The effects of soil, terrain and wind climate on tree root system development and anchorage

Bruce C. Nicoll

Doctor of Philosophy

The University of Edinburgh

2006

Abstract

Windthrow remains as one of the most important constraints for forestry in the British uplands. To develop silvicultural systems and decision support tools that will minimise windthrow losses, we require an improved understanding of tree anchorage and root development. A series of studies was conducted to quantify the relative effects of species, soil, and rooting depth on anchorage; examine the effect of terrain on anchorage and root architecture; and examine the effects of changes in wind loading on radial growth in stems and structural roots.

Firstly, a database was constructed of tree anchorage measurements from almost 2000 trees of 12 conifer species. An analysis revealed that the anchorage of Sitka spruce was best on peat and poorest on gleyed mineral soils. Trees with root depths >80 cm had critical turning moments 10 to 15% larger than shallow rooted trees. There was better anchorage for grand fir and Douglas-fir than Sitka spruce with various soils and rooting depths. Lodgepole pine was less well anchored, as was shallow rooted (<40 cm) Norway spruce on gleyed mineral soil and Corsican pine on medium depth (40-80 cm) mineral soil. All other species had similar anchorage to Sitka spruce on equivalent soil.

Secondly, as most tree pulling had been conducted on relatively horizontal sites, anchorage and root development of Sitka spruce was compared between a steep (ca. 30°) slope and an adjacent horizontal area with similar soil. No overall effect of terrain on anchorage was found, but trees pulled upslope had significantly better anchorage than those pulled downslope. The coarse root systems of these trees were extracted and digitised in 3-D. Non-directional root architecture characteristics were similar between the slope and flat terrain. However, trees on the horizontal had more root mass on the leeward side relative to the prevailing wind, while those on the slope had more mass on the windward side, indicating a possible interaction between slope and wind action on root architecture.

Finally, the radial growth response of tree stems and structural roots to wind loading were examined in two experiments: 1. Growth ring chronologies from stems and structural roots of 46-year-old Sitka spruce trees grown on an exposed upland site, were compared with wind records. Wind speed was well correlated with radial growth of structural roots on the lee side of the tree. There was a positive relationship between structural root radial growth at 0.75 m from the tree centre and mean autumn wind speed. 2. Wind movement, light and photosynthate supply were manipulated on 10-year-old Sitka spruce trees. After 4 years, disks were cut from stems and structural roots, and an analysis of annual radial growth showed that trees responded to reduced photosynthate supply (induced by branch girdling) with an immediate reduction in stem and root radial growth. Trees responded to a stand thinning treatment (increased light and wind movement), and to a thinning and guying treatment (increased light, reduced wind movement), with immediate increases in root radial growth, and increases in stem radial growth that were delayed by a year. The response to thinning alone was greater than the response to thinning and guying, and was considerably greater below-ground than above-ground.

Results from these studies provide a basis for future development of models of tree stability and wind risk to forest stands. For the first time, anchorage can be compared objectively between a range of coniferous tree species, soil groups and rooting depth classes. The results of experiments conducted in forest stands on a steep slope and a neighbouring horizontal area indicate that it will not be necessary for models of tree stability to take the slope into account in anchorage calculations. However, the greater vulnerability of trees to downslope overturning indicates that the accuracy of these models will be considerably improved by incorporating directional differences in calculations of windthrow risk on complex terrain. The potential for extensive soil erosion following windthrow on steep terrain, indicated by this investigation, should be taken into account in future management plans for forest stands on complex or mountainous terrain. The thinning and guying experiment has provided results that can be used to explain and model the increased vulnerability of trees following stand thinning, and their subsequent re-stabilisation, in terms of changes in assimilate allocation between above- and below-ground components in response to mechanical stress.

Declaration

I hereby declare that this thesis is my own composition, that the work described is my own except where assistance is explicitly acknowledged, and that it has not been submitted for any other degree or professional qualification.

Acknowledgements

I wish to thank my supervisors, John Grace and Maurizio Mencuccini, from the School of GeoSciences, Institute of Atmospheric and Environmental Sciences, for their guidance throughout this study.

