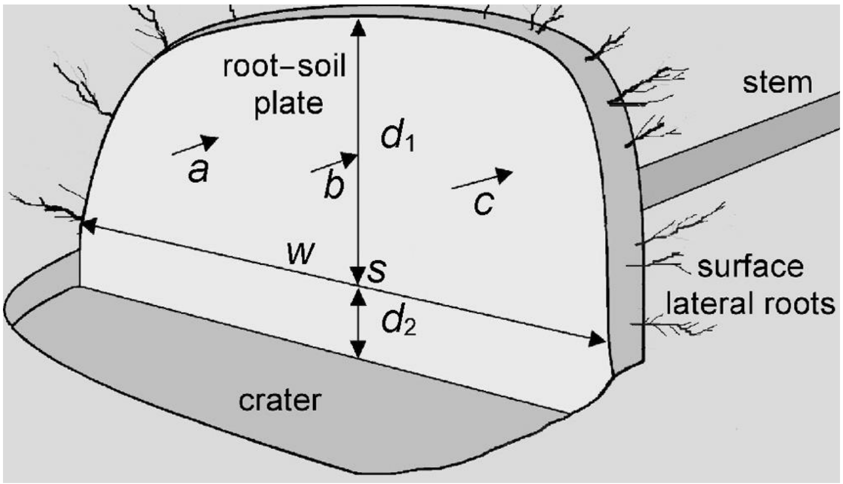

Figure 5: Measurement of the root–soil plate: root width (*w*), distance from the stem centre (*s*) to the windward edge (*d*1), distance from *s* to the hinge (*d*2), and plate thickness at 3 points (indicated by arrows *a*–*c*) across the plate.
Source: Nicoll *et al.* (2005)

The height of the root plate was obtained by summing the distance from the top edge of the plate to the tree centre (d_1) and the distance from the tree centre to the hinge (d_2). A note was also made as to whether or not water appeared beneath the root plate.

The root plates of the trees that had snapped were excavated after winching to record the attributes following the methodology by Nicoll *et al.* (2005) already described.

The stems from all trees were brought to a laboratory where direct measurements of stem weight were taken using a crane attached with a dynamometer. The 6 m stems were cut in two 3 m sections to facilitate transport. Tree weight (W) (N) was calculated as follows:

$$\boldsymbol{W = m * g} \quad \textbf{(Equation 4)}$$

where m is the tree mass (kg), g is the gravitational acceleration (9.8 ms^{-2}) and:

$$\boldsymbol{m = \rho * V} \textbf{ (Equation 5)}$$

where ρ is wood density (400 kgm^{-3} for Sitka spruce; Savill and Sandels, 1983) and V is tree volume (m^3).

Small plots averaging 40 m^2 were set up around each selected tree. For each of the trees within that plot, total height and dbh were recorded. The presence of stumps within the plot was noted to identify trees removed during the first thinning. Basal area per hectare and stems per hectare estimates were derived from the data collected in these small plots (BA small plot; SPH small plot respectively).

The heights and lengths of the mounds on which each tested tree was located were also recorded.

3.4.1 Plot characteristics

A soil pit was dug at the centre of each of the 15 plots. It enabled the soil profile and water table depth to be recorded. Water table depth measurements were recorded in each plot every two weeks from September 2015 to April 2017. Water table depth values for each season were then calculated (i.e. autumn, winter, spring and summer).

Plot level basal area (BA plot) and stems per hectare (SPH plot) estimates were also recorded.

Summary statistics for the tree and plots variables are shown in Table 4.

Table 4: Summary statistics for the tree and plot variables recorded.

Variable	Units	N	Mean	Standard Deviation	Minimum	Maximum
dbh	cm	60	21.04	1.55	17.60	24.60
Ø at 5 cm	cm	60	29.16	3.95	21.90	40.20
Ø at 3 m	cm	60	18.74	1.84	14.90	23.40
Ø at 6 cm	cm	60	15.52	1.97	11.70	21.50
Tree height	m	60	14.89	1.15	11.84	17.49
Stem weight	kg	60	1418.01	346.77	608.59	2454.50
Tree weight	kg	60	3478.01	954.68	1892.26	7082.94
Root plate height	m	57	1.91	0.30	1.36	2.90
Root plate width	m	57	2.25	0.53	1.10	3.80
Root depth	m	57	0.69	0.21	0.39	1.33
Maximum root depth	m	57	0.77	0.26	0.48	1.80
Root plate area	m^2	57	6.23	2.14	1.97	12.77
Root plate volume	m^3	57	4.41	2.55	1.25	13.93
Crown height	m	60	7.05	1.46	3.47	9.87
Crown width	m	60	2.97	0.51	1.80	4.10
Crown length	m	60	7.84	1.63	3.35	11.19
H/dbh ratio		60	71.02	6.20	53.33	82.42
Mound length	cm	60	58.56	8.33	40.00	78.50
Mound height	cm	60	15.41	3.63	7.25	24.00
BA small plot	m^2ha^{-1}	60	55.36	11.66	30.89	84.70
SPH small plot	$stemsha^{-1}$	60	1533.87	407.74	857.63	2682.56
BA plot	m^2ha^{-1}	60	34.67	6.00	26.60	46.10
SPH plot	$stemsha^{-1}$	60	1424.40	396.49	957.00	2198.00
Water table depth	cm	15	63.43	19.66	7.50	100.00

3.5 Calculation of overturning moment and centre of gravity

The critical turning moment ($M_{critical}$) for those trees that were uprooted was calculated at the stem base using a methodology outlined by Achim *et al.* (2005):

$\boldsymbol{M_{critical} = M_{applied} + M_{mass}}$ **(Equation 6)**

where $M_{applied}$ (Nm) represents the maximum turning moment applied by the winch and M_{mass} (Nm) represents the turning moment resulting from the overhanging weight of the leaning tree at the time and angle of stem when the maximum load was reached. Both turning moments were calculated from the measurements shown in Figure 6. The equations used to calculate them are as follows:

$\boldsymbol{M_{applied} = Fcos\theta_1 \cdot L + F\sin\theta_1 \cdot X}$ **(Equation 7)**

$\boldsymbol{M_{mass} = W \cdot x_{<}}$ **(Equation 8)**

where: F is the force recorded by the winch at maximum load (N), θ_1 is the angle of the winch cable relative to horizontal (°), L is the height of the stem at time of maximum load (m), X is the horizontal displacement of the pull tree at time of maximum load (m) and W is the weight of the stem (N). The height of the centre of gravity of the truncated stems at maximum load ($l_{<}$) (m) was calculated as the centre of mass of a truncated cone. The horizontal displacement of the centre of gravity at maximum load ($x_{<}$) (m) was determined assuming that the shape of the stem was a straight beam rotating around its base.

