Wind effects on juvenile trees, with special reference to Radiata Pine growing in New Zealand

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EXECUTIVE SUMMARY

WIND EFFECTS ON JUVENILE TREES, WITH SPECIAL REFERENCE TO RADIATA PINE GROWING IN NEW ZEALAND

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Toppling, or the windthrow, of young (< 2-3 years of age) trees is a problem in some regions of the world, including New Zealand. In that country, the incidence of toppling of young radiata pine (*Pinus radiata* D. Don) trees, particularly on fertile ex-farm sites, has been a concern to foresters. Toppling differs from wind damage in older forests in that trees are not blown completely over, but instead attain a lean; a tree is said to have toppled when this lean exceeds 15° from vertical. Impacts of toppling include a higher incidence of stems with basal sweep and reduced selection choice at time of pruning and thinning which in turn reduces desired final stocking levels. When trees from toppled stands are harvested, basal sweep results in reduced yields of clearwood and increased levels of compression wood in sawn timber.

This paper discusses the phenomenon of toppling and presents an overview of research that has been carried out to identify key factors which contribute to the risk of this occurring and evaluate treatments which reduce this risk.. An overview of a mechanistic model which aims to predict the probability that a tree will topple is presented along with the results from experiments which have been conducted to parameterise this model.

Keywords: wind damage, toppling, tree sway, compression wood, sinuosity

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INTRODUCTION

In mature and semi-mature forests, strong winds can result in damage in the form of stem breakage or uprooting of trees (Coutts and Grace, 1995; Peltola et al., 2000; Ruck et al., 2003). Strong winds (and snow) can also result in damage to younger trees (i.e., those trees typically less than six years of age or between 1 m and 3 m in height), however in this case trees are generally not completely uprooted, but lean at various angles and continue to grow. This type of damage is generally referred to as juvenile instability or toppling. A threshold angle of residual lean of 15 degrees from the vertical has been proposed by Mason (1985) as a quantitative definition of toppling. Trees that have toppled can recover their upright position, either naturally or through intervention by forest managers, but are likely to retain some level of stem sinuosity or basal sweep (Cremer, 1998). This has a negative impact on timber recovery and values, as it results in reduced conversion factors (Cown et al., 1984) and the mechanical properties of the timber, particularly strength and stiffness, may be reduced due to the presence of compression wood which is formed in conifers in response to geotropic stress (Nicholls, 1982; Timmel, 1986). There is also some suggestion that those trees which have toppled may be more susceptible to wind damage in the future due to poor root architecture (Burdett, 1979; Burdett et al., 1986).

Toppling has been observed in a number of species and in many different regions of the world. It has often been associated with fast-growing pine species such as radiata pine (*Pinus radiata* D. Don) growing in Australia (Clarke, 1956), New Zealand (Chavasse, 1969; Mason, 1985) and Chile (Cendoya Hernandez and Munoz Saez, 2002), and lodgepole pine (*Pinus contorta* Dougl. ex Loud.) growing in North America (Burdett et al., 1986), Europe (Martinsson, 1982; Rosvall, 1994), the United Kingdom (Moss, 1971; Lines, 1980) and Ireland (Pfeifer, 1982). However it has also been observed in a number of other species, including *Populus* (Harrington and DeBell, 1996), Scots pine (*Pinus sylvestris* L.) and Corsican pine (*Pinus nigra* Arnold) (Edwards et al., 1963) as well as in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), cider gum (*Eucalyptus gunnii* J.T. Hook*)*, maritime pine (*Pinus pinaster* Ait.), Monterey and Mexican cypresses (*Cupressus macrocarpa* Hartw. ex Gordon and *C. lusitanica* Mill., respectively), western redcedar (*Thuja plicata* Donn ex D. Don) and Port Orford cedar (*Chamaecyparis lawsoniana* (A. Murr.) Parl.) (Chavasse, 1969; Lines 1980; Barton, 1995).

In New Zealand, toppling was observed as far back as the mid 1920’s when the first plantations of exotic species were established (Chavasse, 1969). During the period of rapid expansion of the planted forest area in New Zealand during the mid 1990’s, large areas of forest were established on former farm land which was typically very fertile due to a history of fertiliser application. Significant areas of toppling were observed on these sites, and the phenomenon of toppling was identified as one of the most important issues facing the forest industry at the time.

Toppling first came to the attention of researchers in 1968 following a series of severe storms. Since the 1970’s, a considerable amount of research has been undertaken into the problem of toppling in New Zealand’s radiata pine plantations. The Plantation Management Cooperative has carried out research into toppling over the last decade and produced the following reports.

Report No. 44 (Turner et al, 1998)
Report No. 48 (Moore, 1998)
Report No. 52 (Tombleson & Turner, 1998)
Report No. 53 (Tombleson & Turner, 1998)
Report No. 72 (Tombleson, 2000)

This research has attempted to determine the main causal factors, evaluate a number of risk reduction and remedial treatments and to look at the implications of toppling in terms of the quality of the future timber resource. To our knowledge, there has not been any attempt to synthesise the results of this research, much of which is unpublished. In this paper, previous research which has investigated the causal factors associated with toppling and potential treatments to reduce the risk of toppling or to remedy stands where toppling has occurred is summarised. Finally, recent research focussing on the development of a mechanistic model which attempts to predict the risk of toppling and the effect that different factors have on this risk is presented.

CAUSAL FACTORS ASSOCIATED WITH TOPPLING

The risk that a young stand of trees will topple is a combination of many different factors. Clearly, strong winds (or snow) are required, but a number of other factors can act to predispose trees to toppling. In 1968, a survey of New Zealand Forest Service Conservators (Chavasse, 1969) concluded that toppling was most likely to occur on sites that have wet soils and where there are strong turbulent winds. However, forest managers believed that the susceptibility to toppling could be increased by the choice of tree stocks, poor planting, high soil fertility or by excessive weed competition. These are still viewed by present forest managers as the key factors contributing to the occurrence of toppling and are consistent with those noted by other authors (e.g., Lines, 1980; Burdett et al., 1986).