I am particularly grateful for the inspiration and enthusiasm for the subject that I gained from working with Mike Coutts for the first few years of my career. I will also always be grateful to the late Professor K. J. Anderson for encouraging me to study plant biology and then to do a PhD. I thank my colleagues Barry Gardiner, Alexis Achim and Chris Quine who provided me with unflinching support, encouragement and assistance, as well as stimulating discussion and advice.

I am grateful to the Forestry Commission for providing me with the opportunity, funding and resources to study for a PhD. The European Commission part funded the work described in Chapters 3 and 4 within the ECOSLOPES project 'Eco-engineering and conservation of slopes for long-term protection against landslides, erosion and storms' (QLK5-2001-00289).

I was assisted in gathering the data used in this thesis by many colleagues in Forest Research. I benefited from being able to use tree-pulling data gathered over four decades by many Forestry Commission staff. Bill Rayner provided considerable insight into forest soils and ways that they could sensibly be grouped for the analysis in Chapter 2. Shaun Mochan contributed his expertise to the tree pulling studies described in Chapters 2 and 3, and we were assisted by a large number of staff from the Forest Research Technical Support Unit. Alexis Achim performed the anchorage and critical wind speed calculations presented in Chapter 3. The root systems in Chapter 4 were digitised with assistance from summer students over two summers, in particular Kyriaki Gouskou who showed amazing patience during very tedious work. Stéphane Berthier (supported by an EC Marie Curie fellowship) provided advice and assistance in analysing root architecture using Amapmod software. Thanks also to three students from University of York; Andrew Dunn, Tony Lovat, and Alisdair Blain for sanding

stem and root disks and for measuring growth rings for the study described in Chapter 5. Throughout all of this work I have benefited from advice and assistance with statistical analysis from Tom Connolly and Andrew Peace.

Last, but by no means least, I would like to thank my family. I am very grateful to my parents Eileen and Douglas Nicoll and my sister Alison for giving me so much support throughout and encouraging me to finish. And a particularly big 'Thank you' to my wife Krista and our wonderful sons, Thomas and Matthew, for putting up with me and keeping me sane while I worked on this thesis!

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1. Introduction – Anchorage, Stability and Windthrow of Forest Trees

Wind damage to trees

Wind damage is a natural disturbance process that is a necessary part of forest ecosystem dynamics (Putz *et al.* 1983). Forest gaps created by wind allow tree regeneration, and increased structural and species diversity (Quine *et al.* 1999; Schaetzl 1989). In addition, uprooting of trees disrupts soil horizons and causes beneficial mixing of the soil (Cremeans and Kalisz 1988; Kramer 2001). However, despite being an important feature in natural forests, wind damage in managed forests leads to considerable disruption to the industry (Savill 1983). Overturned trees are expensive to harvest and the risks to forest workers in clearing windthrown sites are increased. If trees snap instead of overturning, the most valuable saw logs from the lower part of the stem are lost (Nieuwenhuis and Fitzpatrick 2002). In addition, windthrow commonly damages stands of trees that have not yet reached their age of optimum economic return (Savill 1983), and as a result the profitability of commercial forests is limited by premature felling.

The British Isles have a particularly windy climate compared to other parts of the world due to their location in the track of most north Atlantic depressions (Troen and Peterson 1989). Wind damage to forests in Britain and Ireland has been reported since the 13th century (Quine *et al.* 1995), but it was not until the late 19th century that damage to forests caused a major oversupply to the timber market in the UK. With the widespread expansion of British forest cover in the 20th century, the potential for storms to damage large areas of commercial forest was increased. As new forest plantations, commonly established in exposed upland areas, started to mature in the mid-20th century, wind emerged as the most important limiting factor for UK forestry (Savill 1983). Storms causing substantial forest damage, of 1 million m^3 or more, occurred approximately each decade of the second half of the 20th century (see Table 1-1).

Table 1-1 The most damaging storms for the UK forest industry, 1950 to present (from Quine *et al.* 1995).