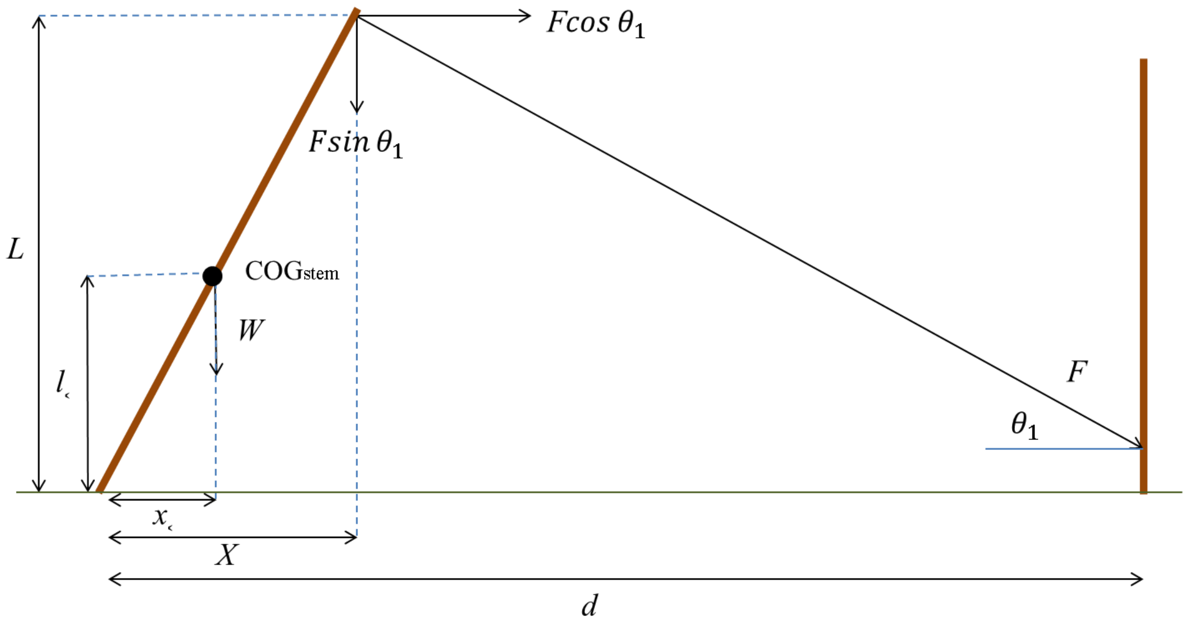

Figure 6: Measurements used in the calculation of critical turning moment: centre of gravity of the stem (COG$_{stem}$), the distance between the anchor tree and the tested tree (*d*), stem weight (*W*), the force applied by the winch (*F*), the horizontal component of the force ($F\,cos\theta_1$), the vertical component of the force ($F\sin\theta_1$), the horizontal displacement of the stem at maximum load (*X*)*,* the horizontal displacement of the centre of gravity at maximum load ($x_{‹}$), the height of stem at maximum load (*L*), the height of the centre of gravity at time of maximum load ($l_{‹}$) and the angle of the winch cable relative to horizontal (θ_1).

The bending strength (σ_{max} in MPa) (former modulus of rupture, MOR) of the trees that snapped was calculated using the following equation (Wood, 1995):

$$\sigma_{max} = \frac{32\, M_{critical}}{\pi\, \phi^3} \quad \textbf{(Equation 9)}$$

where: ϕ is the diameter of the stem at height of rupture (m). Critical turning moment ($M_{critical}$) for the snapped trees was calculated using the force at maximum load multiplied by the distance from the pull point to the break point on the stem as recommended by Gardiner (pers com).

The height of the centre of gravity for the whole tree, COG_{tree}, for all tested trees was calculated using the methodology of Saniga (1985) cited in Stofko (2012) as follows. First the static moment towards the stem base (V_x) (m^3) was calculated:

$$V_x = A_1 \times \frac{CH}{2} + A_2 \times \left(CH + \frac{1}{3} \times CL\right) \quad \textbf{(Equation 10)}$$

where: A_1 is the cross-sectional surface of the stem (m²); A_2 is the cross-sectional surface of the crown (m²); *CH* is the start of the green crown (m) and *CL* is the crown length (m) (Figure 7).

The cross-sectional surfaces (A_1 and A_2) were calculated as follows:

$\boldsymbol{A_1 = DBH \times CH}$ **(Equation 11)**

$\boldsymbol{A_2 = \frac{CW \times CL}{2}}$ **(Equation 12)**

and *CW* is the crown width (m) (Figure 7).

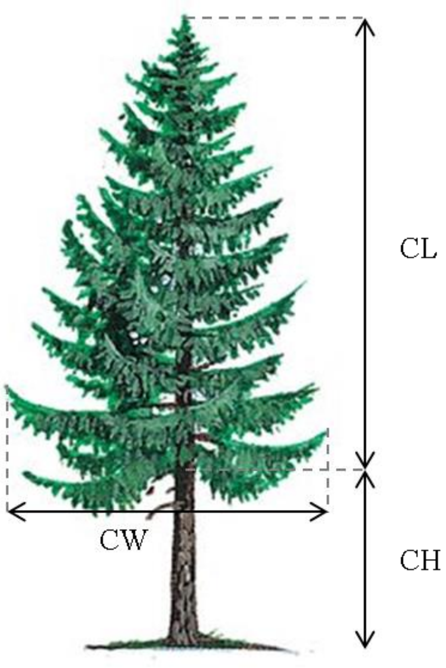

Figure 7: Parameters used in the calculation of the centre of gravity of the tested trees: crown length (*CL*), height of position of green crown (*CH*) and crown width (*CW*).

The height of the centre of gravity, COG_{tree}, was calculated then as follows:

$\boldsymbol{COG_{tree} = \frac{V_x}{A_s}}$ **(Equation 13)**

where: A_s is the cross-sectional area of a tree (m²) calculated as follows:

$\boldsymbol{A_s = A_1 + A_2}$ **(Equation 14)**

3.6 Analytical procedures

For the treatments established in 2010 the experimental design was a randomized block design with three blocks (blocks 1-3) and four treatments. The delayed medium treatment was laid down in an adjacent unthinned area and replicated three times within this area; hence block 4 was a pseudo block. The position of the test trees, i.e. beside a drain or not, hereafter referred to as tree position, was treated as a split plot effect in the analysis.

The first step in the analysis was to determine whether thinning treatment (5 levels; heavy, medium, light, medium delayed and unthinned) and tree position (2 levels) influenced the mode of failure of the test trees, i.e. uprooted or snapped. Logistic regression (PROC LOGISTIC procedure in SAS) was used to test these effects. Stepwise logistic regression was then used to determine which of the tree and plot variables recorded influenced the mode of failure. A significance level of 0.05 was required to a variable to enter the model and a significance level of 0.10 was required to allow them to stay.

For trees that had been uprooted, a mixed linear model (PROC MIXED) was used to analyse the influence of thinning treatment and tree position on critical turning moment. Block was considered as a random effect; treatment and tree position were treated as fixed. Following this, the influence of a range of individual tree and plot variables on critical turning moment was tested using a correlation analysis (PROC CORR on SAS) and a correlation matrix was produced. A generalised linear model procedure (PROC GLMSELECT) with forward selection was then used to determine which of the variables were most influential with respect to critical turning moment of a tree.

For trees that snapped similar analyses to those described in the above paragraph were used for bending strength.

For each of the individual tree parameters, a mixed linear model (PROC MIXED) was used to analyse the influence of thinning treatment and tree position on them. As above, block was considered as a random effect; treatment and tree position were treated as fixed.

4 Results

The results presented in this chapter are divided into five sections. The first section identifies the variables that influenced the mode of failure (i.e. uproot/snap) when maximum force was applied. The second section focuses on those trees that were uprooted and it shows the results of the tests to determine the influence of thinning treatment and tree position on mean critical turning moment. It also shows the influence of individual tree and plot variables on critical turning moment. The third section focuses on the trees that snapped and explores how thinning treatment and tree position influenced the bending strength of these trees. It also shows the influence of individual tree and plot variables on tree bending strength. The fourth section of this results chapter presents the results of the analysis of the effects of thinning treatment and tree position on tree attributes. The final section focuses on the water table depth measurements.

4.1 Mode of failure: influential factors

Of the 60 trees that were pulled, 36 uprooted and 24 snapped. No evidence of rot or fungal infection was observed in any of the tested trees. A higher percentage of trees snapped in the unthinned and medium thinned plots compared to the heavy, light and medium delayed thinning treatments (Table 5). The height of breakage was similar among the treatments, averaging 1.4 m. Logistic regression, however, determined that the mode of failure was not significantly influenced by thinning treatment (P=0.2186) and tree position (P = 0.6464).

Table 5: Mode of failure by thinning treatment and tree position.

Treatment	Plots	Trees	Uprooted		Snapped	
			drain	no drain	drain	no drain
Heavy	3	12	4	5	2	1
Medium	3	12	1	4	5	2
Light	3	12	5	4	1	2
Unthinned	3	12	2	3	4	3
Medium delayed	3	12	5	3	1	3
Total	15	60	17	19	13	11

Stepwise logistic regression was conducted to identify which, if any, tree variable (i.e. those listed in Table 4) as well as centre of gravity, influenced the mode of failure; this analysis identified that the key influential variables for the mode of failure were maximum root depth and root plate height (Table 6). Trees that were more deeply rooted and had larger root plate heights were more likely to snap than be uprooted.