Site Factors

The key site factors which affect the risk of toppling are believed to be the degree of wind exposure in relation to topography, rainfall, and soil texture, consistency and fertility, particularly nitrogen and phosphorous levels. Many regions of New Zealand experience strong winds as evidenced by damage which has occurred in older forests. This damage is usually the result of winds associated with sub-tropical cyclones or winds enhanced by topography (Littlejohn, 1984; Reid, 1984). A number of managers have observed that toppling does not appear to occur on sites directly exposed to high winds, but is more likely on the leeward side of a ridge where there is enhanced wind turbulence, or in areas where the wind is channelled (Chavasse, 1969).

A number of soil factors are also thought to affect the risk of toppling. A survey by Chavasse (1969) indicated that toppling was more likely to occur on heavy silt or clay soils than on those of a more open texture. The distribution and anchoring ability of tree roots are affected by soil texture and consistency (Mergen, 1954). In turn, the factors determining consistency are cohesive and adhesive strength and the angle of internal friction (Craig, 1990); the cohesion of clay soils is dependent on moisture content and is greatest when the soils are dry. Conversely, non-cohesive soils anchor tree roots mainly through frictional forces and are most resistant when their moisture content is at or close to field capacity (Mergen, 1954).

The interaction between soil physical properties, wind speed, rainfall and drainage is, therefore, likely to have an impact on the risk of toppling. For example, it could be expected that the likelihood of toppling on a site which has clay soils will be higher if a wind event is associated with heavy rain (i.e., the soils are saturated) than if the same wind event occurred when the soils were dry.

In addition to soil physical factors, soil chemistry or fertility can also affect the risk of toppling. As well as having low shear strength when wet, many clay soils in New Zealand, particularly those which have been under pasture, have high fertility. High rates of toppling have been observed on ex-farmland sites (Chavasse, 1969); on such sites radiata pine trees can reach heights of up to 3 metres by age two years. Increased rates of toppling on more fertile sites have also been observed in other countries (e.g., Lines, 1980; Burdett et al., 1986). However, the mechanism which results in an increased incidence of toppling on these sites is unclear. There is some evidence which suggests that high fertility levels result in an increase in above-ground biomass that is greater than the corresponding increase in root biomass, leading to an overall reduction in the root to shoot ratio (Nambier, 1980; Auberlinder, 1982). It is assumed that the forces which act to destabilise the tree are proportional to the above-ground biomass, while those that act to resist applied loads are proportional to the below ground biomass. Therefore, a reduction in the root:shoot ratio will result in an increase in the risk of toppling. However, other studies (Richardson, unpublished data) have shown that there is no difference in the root:shoot ratio between radiata pine seedlings grown on fertile ex-farm sites and those grown on ex-forest sites.

Genetics

The susceptibility of lodgepole pine to toppling is influenced by provenance (Lines, 1980; Burdett et al., 1986). In the United Kingdom, an increase in the rate of toppling was observed when faster growing provenances of lodgepole pine from coastal Oregon and Washington replaced those from the interior of British Columbia (Lines, 1980). However, this observed increase in the frequency of toppling may not be due to the rate of growth per se, but rather to differences in root:shoot ratios. A study investigating the root:shoot ratios of 18 provenances of lodgepole pine (Lines, 1971) found that southerly provenances had lower root:shoot ratios than northerly ones, and that low-elevation ones had higher root:shoot ratios than high-elevation ones.

Radiata pine naturally occurs at five locations in North America; Año Nuevo, the Monterey Peninsula and Cambria in California and the Mexican islands of Cedros (*Pinus radiata* var cedrosensis) and Guadalupe (*Pinus radiata* var binata) (Burdon and Bannister, 1973). While there is a great deal of variation between the natural provenances, nearly all commercial stands of radiata pine have their origin in the Año Nuevo and Monterey provenances. There is some suggestion that the two island provenances may have greater windfirmness due to more prominent taproot development (Burdon, 1992) and there have been trials established to investigate the growth and stability of Guadalupe hybrids.(Tombleson and Penman, unpublished data). Most of the tree breeding in New Zealand has focussed on improving the characteristics of trees grown from the original Año Nuevo and Monterey provenances. This had resulted in trees which have improved growth and form compared with the unimproved material. However, one question that has been asked by both managers and researchers alike is whether this selection for improved growth and form has resulted in trees which have a lower root:shoot ratio and therefore a higher risk of toppling (e.g., Nielsen, 1992). While Mead et al. (1993) found marked differences in the rates of toppling between treatments in an agroforestry experiment containing different radiata pine genotypes, these differences were mainly due to differences in planting stock (i.e. bare-rooted seedlings and cuttings), rather than the genotypes themselves.

Tree Stocks

Nursery practices and the quality of planting have been frequently identified as key factors associated with the occurrence of toppling (e.g., Chavasse, 1978; Pfeifer, 1982; Mason, 1985; Burdett et al., 1986). This conclusion is based on the observation that stands which have historically been established via direct seeding contain trees that have well-defined tap roots, a well-distributed array of lateral roots, and seldom topple (Chavasse, 1978; Burdett et al., 1986). However, a static winching study comparing direct seeded radiata pine with bare-root seedlings and cuttings showed no increased stability of the direct seeded tree stocks (Fawkner, 2001). The process of raising trees in a nursery and the subsequent out-planting can result in a distorted root system, which in turn can increase the risk of toppling (Chavasse, 1978; Burdett et al., 1986; Hakansson and Lindstrom, 1994; Lindstrom and Rune, 1999). Many problems were encountered with the early container-grown stock due to the roots becoming deformed once they made contact with the edge of the pot in which they were growing (Hulten and Jansson, 1978; Tinus, 1978). However, improvements in the techniques for raising containerised stock have dramatically reduced these problems. In contrast to many regions of the world, most trees planted in New Zealand are bare-rooted seedlings (Chavasse, 1978). A system of nursery conditioning has been developed which is designed to produce a root system than allows the seedling to be easily lifted in the nursery, planted without gross distortion and ensures a high rate of survival following out-planting (van Dorsser and Rook, 1972). This conditioning process results in seedlings with numerous small-diameter fibrous roots, but few structural roots at the time of planting. Therefore, the tree is at greater risk of toppling until the structural root system can be established.