Date of storm	Wind speed of maximum recorded gust (m s^{-1})	Volume of windthrown timber (m^3 x 10^6)	% of forest stock damaged
31 January 1953	50	1.8	10-25
15 January 1968	52	1.6	15-30
2 January 1976	47	1.0	<5
16 October 1987	51	3.9	13-24
25 January 1990	48	1.3	1-3

In other parts of Europe, wind speeds high enough to cause forest damage are less common, but the percentage of land cover devoted to forestry is greater. Wind causes substantial amounts of damage annually across Europe, with up to 10 million m^3 timber being windthrown most years (ECE/FAO 2000). In addition, storms that have overturned 20 million m^3 or more of forest have occurred six times in the last 50 years in Europe (Table 1-2), including storms of unusual severity during January 1990 and December 1999 that overturned 120 million m^3 and 193 million m^3 respectively. The December 1999 damage resulted from two separate storm systems that tracked across France and then continued to cause substantial damage in Germany, Switzerland, Denmark and several countries in eastern Europe. The resulting damage to forests in overturned and snapped trees was equivalent to 2 years harvest of timber in the affected countries (ECE/FAO 2000).

Management to reduce windthrow

In Britain, forest management techniques have been modified to reduce the losses to windthrow. For example, deep ploughing that restricts root spread (Savill 1976), line thinning that allows wind to penetrate vulnerable crops (Quine *et al.* 1995), and planting next to the stumps of old trees that leads to the development of asymmetric root systems (Prest *et al.* 1991; Quine *et al.* 1991), are now discouraged, especially in areas where potentially damaging winds are frequent. In addition, trees are harvested before they reach a height where they would be particularly susceptible to damage. In the 1970s and 1980s the 'Windthrow Hazard Classification' developed by the

British Forestry Commission used data on site conditions and wind exposure to produce a 'critical' and 'terminal' height of a stand, at which damage would be expected to start, and at which damage would reach a level necessitating clearance, respectively (Miller 1985; Quine and Gardiner 1998). More recently, this was replaced by a windthrow risk model 'ForestGALES' (Quine and Gardiner 1998) that uses data on forest stands, soil and wind climate, to calculate the probabilities of tree snap and overturning (Dunham *et al.* 2000; Gardiner *et al.* 2004).

Table 1-2. Forest damage caused by major storms in Europe from 1950 to present.

Date	Location	Million m^3
JAN 1953	N.E. Scotland	1.8
1954	Sweden	18
NOV 1966	Austria & N. Italy	2.3
JAN-FEB 1967	Central Europe	23.4
OCT 1967	Denmark	2.4
JAN 1968	Central Scotland	1.6
1969	Sweden	36
NOV 1972	N. France & N. Germany	25.9
JAN 1976	Wales & C. England	1.0
DEC 1976	France	2.0
NOV 1981	Denmark	3.0
NOV 1982	C. France	12.0
JULY 1984	N.E. France	1.8
NOV 1984	C. Germany & S. Belgium	11.0
OCT 1987	S. England & N. France	11.5
JAN-MAR 1990	Britain, N. & C. Europe	120.0
DEC 1999	Central Europe and Scandinavia	193.0
JAN 2005	N Europe (esp. Sweden and Latvia)	86.5

By applying these management techniques, losses to windthrow in conventional plantation forest stands have been reduced (Gardiner and Quine 2000; Quine *et al.* 1995). However, the priorities of forest management in the 21st Century are changing towards lower impact silviculture, longer retentions of trees, wider spacings, and continuous cover forestry (CCF) with mixtures of species and irregular age structures (Mason and Quine 1995). These changes are expected to influence crop stability (Mason 2002), and it will therefore be necessary to improve our understanding of tree stability and growth responses to wind loading, so that we can quantify the risks to forests managed using these systems.