Table 6: Mode of failure: maximum likelihood estimates for key variables.

Parameter	DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	1	-13.0252	3.6483	12.7461	0.0004
Maximum root depth	1	9.6	2.5079	14.6523	0.0001
Root plate height	1	2.6473	1.3782	3.6894	0.0548

4.2 Uprooted trees

In this section of the results the analysis of the critical turning moments of the uprooted trees are presented.

4.2.1 Critical turning moment: the effect of thinning treatment and tree position

On average, critical turning moments of the tests trees in heavy, medium and light thinned treatments were greater than those in the unthinned treatment. In addition, the average critical turning moment was greater for tested trees in the medium thinning treatment compared to those in the delayed medium treatment (Figure 8). However, these differences were not statistically significant (P=0.64); neither was the influence of tree position significant (P=0.63).

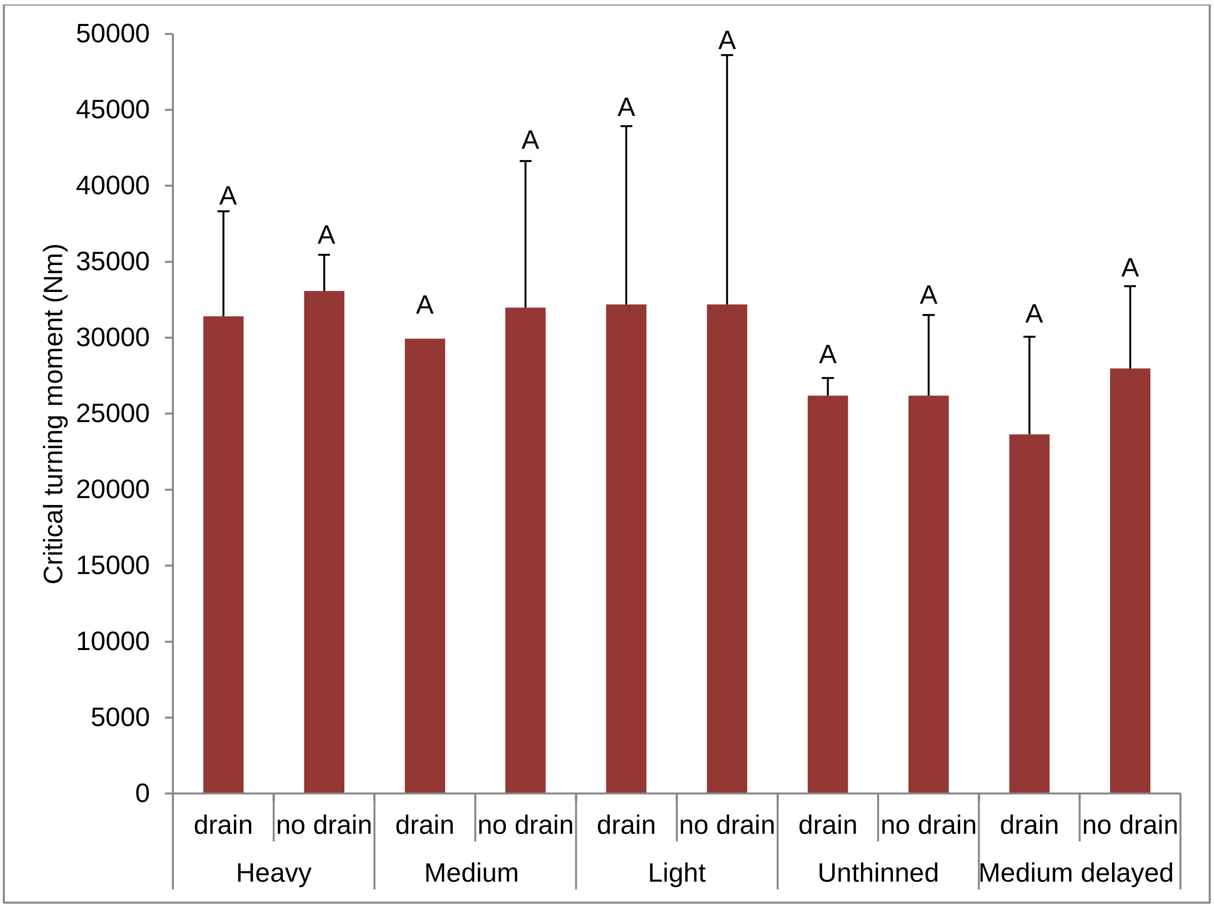

Figure 8: Mean values and standard errors for the critical overturning moment by treatment and tree position.
* Means with same letters are not significantly different.
** Means with error bars when n≠1.

4.2.2 Critical turning moment: the influence of tree and plot variables

A correlation analysis was performed to determine the strength of the relationships between a range of tree and plot variables (from Table 4) and the critical turning moment (n=36) (Table 7 and Table 8). Tree weight and stem weight were the variables most closely correlated with critical turning moment (r = 0.611 and r = 0.650 respectively, $P < 0.0001$). Dbh, Ø at 5 cm, Ø at 3 m and Ø at 6 m, tree height and crown width were also significantly correlated with critical turning moment.

Table 7: Correlation matrix (a) showing the degree of association (r values) between tree and plot variables for trees that were uprooted.

	dbh	Ø at 5 cm	Ø at 3 m	Ø at 6 m	Tree height	Stem weight	Tree weight	Root plate height	Root plate width	Root depth	Maximum root depth	Root plate area	Root plate volume
Critical turning moment	0.459	0.411	0.547	0.569	0.459	0.611	0.650	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
dbh		0.492	0.818	0.756	*NS*	0.651	0.700	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
Ø at 5 cm			0.357	0.369	0.478	0.700	0.577	0.369	*NS*	*NS*	*NS*	*NS*	*NS*
Ø at 3 m				0.801	*NS*	0.593	0.739	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
Ø at 6 cm					*NS*	0.807	0.922	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
Tree height						0.498	0.592	0.384	*NS*	*NS*	*NS*	*NS*	*NS*
Stem weight							0.929	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
Tree weight								*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
Root plate height									0.353	*NS*	*NS*	0.554	0.398
Root plate width										*NS*	*NS*	0.930	0.664
Root depth											0.954	*NS*	0.504
Maximum root depth												*NS*	0.496
Root plate area													0.769
Root plate volume													
Crown height													
Crown width													
Crown length													
Centre of gravity													
H/dbh ratio													
Mound length													
Mound height													
BA small plot													
SPH small plot													
BA plot													

**NS*: Not significant at P=0.05

Table 8: Correlation matrix (b) showing the degree of association (r values) between tree and plot variables for trees that were uprooted.

	Crown height	Crown width	Crown length	Centre of gravity	H/dbh ratio	Mound length	Mound height	BA small plot	SPH small plot	BA plot	SPH plot
Critical turning moment	*NS*	0.458	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
dbh	*NS*	*NS*	*NS*	*NS*	-0.579	*NS*	*NS*	*NS*	-0.290	-0.455	-0.606
Ø at 5 cm	*NS*	0.600	0.377	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	-0.527
Ø at 3 m	*NS*	0.336	*NS*	*NS*	-0.367	*NS*	*NS*	*NS*	-0.338	-0.461	-0.512
Ø at 6 cm	*NS*	0.493	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	-0.387	-0.524
Tree height	*NS*	0.345	0.490	0.592	0.692	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
Stem weight	*NS*	0.613	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	-0.336	-0.613
Tree weight	*NS*	0.584	0.377	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	-0.535
Root plate height	*NS*	*NS*	0.549	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	-0.351	-0.336
Root plate width	-0.465	*NS*	0.485	*NS*	*NS*	*NS*	*NS*	-0.397	*NS*	-0.371	*NS*
Root depth	0.400	*NS*	-0.333	*NS*	*NS*	*NS*	*NS*	0.356	*NS*	0.370	0.434
Maximum root depth	0.430	*NS*	-0.387	*NS*	*NS*	*NS*	*NS*	0.339	*NS*	0.366	0.435
Root plate area	-0.426	*NS*	0.529	*NS*	*NS*	*NS*	*NS*	-0.408	*NS*	-0.452	-0.417
Root plate volume	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
Crown height		*NS*	-0.691	0.534	*NS*	*NS*	*NS*	0.461	0.590	0.682	0.456
Crown width			0.392	*NS*	*NS*	*NS*	*NS*	*NS*	-0.379	-0.345	-0.506
Crown length				*NS*	*NS*	*NS*	*NS*	-0.589	-0.637	-0.515	-0.503
Centre of gravity					0.675	*NS*	*NS*	*NS*	*NS*	0.628	0.538
H/dbh ratio						*NS*	*NS*	*NS*	*NS*	0.449	0.347
Mound length							0.392	-0.452	-0.374	*NS*	*NS*
Mound height								-0.421	-0.494	*NS*	*NS*
BA small plot									0.629	*NS*	0.441
SPH small plot										0.529	0.524
BA plot											0.806