Vegetative propagation is becoming more common for multiplying up superior seed and improving the form of young stands (Menzies et al., 1991). In particular, radiata pine is well suited to the production of rooted cuttings (Thulin and Faulds, 1968). Cuttings from donor trees aged between 2-4 years or collected from nursery stoolbeds aged two years or more are known as "physiologically-aged" cuttings and have stiffer root systems and more open and permeable crowns compared with seedlings (Menzies et al., 1991). Field trials have shown that significantly lower rates of toppling occur in physiologically aged cuttings compared with juvenile cuttings and seedlings grown on the same site (Aimers-Halliday et al., 1999; Coxe and Mead, 1999).

Excavation of three-year old direct-sown seedlings, bare-root seedlings, and cuttings showed no differences between plant types in below ground biomass, root:shoot ratio, tap root, or sinker root biomass (Watson and Tombleson, 2002). Significant differences between plant types were found for total above-ground, branch, foliage, root bole and lateral biomass. It was proposed that an increase of biomass allocated to the near-stem portion of the root system, particularly on the leeward side of a tree, can be considered as an early indicator of emerging tree stability.

Other systems of preparing tree stocks, such as super-trim and box-pruned seedlings where seedling roots are trimmed back are possibly more stable than bare-root seedlings (Chavasse, 1978; Mason, 1985). Results from Coxe and Mead (1999) however, suggest there is no difference.

Planting
Planting quality has been claimed to affect the risk of toppling (e.g., Chavasse, 1978; Brunsden, 1980). In New Zealand, most tree stocks are planted by hand using a spade, although there are some areas where machine planting is undertaken (Balneaves and Cullen, 1981). There have been a number of operational studies conducted to determine the best method for planting a tree which ensures that the vertical roots are not distorted, and horizontal roots are well distributed and not pointing upwards. However, instances of poor quality planting still occur. These usually arise when planting is undertaken by unskilled labour, who are poorly trained and paid based on the number of trees planted rather planting quality (Trewin, 2003). In severe cases, a single planting slit is created and the tree placed into it – this is often referred to as "slit and stuff planting". These poorly planted trees often have roots that are swept upward when the trees are put into the slit created by the spade. This leads to a "J-shaped" vertical root system with a poor radial distribution of lateral roots. Despite evidence of the effect of planting quality on root form of young trees, there is little direct evidence of a link between planting quality and the incidence of toppling. Most of the so-called evidence which suggests a link between planting quality and the incidence of toppling comes from field observations. The few well-designed trials that have been established (e.g., Brunsden and Bowles, unpublished data; Menzies unpublished data) have generally yielded inconclusive results. Planting tree stocks 8 to 10 cm deeper than they were growing in the nursery has become a common planting practice, however no formal studies have been undertaken to investigate the effects of planting depth on the risk of toppling.

Cultivation
Until relatively recently, cultivation prior to planting in New Zealand was mainly in the form of ripping to break up compacted sub-soil layers (Mason and Cullen, 1986). Ripping, generally in association with mounding led to increased growth and survival of trees and to a reduction in the incidence of toppling (Mason and Cullen, 1986). Trees planted on sites which had been ripped had better root form and vertical root growth than trees growing in unripped control (Mason et al., 1988). However, there has also been a suggestion that cultivation can increase the risk of toppling. Trees planted on sites which have only been disc cultivated or rotary-hoed are more likely to topple because the sub-soil remains compacted, which inhibits vertical root development, but the strength properties of the topsoil have been reduced (Mason and Trewin, 1987). Spot cultivation has become more common as a site preparation technique and has replaced line cultivation on many reforestation sites. There is evidence from a trial in which trees were winched over to indicate that, immediately following planting, trees planted on mounds may be less stable than trees growing on uncultivated soil.

Weed Control
Poor weed control has been identified as a factor associated with increased rates of toppling (Chavasse, 1969), however there is also some anecdotal evidence to suggest that in some situations weed control could lead to an increase in the incidence of toppling (Dawn and Coxe, 2001). On ex-pasture sites in those areas of the North Island with a milder climate, a second dose of herbicide is commonly applied in the spring following planting to kill emerging summer grasses. As a result, the ground immediately adjacent to the trees is often completely bare earth and there appears to be an increased risk of toppling in the first year of growth. On such sites, the presence of grass roots to bind the soil immediately around the base of the stem is believed to improve early tree stability (Turner and Tombleson, unpublished data), however there may be a reduction in early tree growth due to shading and reduced soil moisture. This hypothesis has yet to be tested experimentally.

RISK REDUCTION AND REMEDIAL TREATMENTS

A number of options are available to forest managers to reduce the risk of toppling. The location of a stand of trees can have a substantial effect on the risk of toppling, as it will determine the wind exposure and soil characteristics, but the decision as to where to plant may have already been made. However, if several sites are being evaluated for an afforestation project, then toppling is an important risk factor for due consideration. For a given site, the perceived risk of toppling will determine what, if any, treatments might be employed to reduce such risk. These include: choice of plant type, and pruning to reduce the area of crown exposed to the wind.

Choice of Plant Types

As noted previously, results from field trials indicate that the incidence of toppling is less in trees grown from physiologically-aged cuttings than in trees grown from seedlings or juvenile cuttings. Therefore, the use of physiologically-aged cuttings has been advocated particularly on sites where there is a high risk of toppling (Aimers-Halliday et al., 1999). Other options potentially available for high risk sites are direct seeding and the direct setting of cuttings in the field. Up to about 1970, substantial areas were reforested using seed which was broadcast from aircraft (Levack, 1973). However, this approach was abandoned because of the cost, seed predation and the investment in blanking and thinning required to achieve a uniform stand. Furthermore, this method is only likely to be suitable for reforestation where the correct mycorrhizae are already present on site. Therefore, it is unlikely to be appropriate for afforestation of ex-pasture sites unless the issues of variability, seed predation and mycorrhizae can be addressed. It is also possible to directly set un-rooted cuttings of radiata pine in the field (Aimers-Halliday et al., 1999). A further disadvantage of direct-seeding and setting of cuttings into the field compared to establishment using nursery stock is the loss of one years growth. Field trials conducted by Fawkner (2001) indicate that the incidence of toppling in direct-set cuttings are similar to those in rooted cuttings, but significantly lower than those in planted seedlings.