**NS*: Not significant at P=0.05

4.2.3 Stepwise regression analysis of critical turning moment and tree and plot variables

A stepwise regression analysis was carried out to determine which were the key tree and plots variables influencing critical turning moment. The two variables that were identified in the stepwise procedure as key variables were weight of the tree and the root plate width; these two variables explained 46.4% of the variability in critical turning moment (Table 9).

Table 9: Critical turning moment modelled against tree weight and root width.

Parameter	DF	Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	18292	5340.453264	3.43	0.0017
Tree weight	1	6.228431	1.138280	5.47	<.0001
Root plate width	1	-4298.355964	1983.401551	-2.17	0.0375

To determine whether the relationship between tree weight and critical turning moment was the same for the five thinning treatments the slopes of the regression lines (fitted through zero) for the five treatments were compared and no significant differences were noted (P=0.22) (Figure 9).

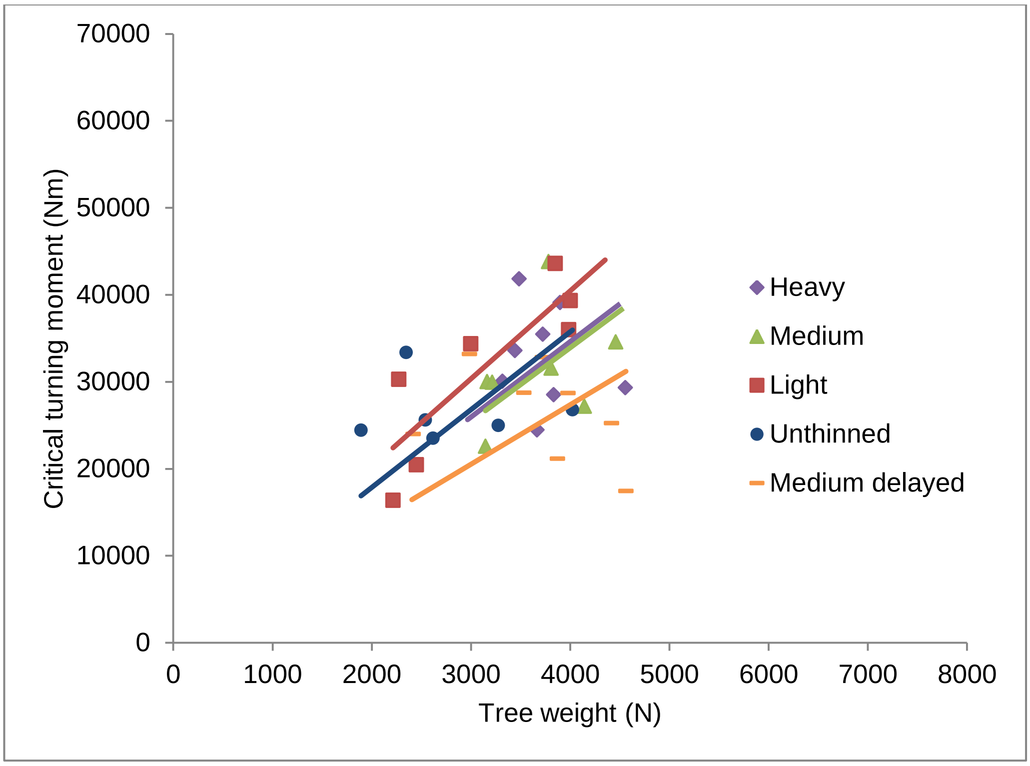

Figure 9: Critical turning moment against tree weight for all thinning treatments.

4.3 Snapped trees

In this section of the results the analysis of the bending strength of the snapped trees are presented.

4.3.1 Bending strength: the effect of thinning treatment and tree position

The mean bending strength of the snapped trees was 31.29 MPa. There were little differences in mean bending strength for thinning treatments and tree position (Figure 10). However, it was not possible to statistically test the influence of thinning treatment and tree position as some of the combinations of these two factors had only 1 observation.

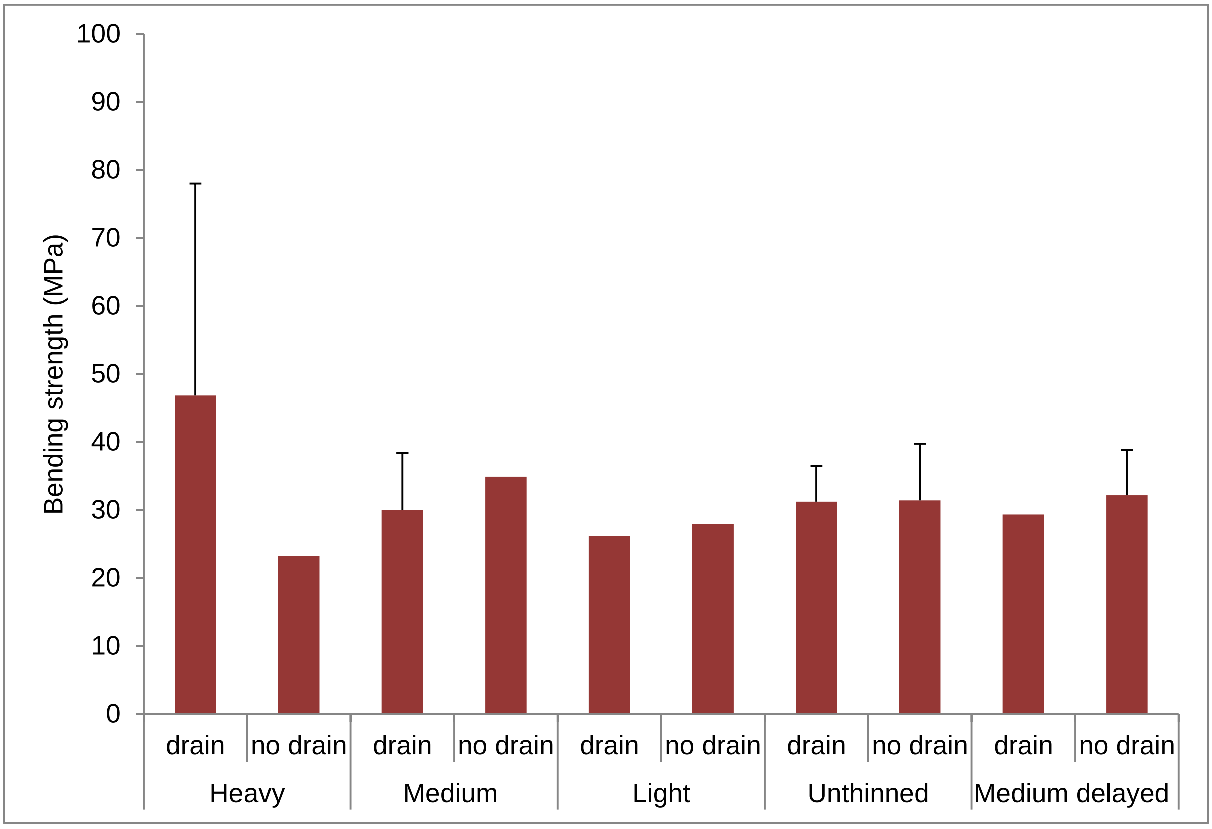

Figure 10: Mean values and standard errors for the bending strength by thinning treatment and tree position.
* Means with error bars when n≠1.

4.3.2 Bending strength: the influence of tree and plot variables

None of the tree or plot variables (from Table 4) were shown to be significantly correlated with bending strength (n= 24) (Table 10 and Table 11).

4.3.3 Stepwise regression analysis of bending strength: tree and plot variables

A stepwise regression analysis confirmed that none of the tree and plot variables significantly influenced bending strength.

Table 10: Correlation matrix (a) showing the degree of association (r values) between tree and plot variables for trees that snapped.

	dbh	Ø at 5 cm	Ø at 3 m	Ø at 6 m	Tree height	Stem weight	Tree weight	Root plate height	Root plate width	Root depth	Maximum root depth	Root plate area	Root plate volume
Bending strength	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
dbh		0.494	0.857	0.827	0.508	0.784	0.825	0.531	0.643	*NS*	*NS*	0.692	0.556
Ø at 5 cm			*NS*	0.412	*NS*	0.754	0.499	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
Ø at 3 m				0.856	0.505	0.735	0.822	*NS*	*NS*	*NS*	*NS*	0.444	0.497
Ø at 6 cm					0.546	0.870	0.969	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
Tree height						0.433	0.643	*NS*	*NS*	0.500	0.564	*NS*	0.529
Stem weight							0.926	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
Tree weight								*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
Root plate height									0.603	*NS*	*NS*	0.830	0.571
Root plate width										*NS*	*NS*	0.938	0.744
Root depth											0.872	*NS*	0.755
Maximum root depth												*NS*	0.771
Root plate area													0.771
Root plate volume													
Crown height													
Crown width													
Crown length													
Centre of gravity													
H/dbh ratio													
Mound length													
Mound height													
BA small plot													
SPH small plot													
BA plot													

**NS*: Not significant at P=0.05

Table 11: Correlation matrix (b) showing the degree of association (r values) between tree and plot variables for trees that snapped.

	Crown height	Crown width	Crown length	Centre of gravity	H/dbh ratio	Mound length	Mound height	BA small plot	SPH small plot	BA plot	SPH plot
Bending strength	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
dbh	-0.511	0.748	0.706	-0.658	-0.673	*NS*	*NS*	*NS*	-0.464	-0.718	-0.676
Ø at 5 cm	*NS*	*NS*	*NS*	-0.513	-0.563	*NS*	*NS*	*NS*	*NS*	*NS*	-0.409
Ø at 3 m	-0.478	0.715	0.677	-0.521	-0.523	-0.436	*NS*	*NS*	*NS*	-0.615	-0.474
Ø at 6 cm	-0.430	0.656	0.660	-0.578	-0.460	-0.457	*NS*	*NS*	*NS*	-0.618	-0.537
Tree height	*NS*	*NS*	0.565	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
Stem weight	*NS*	*NS*	0.501	-0.652	-0.512	*NS*	*NS*	*NS*	*NS*	-0.570	-0.551
Tree weight	*NS*	0.556	0.649	-0.555	*NS*	-0.413	*NS*	*NS*	*NS*	-0.595	-0.530
Root height	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	-0.502	-0.473	-0.632
Root plate width	-0.531	0.478	0.589	-0.576	-0.479	*NS*	*NS*	*NS*	-0.486	-0.711	-0.690
Root plate depth	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
Maximum root depth	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
Root plate area	-0.454	0.528	0.539	-0.545	-0.506	*NS*	*NS*	*NS*	-0.554	-0.714	-0.746
Root plate volume	*NS*	*NS*	0.498	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	-0.581	-0.599
Crown height		-0.596	-0.829	0.667	0.565	*NS*	*NS*	*NS*	0.574	0.685	0.589
Crown width			0.619	-0.498	-0.618	*NS*	*NS*	-0.459	-0.603	-0.614	-0.426
Crown length				-0.570	*NS*	*NS*	*NS*	*NS*	*NS*	-0.727	-0.638
Centre of gravity					0.705	*NS*	*NS*	*NS*	0.465	0.876	0.809
H/dbh ratio						*NS*	*NS*	0.419	0.572	0.549	0.531
Mound length							0.440	*NS*	*NS*	*NS*	*NS*
Mound height								*NS*	*NS*	*NS*	*NS*
BA small plot									0.565	*NS*	*NS*
SPH small plot										0.556	0.527
BA plot											0.877

**NS*: Not significant at P=0.05

4.4 The effect of thinning treatment and tree position on tree variables

Mean values for the tree variables listed in Table 4 as well as centre of gravity for the tested trees were analysed to determine whether they differed significantly by thinning treatment and/or tree position (Table 12).

The effect of treatment was significant for dbh ($P = 0.10$), Ø at 3 m, Ø at 6 m, crown height (all $P < 0.05$), crown width, root depth (both $P=0.10$), crown length, and centre of gravity and h/dbh ratio (all $P < 0.05$). The effect of tree position was only significant for dbh ($P < 0.05$). The interaction effect of thinning treatment and tree position was only significant for h/dbh ratio (Table 12). In general, tested trees in the thinned plots (light, medium, heavy and medium delayed) had greater diameters, greater crown lengths and crown widths and smaller crown heights than those in the unthinned plots. In addition, tested trees in the thinned plots had lower centres of gravity and smaller average root depths than the tested trees in the unthinned plots (Figure 11). Trees in unthinned plots had higher h/dbh ratios than those in plots that were thinned with h/dbh ratio declining with increasing thinning intensity; differences in h/dbh ratio according to tree position were not consistent across all thinning treatments; for some thinning treatments trees close to a drain had higher h/dbh ratios (i.e. heavy, medium and unthinned) while for the light and medium delayed treatments this was not the case.

There was no significant difference in the mean values for the tree variables recorded for the medium thinning treatment and the delayed medium thinning.

Table 12: Mean values of the tree variables by thinning treatment and tree position.

	Units	Heavy		Medium		Light		Unthinned		Delayed Medium		P-values		
		drain	no drain	drain	no drain	drain	no drain	drain	no drain	drain	no drain	Treatment	Position	Treatment* Position
dbh	cm	22.02	22.17	21.55	22.85	20.78	20.88	19.12	19.78	20.35	20.92	0.0869	0.0204	0.4086
Ø at 5 cm	cm	31.07	29.08	28.77	31.85	29.40	28.78	26.17	25.63	29.47	31.37	0.3682	0.6867	0.4169
Ø at 3 m	cm	19.15	20.25	19.78	21.25	18.12	18.60	17.02	17.40	17.38	18.43	0.0412	0.0159	0.8025
Ø at 6 m	cm	16.72	16.53	16.75	17.32	14.62	15.25	13.75	14.13	14.33	15.83	0.0287	0.1876	0.7866
Tree height	m	14.98	14.51	15.12	15.00	13.93	15.47	14.97	14.41	14.96	15.55	0.9372	0.4078	0.0683
Stem weight	N	1604.89	1489.84	1491.54	1700.83	1360.99	1418.79	1054.21	1119.03	1374.10	1565.86	0.2034	0.2863	0.6482
Tree weight	N	4003.41	3727.27	3900.81	4324.46	3016.27	3490.91	2682.21	2753.33	3102.20	3779.25	0.1479	0.1761	0.5577
Root plate height	m	2.00	2.03	1.95	2.03	1.72	2.05	1.68	1.69	2.04	1.89	0.1436	0.5169	0.6019
Root plate width	m	2.53	2.51	2.65	2.34	2.07	2.32	1.84	1.91	2.30	1.88	0.1674	0.6223	0.6612
Root depth	m	0.72	0.55	0.82	0.70	0.63	0.73	0.70	0.83	0.56	0.61	0.0855	0.9277	0.1504
Maximum root depth	m	0.83	0.62	0.90	0.76	0.73	0.92	0.78	0.89	0.62	0.67	0.3740	0.9037	0.3299
Root plate area	m^2	7.27	7.77	7.60	6.69	5.08	6.67	4.48	4.57	6.48	5.04	0.1069	0.9882	0.5834
Root plate volume	m^3	5.73	4.34	6.23	4.91	3.24	5.32	3.05	3.88	3.76	3.10	0.1292	0.9541	0.5099
Crown height	m	6.94	6.24	6.09	5.48	6.85	6.79	9.04	8.55	7.04	7.46	0.0227	0.1216	0.2793
Crown width	m	3.13	3.39	3.16	3.24	2.55	3.24	2.44	2.68	2.93	2.92	0.0929	0.0788	0.5162
Crown length	m	8.04	8.27	9.03	9.52	7.08	8.67	5.92	5.86	7.92	8.10	0.0128	0.1024	0.3922
Centre of gravity	m	8.41	8.25	8.69	8.67	8.99	9.46	10.14	9.93	8.98	9.41	0.0043	0.4358	0.3077
H/dbh ratio		68.10	65.63	70.17	65.61	67.26	74.18	78.38	72.78	73.65	74.49	0.0470	0.3615	0.0148