Pruning

A number of different pruning treatments – collectively these are often referred to as “crown lightening” – have been applied to trees to reduce the area of crown exposed to the wind, which in turn will reduce the applied force acting on the tree. Pruning treatments include: (1) removal of branches from the bottom third of the stem; (2) removal of every third branch; (3) removal of branches from the middle 50 percent of the tree stem; (4) reducing the length of branches along the entire stem; and (5) reducing the length of those branches in the upper half of the crown (Barton, 1995; Davies-Colley and Turner, 1999). The effectiveness of this latter treatment, referred to as “wind proofing”, was examined in a replicated trial subjected to strong winds with wind gusts of up to 95 km hr^{-1} and heavy rain shortly after it was installed. No toppling was observed in the wind-proofed trees, while 50 percent of the untreated controls had toppled to some extent – 34% of these to an angle of more than 15º (Davies-Colley and Turner, 1999). This treatment is relatively inexpensive to apply and no significant loss in growth was observed in the treated trees (Davies-Colley and Turner, 2001). Therefore, it appears to offer significant potential as a means of reducing the risk of toppling, particularly on high risk sites.

Remedial Action for Toppled Trees

If toppling has occurred, any follow-up action ranges from doing nothing and allowing the trees to correct themselves naturally (assuming lean is not too severe), to complete replanting of the affected areas. The choice of method employed will depend on a number of factors including: tree size, severity of tree lean, area affected, whether the number and distribution of non-toppled trees is adequate for a final crop, cost of remedial action, and likelihood of remedial action being effective. Toppled trees up to approximately 1 m tall can be straightened and held vertical using a block of soil wedged against the base of the tree – a method known as "sodding" or "turfing". However, field trials indicate that depending on tree age and size, this method could be ineffective as the majority of trees re-toppled in the following year, in part due to the straightening process which often broke roots of severely toppled trees (Coxe, 2004). Toppled trees can also be held vertical with guy ropes which is extensively used in Chile as a remedial action following toppling of two year old trees. Tying the tree to a wooden stake hammered into the ground next to the tree also appears to be an effective treatment for moderately toppled larger trees (Menzies, unpublished data).

In all cases, remedial action needs to be applied to the trees as soon as possible after toppling to prevent further damage to the root systems. Furthermore, if left for more than approximately one month the new height growth adopts a vertical orientation which, depending on the time of year may not re-straighten following staking or turfing. In situations where there is a low incidence of toppling scattered throughout the stand, or the severity of toppling is not great, it may be preferable to do nothing and remove the affected trees when the stand is thinned. Where there is widespread and severe toppling, the main stem can be pruned off above the lowest whorl and the most vertical branch in this whorl selected to become the replacement leader. If this lowest whorl is close to the base of the tree, the resulting stem distortion is minimal (Mason, unpublished data). However, 'topping' has also shown to be an ineffective remedial treatment, possibly due to roots being damaged and broken in the toppling process (Coxe, 2004).

Overall, reducing the risk of toppling through the choice of aged cuttings coupled with good quality planting practices is preferable to applying remedial treatments to a toppled stand. Crown lightening treatments applied to those stands approaching two years of age can also help to reduce the risk of toppling and may be warranted on high risk sites. Due to the high labour costs associated with applying remedial treatments as well as their ineffectiveness, the most cost effective option following widespread and severe toppling may be to replant the stand.

DEVELOPMENT OF A MECHANISTIC RISK MODEL

Much of the information pertaining to the multitude of factors that are associated with toppling is either speculative or anecdotal, often based on informal observations made by forest managers or researchers. Few quantitative studies have been undertaken to investigate the factors associated with toppling. These have generally either been:

1. Case-control type studies where the characteristics (typically the root morphology) of toppled trees are compared with those of adjacent non-toppled trees (e.g., Mason, 1985), or
2. Designed experiments where different treatments are applied and the rates of toppling and/or the morphological characteristics are compared between treatments (e.g., Coxe and Mead, 2001; Davies-Colley and Turner 2001; Watson and Tombleson, 2002).

While such studies have yielded a considerable amount of useful information about the factors associated with toppling, they do not provide any information on the causal mechanisms that lead to toppling or the likelihood that toppling will occur. Because there appears to be a complex interaction between the factors associated with toppling, it is often difficult to identify those factors associated with toppling from case-control studies. Similarly, designed experiments require good experimental control to minimise the effects of confounding influences. In addition, these trials require wind and rain events of a suitable magnitude during the lifetime of the experiment for toppling to occur in the trial, as well as detailed meteorological data to be collected during such storm events. For this reason, prospective experiments can be problematic for studying rare events such as toppling (Harrington and DeBell, 1996) and have often produced inconclusive results.

Where experiments have yielded positive results, they still do not provide information on the causal mechanisms associated with toppling. Many of the factors measured have been surrogates for the actual parameters of interest. For example, studies which have investigated the effects of different factors on root systems of trees have measured the overall mass and orientation of the roots as surrogates for the strength of the root anchorage (e.g., Mason, 1985; Coxe and Mead, 1999; Watson and Tombleson, 2002). The absence of significant differences in these parameters between the treatments of interest may not mean that there is no difference in the strength of root anchorage. In order to represent the complex interactions between the factors associated with toppling and to provide a quantitative assessment of the risk of toppling, a mechanistic model is being developed. This model is similar to quantitative risk models that have been developed for wind damage in older stands (Moore and Somerville, 1998; Gardiner et al., 2000; Gardiner and Quine, 2000). The model calculates the threshold (critical) wind speed required to topple a tree of given characteristics (i.e., stock type and size) growing under certain conditions (i.e., soil type and moisture, planting quality, and weed control). Knowledge about the relative exposure of the site is then used to calculate the probability that this threshold wind will be exceeded in any one year (Figure 1).