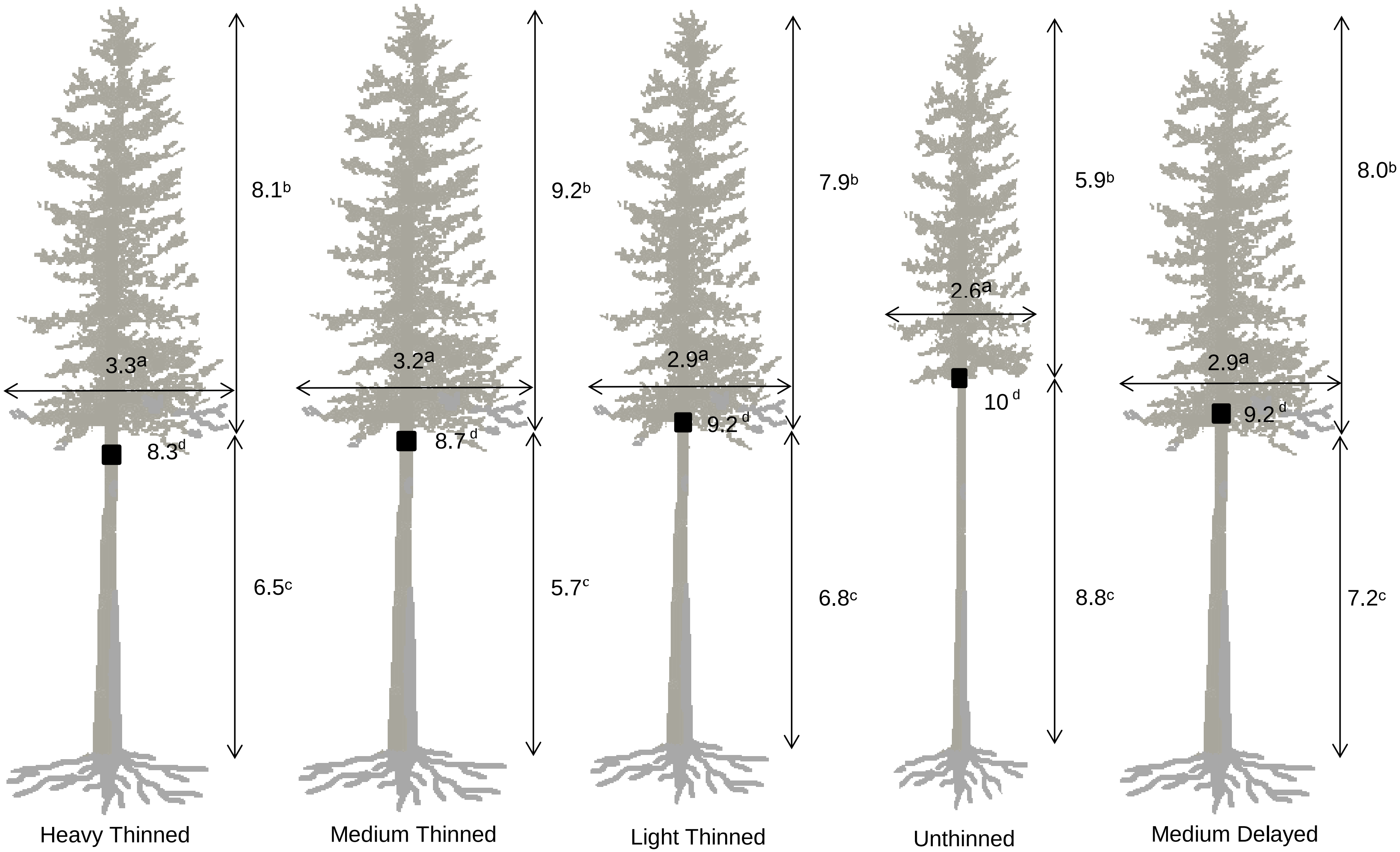

Figure 11: Representative trees for the different thinning treatments with the following parameters (all in m): crown width (a), crown length (b), crown height (c) and tree centre of gravity (d)

4.5 Water table depth

An average water table depth of 65.35 cm was recorded in the forest for the studied period of time. The highest water table depth measurement was recorded in January while the lowest was recorded in the month of June. On average, heavily thinned plots had the highest water table depths while the unthinned plots had the lowest (Figure 12).

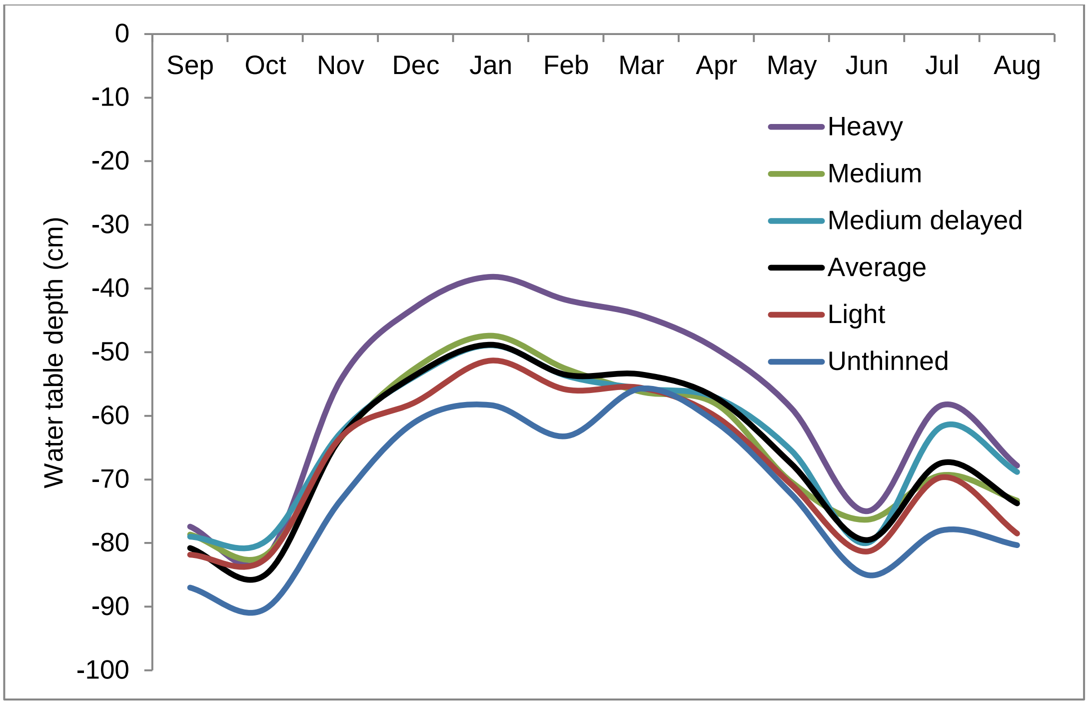

Figure 12: Water table depth for the different thinning treatments and the average for the studied period of time.

4.5.1 Relationship between water table depth and root depth

Maximum root depth was shown to be the key variable influencing the mode of failure of the trees (section 4.1). To determine which tree, plot or site variables were key variables influencing maximum root depth stepwise regression was conducted with maximum root depth as the dependent variable. This identified two key variables: the tree height and the autumn water table depth (these collectively explained 17.9% of the variability) (Table 13).