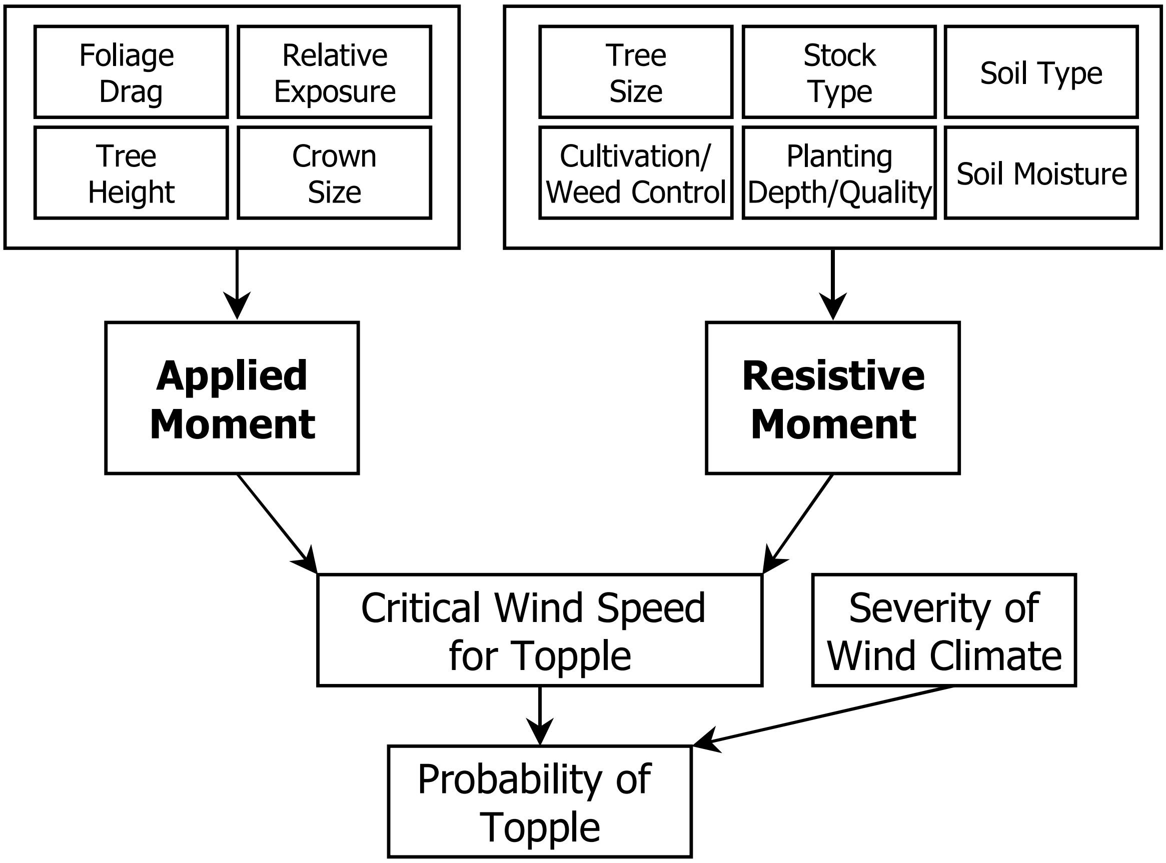

Figure 1. Overview showing the components of the mechanistic model for predicting the probability of toppling.

The initial focus of research has been on quantifying the resistance of trees to applied loads. In particular, the aim has been to quantify the effect of plant type, tree size, soil type, soil moisture content, planting quality, planting depth, weed control and cultivation on this resistance. This has been achieved by using a winch and cable system to apply loads to the tree at a height of 0.4 m above the ground and to measure the resulting deflection of the stem at 0.1 m above the ground. Such an approach is similar to that used in other studies on small trees (e.g., Burdett, 1979; Mason unpublished data) as well that used in the study of larger trees (e.g., Moore, 2000).

To provide a source of trees to winch over, trial stands were established between 1998 and 2000 at sites located throughout New Zealand. Across these sites, more than 500 trees have been winched over. The load-deflection data from these winching trials indicates that there is an elastic region (i.e., within this region the tree will return to its original position when the load is removed) up until an angle of deflection of approximately 10 degrees, followed by plastic deformation (i.e., the tree will not return to its original upright position when the load is removed, but will have a residual lean) as roots break, are pulled through the soil or the soil itself deforms (Figure 2). The stiffness of each tree in the elastic and plastic range was calculated from the slope of the load-deflection curve and expressed in units of kg/degree.

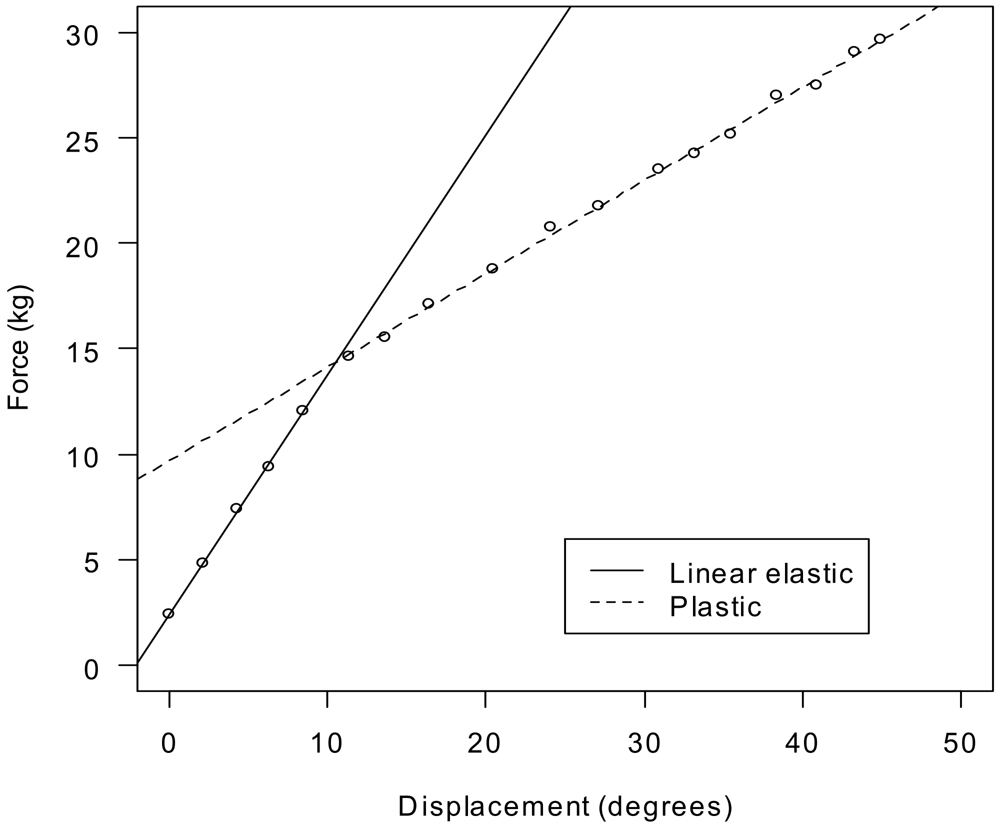

Figure 2. An example showing the relationship between load and deflection for a tree that was winched to an angle of 45 degrees. The open circles show the actual deflection measurements, while the two lines correspond to the stiffness models fitted to the data.