Table 13: Maximum root depth modelled against tree height and autumn water table depth.

Parameter	DF	Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	-1.030157	0.482427	-2.14	0.0373
Tree height	1	0.068647	0.027278	2.52	0.0149
Autumn water table depth	1	0.011679	0.004816	2.43	0.0187

5 Discussion

This study set out to analyse the influence of thinning intensity and timing of thinning on stability in Sitka spruce, the most common species in Irish forests. At the time the experiment was being implemented an additional aim was formulated, i.e. whether proximity to mound drains influenced tree stability. Previous work on windthrow in Ireland has focused mainly on employing empirical approaches, while the few mechanical studies that have been conducted have studied the effects of different cultivation methods on tree stability. In this chapter what the results reveal about the influence of different thinning treatments on the mode of failure, critical turning moment, bending strength and tree growth and development is discussed.

5.1 Mode of failure

While the most common form of failure noted during tree pulling was uprooting, the occurrence of stem breakage was exceptionally high, with 40% of stems exhibiting this form of failure. This figure contrasts with those from two of the most extensive tree-pulling studies, i.e. Nicoll *et al.* (2006) in the UK and Peltola *et al.* (2000) in Finland in which only 8.4% and 18% (excluding those trees winched under frozen soil conditions) of trees exhibited stem breakage respectively. Blackburn's (1986) study was the only one, to the best of the author's knowledge, to record a higher percentage of snapped trees, i.e. 75%. Peltola *et al.* (2000) noted that on well-drained soils a rough balance between uprooting and breakage is to be expected; on all other soils higher levels of uprooting are to be expected. Although the trees in this study were planted in a gley soil type, the mean maximum root depth was 77 cm (ranging from 48 cm to 1.8 m). Based on Miller's (1985) classification of soils this would be classed as deep rooting. Such deep rooting was shown to be associated with the low water table depth for the autumn months on the site. Ray and Nicoll (1998) similarly found a relationship between root depth and water table depth. Why such low water table depths were recorded in this study is not clear. It does not appear to be related to precipitation; for the studied period the level of precipitation was not abnormal. What may have been a contributing factor was the presence of a big drain in the southern edge of the forest.

Analysis of the factors influencing the mode of failure identified that thinning treatment or tree position were not important. Instead the key influential factors were related to the roots, i.e. maximum root depth and root plate height; with the former being the most important. As the maximum root depth of a tree increased, the probability that a tree would suffer stem breakage rather than be uprooted increased. Coutts (1986) and

Ray and Nicoll (1998) similarly suggested that the strength of the root anchorage influences the mode of failure. Root plate height also influenced the mode of failure. Trees with larger root plate heights were more likely to suffer stem breakage rather than uprooting, although it has to be considered that these measurements were not accurate as root plate suffered breakage. Root plate height is a measure of the spread of the roots in the windward direction. Quine *et al*. (1995) noted the importance of windward root spread in root anchorage and resistance to uprooting; thus it is not surprising that an increase in root plate height would increase the likelihood of stem breakage. However, it is important to note that root plate measurements may not have been as accurate as desired as many roots broke during tree pulling, especially in trees with wider root plates, but it was decided, nevertheless to include them in the analysis.

5.2 The influence of thinning treatment on tree stability and strength

As expected trees from thinned plots had a higher critical turning moment than trees from unthinned plots, with the critical turning moment increasing as the intensity of thinning increased albeit not to a statistically significant extent. Nicoll *et al.* (2006) similarly noted in a tree pulling study in Sitka spruce that wide spacing (resulting from a respacing conducted at age 11 and tree pulling conducted 22 years later) did lead to higher critical turning moments but only because trees at wide spacing had larger stem mass.

The findings in relation to critical turning moment would initially suggest that heavy thinning would increase stability. However, it is important to note that whether this is the case not only depends on anchorage but also on the extent of wind loading on the tree crown. The latter was not accounted for in this study. In studies where both parameters were measured such as that by Nicoll *et al.* (2009) critical wind speeds were lower in heavily respaced stands compared to those with less intensive respacing. The calculation of critical wind speed takes into account the relationship between the drag of the air on a surface and the aerodynamic roughness of the surface, in this case the crown (Gardiner *et al.,* 2000). As crowns tend to be wider and deeper in heavier thinned stands, the critical wind speed required to uproot trees decreases.

The lack of statistical significance noted for the thinning treatment means for critical turning moment is likely to be attributed in part to the high variability in the critical turning moment values within each thinning treatment and the small number of trees for which this parameter was recorded (arising from the high number of trees that snapped). Another factor contributing to this variability is the actual treatments themselves. The thinning treatments were applied at plot level with various intensities of basal area being removed from each plot. Within each plot therefore there is likely to have been variation in the number of trees and the size of trees around each tree. The critical turning moment was measured at tree level, hence it is the characteristics of that tree and it surrounds that are likely to influence the critical turning moment rather than the plot level treatment. The correlation and regression analyses of the critical turning moment data and crop parameters confirmed that this was indeed the case. The results showed that tree and stem weight, diameters measured at different heights (i.e. Ø at 5cm, dbh, Ø at 3 m, Ø at 6 m), tree height and crown width were the variables that exhibited strong correlation with critical turning moment; tree and stem weight being the most strongly correlated. Similar results have been found in previous tree pulling studies (i.e. Gardiner *et al.* 1997; Moore, 2000; Peltola *et al.* 2000; Achim *et al*. 2005; Lundstrom *et al.* 2007, and Bergeron *et al.* 2009). Surprisingly, in contrast to the findings of Nicoll *et al.* (2006); Nicoll *et al.* (2008) and Achim and Nicoll (2009) no variable related to root soil plate, including root depth, was found to be significantly correlated with critical turning moment.

Tree weight was identified as the key influential variable in the stepwise regression. Previous studies have also found tree weight to be the best predictor of critical turning moment in Sitka spruce (Fraser and Gardiner 1967; Blackburn 1986; Cucchi *et al.* 2004; Achim *et al.* 2005). The results also show that the relationship between tree weight and critical turning moment was unaffected by the intensity and timing of the thinnings. Similar results were found by Blackburn (1986), Gardiner *et al.* (1997), Achim *et al.* (2005) and Nicoll *et al.* (2009) who found that the relationship between tree weight and critical turning moment to be independent of respacing intensity, although larger tree weights were found in wider spaced stands as well as those that had been heavily thinned. In this study tree weight increased with increasing thinning intensity (albeit not to a statistically significant extent).

A number of the tree variables, i.e. crown width, tree height and diameters at different heights, which were shown to be significantly correlated with critical turning moment, were not identified as key influential variables in the stepwise regression. However, all of these variables were in themselves correlated with the tree weight, so their influence was likely to have been accounted for by this variable. Surprisingly, root width was identified as an influential variable for critical turning moment despite not being correlated with it. Even more surprising is that the parameter estimate for root width is negative suggesting that as root width increases the critical turning moment declines. It's difficult to see any logic to such a finding as one would expect increasing root spread would improve anchorage and thus increase the critical turning moment. However, as outlined previously, root plate measurements may not have been as accurate as desired.

Values for bending strength (MOR) ranged from 21.0 to 69.7 MPa. The mean value for the 24 samples that suffered stem breakage was 31.29 MPa. Moore *et al.* (2009)

obtained values that ranged from 16.7 to 65.4 MPa and a mean value of 35.0 MPa for Sitka spruce in the UK. In this study, the highest mean value was recorded in the plot that received the heaviest thinning although no statistical test could be conducted due to lack of data. Both the correlation and the stepwise regression analyses found none of the variables tested to be significantly related to bending strength. In considering these results the following points should be noted: First, the small sample size limited the analysis that could be conducted on the data and the conclusions that could be drawn regarding snapped trees. As highlighted earlier the relatively high level of snap was unexpected; instead it was expected uprooted trees and the characteristics thereof would be the focus of this research. Second the bending strength values may underestimate the true bending strength since it was the overbark diameter rather than the underbark diameter that was used to calculate it, a point similarly noted by Achim *et al.* (2005). Finally, these bending strength values could also be affected by the height of cable attachment, a point noted by Peltola *et al.* (2000). In this study the height at the point of breakage averaged 1.4 m above the ground while Peltola *et al.* (2000) recorded 0.3 m using the same height of cable attachment, although Sitka spruce was not a species of her study.