A similar calculation was undertaken for the region where plastic deformation occurs. From these relationships it is possible to predict the deflection of a tree for a given applied force, as the stiffness in the both the elastic and plastic ranges is strongly related to tree size (Figure 3). Differences in the stiffness of root systems between plant types, cultivation methods, planting quality, soil types and soil moisture content can then be compared through analysis of covariance.

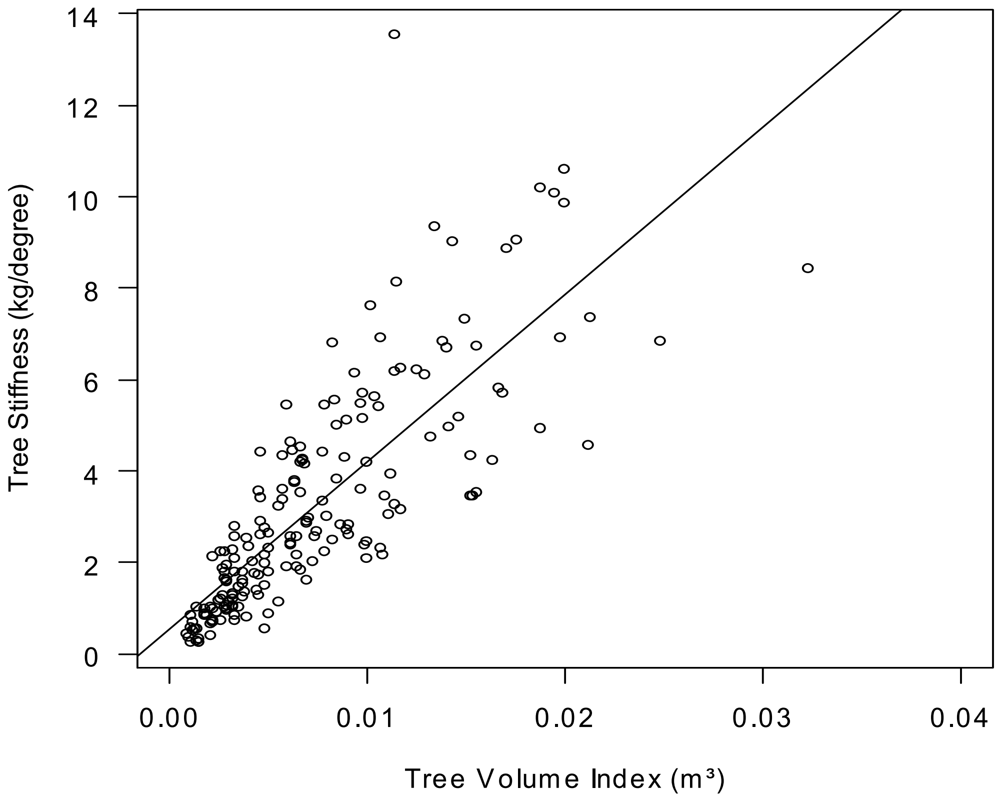

Figure 3. Relationship between tree stiffness in the elastic range and tree size. Tree volume index is calculated as the product of the square of root collar diameter and tree height. The solid line was fitted using ordinary least squares regression.

The wind speed required to deflect a tree by a certain amount can be calculated by determining the force required to deflect the tree by this amount and then calculating the wind speed necessary to create a force of this magnitude given the size of the tree and, in particular, the size of its crown. The total drag force (D, kg) acting on the crown of a tree for a given wind speed (U, m s^{-1}) can be determined from its crown mass (M, kg) using the following relationship derived from wind tunnel tests (Mayhead et al., unpublished data):

$$D = U^2 M^{0.667} (0.025 e^{-0.004124 U^2} + 0.01643) \qquad [1]$$

Research is currently being undertaken to develop functions to predict the crown mass of trees from readily measurable characteristics such as root collar diameter and total height and to compare these values between plant types. Information on differences in above-ground characteristics can then be combined with the results from the comparisons of below-ground characteristics to determine the overall differences in the threshold wind speeds and rainfall required to induce toppling as a function of site, plant type, planting quality, etc.

The risk (i.e., probability) of toppling can then be calculated as the probability that this wind speed and rainfall is exceeded in any one year based on historical meteorological data for the region. This probability is the inverse of the long-term average return period and can be determined from the analysis of long-term data on extreme wind speeds (Figure 4; Cook, 1985).

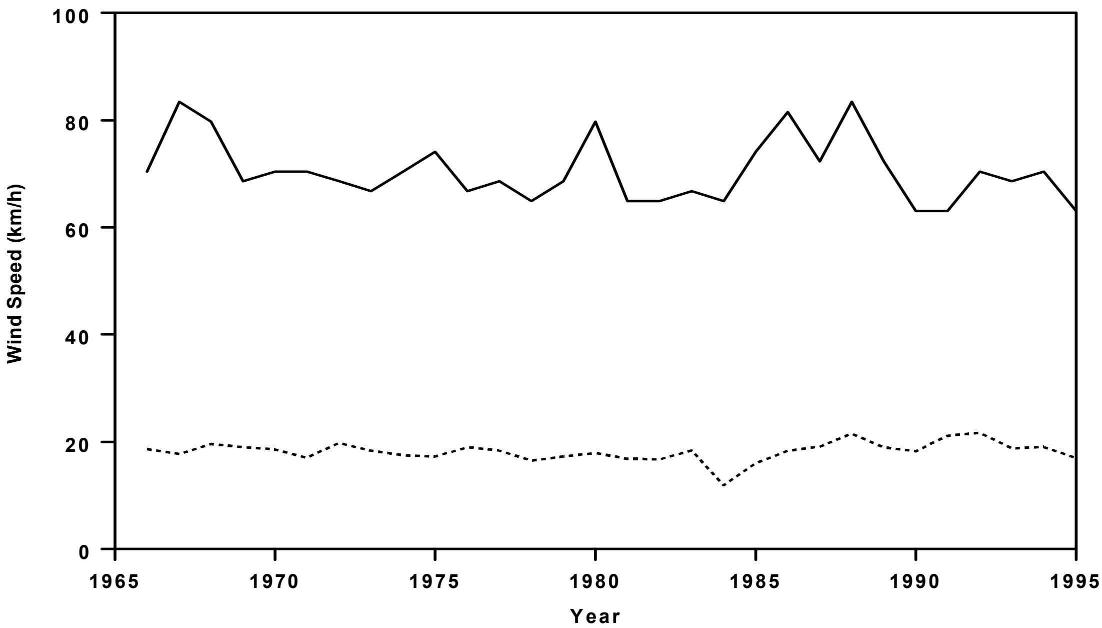

Figure 4. Time series of wind speed from Auckland Airport between 1966 and 1995. The solid line indicates the annual maximum 10 minute wind speed, while the dotted line indicates the average annual 10 minute wind speed.

An example of a return period function fitted to a time series of hourly wind speed data from Auckland Airport (Figure 5) shows that below a wind speed of approximately 65 km/h, the return period is constant and equal to one year. However, above 70 km/h, the return period increases rapidly with increasing wind speed. If the threshold wind speed for toppling is above this value, then factors which affect this threshold wind speed will have a large effect on the risk of toppling.

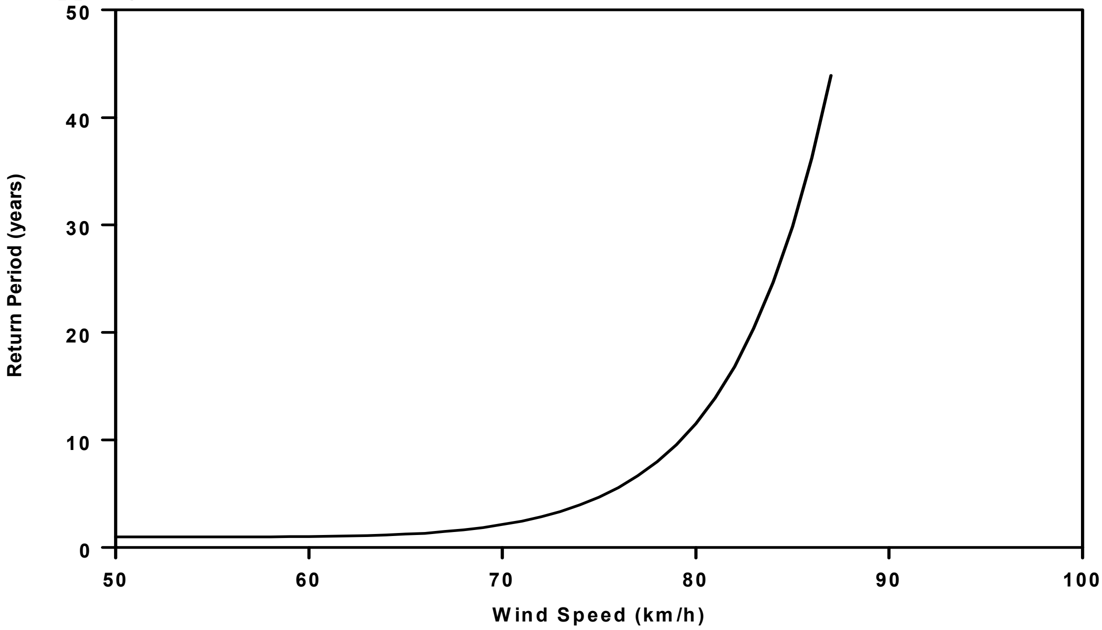

Figure 5. Relationship between wind speed and return period for Auckland Airport, New Zealand. The equation for the line was calculated from the time series of annual maximum wind speeds shown in Figure 4.

Dynamic behaviour of trees
While the mechanistic model presented provides a good basis for understanding the behaviour of young trees subjected to wind loading, it is a simplification of reality. Trees are dynamic systems and their response to applied wind loading is frequency dependent, with the tree responding most to wind gusts at frequencies close to its resonant frequency and its harmonics (Gardiner, 1992). In these situations the dynamic effects are likely to increase the bending of stems and hence the load on the root system (Milne 1991). Dynamic oscillations of young trees appear to be particularly important factor when considering the processes leading to toppling. It is believed that tree sway contributes to the progressive deformation of the soil around the root collar – a phenomenon often referred to as "socketing". In situations where socketing has occurred, the trees are more likely to subsequently topple (Mason, 1985).

The mechanistic model for toppling is currently being extended to include dynamic effects. Swaying studies have been conducted to collect information on the natural frequency and damping ratio of twenty young radiata pine trees using the approach described in Moore and Maguire (2005). Natural frequencies of young trees ranged between 1.4 Hz and 2.2 Hz were higher than those observed in older trees (Moore and Maguire, 2004). Damping ratios were between 0.04 and 0.08 (i.e., 4% to 8%). In the swaying trials, the natural frequency and damping ratio were measured before and after the trees received a wind proofing pruning treatment identical to that described in Davies-Colley and Turner (1999). Interestingly, in almost all the trees measured the damping ratio increased following the removal of crown mass (Figure 6).