5.3 Effect of thinning on tree development and growth

Thinning and the intensity thereof bring about changes in crop structure. In this study the trees were measured 5 (or 3 in the case of delayed thinning) growing seasons after the first thinning intervention and immediately after the second thinning. The following section looks at the characteristics of the trees (i.e. the mean dbh trees that were pulled) after those five years.

5.3.1 Stem parameters

Some of the diameter measurements were influenced by thinning treatment; the diameters at 3 m and 6 m above the base were significantly lower in trees from the unthinned plots compared with those from the plots that had either a heavy or medium thinning. Nicoll *et al.* (2009) noted similar results with respect to respacing intensity in Sitka spruce in Scotland and Cucchi and Bert (2003) for maritime pine in Southwest France. The trends in dbh were similar (albeit statistically significant at the 10% level rather than 5%). Tree height was unaffected by thinning treatment. The net result was significant differences in the h/dbh ratio, with trees in the unthinned plots exhibiting the highest h/dbh ratio (i.e. 76); significantly higher than the value for the heavy and medium thinned plots (i.e. 66 and 67 respectively). Wonn and O’Hara (2001) found that the threshold h/dbh value is 80 with trees with higher ratios than this more likely to experience windthrow than those with ratios below this value. Based on this definition all trees were stable, with the unthinned plots closest to this threshold figure.

5.3.2 Crown parameters

Among the tree parameters recorded, thinning treatment seemed to have the greatest influence on the crown parameters. Crown height, i.e. the height at which the crown started was lower with increased thinning intensity (except for the delayed thinning treatment); crown length was greater similarly with increasing intensity. Crown width also increased with increasing thinning intensity. These findings confirm what is well understood, i.e. wider spacings arising from heavier thinning intensities promote deeper and wider crowns. This in turn helps to bring down the centre of gravity of the tree (e.g. Deans and Milne (1999)), a trend again confirmed in this study; the centre of gravity of trees from the heavy thinned plots were lower than those for trees from the unthinned and light thinned plots.

5.3.3 Root parameters

Among the root parameters recorded, only average root depth was significantly influenced by thinning treatment albeit only at the 10% level. Average root depth was greater in the unthinned stands than in thinned stands; within the thinned stands however there was no clear trend associated with thinning intensity. This finding may be attributed to the assumption that a higher percentage of rain would be expected to be retained in unthinned stands compared to thinned stands.

5.4 Tree position and tree stability

It was intended that the focus of this study would be the influence of the timing and intensity of thinning on stability. When trees were being selected for study a decision was made to choose some next to drains and others not with the hope that this would provide some interesting insights into the role of proximity to drains on tree stability. However, the results revealed tree position did not have a significant influence on the stability and growth parameters recorded. It was expected that trees next to a drain would have lower critical turning moments in comparison to trees that were not close to a drain within the same plot because root spread was expected to be restricted on the drain side of the root plate. However, the results show that this was not the case, with tree position having no significant effect on root plate width or root plate height. What may have partly contributed to the lack of significant difference in root spread indicators with regard to tree position was that all trees were pulled in the direction of the prevailing wind. This meant that for some trees next to a drain the windward roots, i.e. those that were measured, were not those by the drain.

5.5 Considerations and limitations associated with the methodology

The main aim of this study was to compare the stability of Sitka spruce in relation to different thinning intensities and the timing of those thinnings. Stability can be determined in a different number of ways; empirically, mechanistically or using a combination of both. Mechanistic studies have focussed on the calculation of critical turning moments and more recently on critical wind speeds to assess the stability of trees. Critical turning moment is an index of root anchorage while critical wind speed calculated from the same type of study is a better indicator of the overall stability of a tree, as both underground and aboveground parameters are accounted for. In this study only critical turning moments were calculated hence stability from the point of view of root anchorage only is accounted for. It is acknowledged that calculations of critical wind speed could have given a more complete assessment of tree stability, as noted by Nicoll *et al.* (2009). However, this was beyond the scope of the existing project.

As highlighted above the primary aim was to investigate the influence of thinning on stand stability. The influence of thinning on a stand has a progressive component. First, when a stand is thinned, the removal of neighbouring trees brings about an immediate increase in wind loading; whereas the influence on size is more gradual. It is for this very reason that forest stands have been found to be more unstable during the first years after the thinning intervention; thereafter trees regain some stability. In this study the plots had experienced two thinning interventions, with the trees being pulled immediately after the second thinning. Hence while the trees in the thinned plots had had 5 years (or 3 years in the case of the delayed thinning plots) of acclimative growth; their crowns, stems and roots would not have had the opportunity to respond to the greater growing space available after the second thinning but would have experienced the effects of increased wind loading. These considerations highlight the importance of the timing of the tree pulling in the context of the thinning intervention. It would desirable therefore to repeat the tree pulling test before and after future thinning interventions.

In this study the stems were truncated in advance of tree pulling primarily so as to not disturb the rest of the stand. In other tree pulling studies, some have chosen to truncate the stem (e.g. Rodgers *et al.,* 1995; Mulqueen *et al.,* 1999; Rodgers *et al.,* 2006) while others did not (e.g. Fraser and Gardiner, 1967; Blackburn, 1986; Peltola *et al.,* 2000; Achim *et al.,* 2005; Nicoll *et al.,* 2005; Nicoll *et al.,* 2006; Achim and Nicoll, 2009). It is acknowledged that truncation is likely to have had influenced the critical turning moment as the latter is a measure of both the turning moment of the force applied by the winch and the turning moment of the overhanging weight when maximum load applied. Nevertheless, given that the greatest proportion of the tree weight is concentrated in the lower part of the stems, it is expected that the inclusion of the whole tree weight would have only had a minor influence on critical turning moments recorded.

It is important to note the limitation of tree pulling tests, i.e. they don’t take into account the neighbouring effects, so the transfer and dissipation of energy to neighbouring crowns is not taken into account.

6 Conclusions and recommendations

The present study investigated whether the timing and intensity of thinning influenced stability in Sitka spruce as measured by critical turning moment. While the trends in the data were that trees in stands thinned on time had greater mean critical turning moments than those unthinned or where thinning was delayed, the lack of statistical significance associated with these trends limits the inferences and conclusions that can be drawn from them. However the study did show that the thinning treatments were already having an influence on some tree parameters; tree diameter (at different heights) and crown width and height were significantly greater in the thinned plots compared to the unthinned plots. Additionally tree parameters that are related to tree stability e.g. h/dbh ratio and centre of gravity, were lower in thinned plots than the unthinned ones. Further testing is required to determine whether these initial trends in both critical turning moment and tree parameters hold up. It would also be desirable to monitor trends over time to account for the progressive influence of thinning as a stand develops and to replicate the study over a range of different forest stands (i.e. different soil types, water table depth, etc.). The scope of testing should also expand to include estimates of critical wind speed so as to provide a more holistic view of tree stability.

Changing management practices in an effort to increase stability often involves a trade-off. Increasing root anchorage for example, in an effort to reduce the risk of uprooting in turn may increase the risk of snapping. In this study this risk was highlighted with the low water table levels (which may be attributed to the large drain on the site) contributing to the deep rooting which in turn was associated with the relatively high breakage levels.

In conclusion this is the first study conducted in Ireland to investigate how different thinning practices influence critical turning moments. It is also one of a very small number that have been conducted worldwide on this topic. The results therefore add to the knowledge base on tree stability and windthrow risk. Research conducted throughout Europe suggests that storms, and hence windthrow, are likely to become more frequent in the future (Haarsma et al., 2013; Mölter et al., 2016). This study should provide a good platform from which repeat studies may be conducted, allowing for a better understanding of tree stability in windy climates.

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