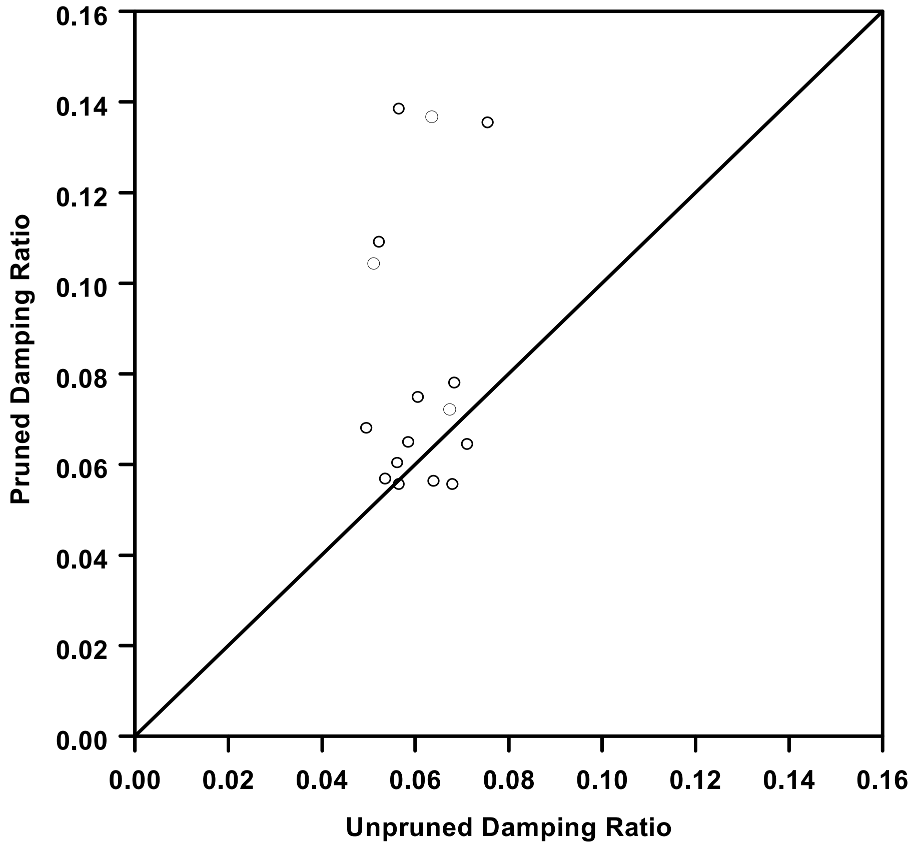

Figure 6. Damping ratio of young radiata pine trees before and after receiving the wind proofing treatment.

Therefore, not only does it appear that the wind proofing treatment may lower the risk of toppling by reducing the area of crown exposed to the wind, but trees receiving this treatment may also be more effective at dissipating energy absorbed from the wind. The mechanism by which this occurs is not properly understood, and further studies are required to investigate this. Information on natural frequency and damping ratio will be included in the updated model and will allow the response to different frequencies of wind loading to be determined.

DISCUSSION AND CONCLUSIONS

While the development of a mechanistic model for toppling is still ongoing, it represents an important first step in codifying knowledge about the processes which lead to toppling. The model has been developed using a combination of engineering mechanics, wind speed data, and data from experiments designed to develop empirical relationships for predicting root anchorage characteristics. Because of this, experiments can be undertaken with the purpose of yielding data to parameterise the model, and therefore do not rely on toppling occurring in order to yield useful information. This overcomes many of the difficulties encountered in using prospective studies to investigate rare events. The model also represents an important first step in linking the various factors associated with toppling, rather than considering them individually or as interaction terms in factorial experiments. In previous research, above and below-ground characteristics have been considered separately, even though it has been recognised that the risk of toppling is likely to be a function of both. For example, the lower incidence of toppling observed in physiologically-aged cuttings has been attributed to a combination of better root anchorage and a more open and permeable crowns (Aimers-Halliday et al., 1999), but the relative contribution of these effects has not been considered previously. Using a mechanistic model, the threshold wind speed and rainfall required for toppling can be calculated for juvenile cuttings, physiologically-aged cuttings and seedlings of the same size or time since planting, and this information used to calculate the differences in the risk of toppling.

The model also adopts a probabilistic approach to the phenomenon of toppling. It recognises that there is a considerable stochastic element associated with toppling and therefore provides a prediction of the probability that toppling will occur, rather than a binary response, i.e., will topple or will not topple. This probability of damage is based on long-term average wind speed and rainfall data. Whether or not toppling actually occurs will depend on the interaction of the stand of interest and a variable wind climate (Quine, 1995). For example, even if the risk of toppling is predicted to be high, toppling may not actually occur because lower than average intensity wind storms occur in the particular year of interest. Conversely, damage may actually occur even though the risk is predicted to be low due to the particular year of interest having higher than average intensity wind storms. The actual level of damage is assumed to depend on the amount by which the threshold wind speed and rainfall for the onset of toppling is exceeded.

This type of integrated risk model is an important risk management tool as it allows forest managers to evaluate risks and to decide on the appropriate course of action. One of the greatest challenges in risk management is the process of risk assessment and the evaluation of management options (Gardiner and Quine, 2000), and a model such as the one presented here makes this possible. It recognises that the risk of toppling is site specific, and therefore allows forest managers to develop and test risk management strategies based on their knowledge of the background level of risk for a given site. On sites where the risk of toppling is high, the potential options for altering the risk will tend to be limited, whilst for sites where the risk is lower the options will be greater and goals other than risk-minimisation are likely to take precedence. It is on sites that have a moderate risk where the greatest potential and benefit exists to reduce risk through careful management (Gardiner and Quine, 2000).

Attempting to reduce the risk of toppling, e.g., through the choice of plant type and crown pruning are two current options available to forest managers. Good quality planting coupled with quality control assessment and documentation is also considered necessary to reduce the risk of toppling (Trewin, 2003). However, it is acknowledged that good quality planting using aged cuttings followed by crown lightening does not necessarily ensure that toppling will not occur during any storm events which may occur during the first few topple-prone years of the stand. Therefore, forest owners may choose to share the risk through insurance schemes which have been specially designed for forestry, or they may simply accept the prevailing risk. Ultimately, the response of forest managers to the risk of toppling will be influenced by the level of calculated risk, their attitude to risk, and the context which is a function of factors including the objectives of management, and the scale of their enterprise. Robust risk analysis models such as the one presented in this paper are therefore a key element of a risk management strategy as they not only provide information on the level of risk, but can also allow a forest manager to examine how various management options affect this risk to way the cost of the management options against the expected loss.

The mechanistic model described in this paper is still being developed and there is still a considerable amount of work required to parameterise it and to identify all of the relationships that are important. However, once this is completed it will provide a tool to:

(a) Enable a better understanding of the influences and their interaction on the process of toppling and if possible apply this knowledge to further reducing the incidence of toppling.
(b) Enable the incidence and severity of topple to be predicted for a given terrain based on local historic meteorological data.
(c) Enable toppling risk to be quantified and incorporated into the decision process for evaluating forestation projects within and between potential sites.
(d) Enable broad scale categorisation and mapping of toppling risk for New Zealand.

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SPECIAL NOTE

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