Restriction of rooting depth

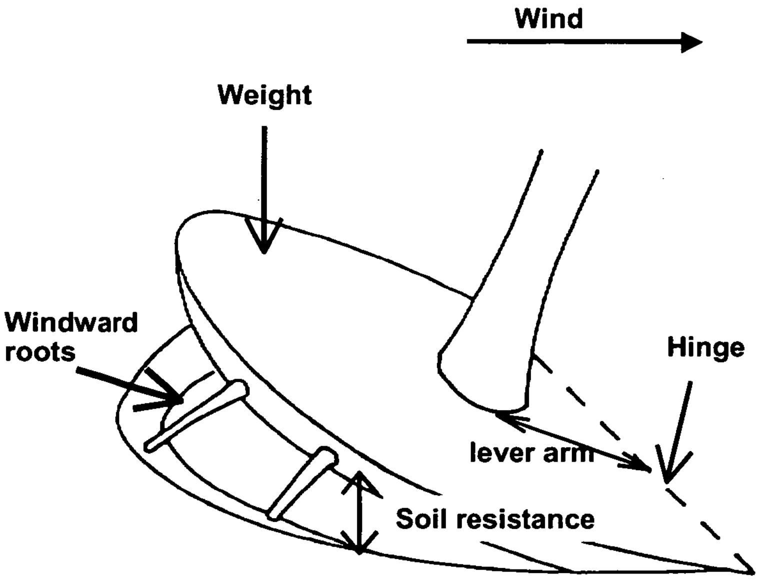
Tree root systems commonly have shallow development due to soil conditions that restrict root growth. In upland areas of the UK where soils have low hydraulic permeability, water-tables that fluctuate close below the soil surface for much of the year are common (King *et al.* 1986; Ray and Schweizer 1994). These restrict downward root growth (Kozlowski 1982) producing shallow root-soil plates (Armstrong *et al.* 1976) unless the water table is lowered by site drainage. In an investigation of 46-year-old Sitka spruce trees grown on peaty-gley and surface water gley soils, roots survived only 9 to 16 cm deeper than the shallowest winter water-table depth (Ray and Nicoll 1998). Nicoll and Coutts (1998) described Sitka spruce roots, in a controlled flooding experiment, surviving to between 18 and 27 cm below a static winter water-table, with trees that had earlier root dormancy in the autumn surviving deepest. Another factor limiting root depth in many forest sites is high soil density. Soils of bulk density greater than 1.6 g cm^{-3}, and penetrometer resistance of 2.3 MPa, are known to cause severe restriction to root growth (Day and Bassuk 1994) and commonly occur within a metre of the surface on upland forest sites. Without soil cultivation, tree root systems on these sites will remain shallow (Paterson and Mason 1999).

Damage to root systems by wind movement

On mature forest sites with restricted root depth, wind speeds as low as 2 m s^{-1} produce sufficient stem movement to result in movement of shallow, horizontal, structural roots (Rizzo and Harrington 1988). Hintikka (1972) described a 3° stem displacement of spruce trees growing on clay soil, lifting the soil surface by up to 14 mm. Rizzo and Harrington (1988) found that red spruce and balsam fir root movement could be recorded for 80% of the time during the six windiest months of the year, on exposed sites in New Hampshire, USA, with 30% of root movements exceeding 10 mm. Roots transmit the energy of the moving stem to the soil and assist in the damping of stem sway (White *et al.* 1976). The amount of mechanical damping in the root system will be affected by soil water content, and Mayer (1987) described a reduced friction resistance of roots in moist soil compared to dry soil. Large scale damping by roots would however coincide with damage to the root system. Grace (1977), and O'Sullivan and Ritchie (1993) estimated that up to 20% of the energy in the system can be lost through roots and soil during each loading cycle of a wind damaged root plate.

Stone (1977) described root damage caused by large tree movements that ultimately would risk the health and stability of the tree. Root damage creates entry sites for pathogens (Rizzo and Harrington 1988) and reduces the uptake of water and nutrients. Breakage of fine roots reduces the amount of soil held by the system, and the tree must divert resources to renew the roots (Rizzo and Harrington 1988). Damage to larger roots reduces the rigidity of the root system (Coutts 1983b). When the roots and soil under the tree fail, the underside of the "root-soil" plate is formed, and most anchorage will now be provided by roots at the edge of the plate acting under tension (Coutts 1986).

Figure 1-1. Components of anchorage of a shallow rooted tree (adapted from Coutts 1986).



The root-soil plate is now free to rock in its crater without the cohesion of soil under the plate, and anchorage is progressively reduced by fatiguing of the system (O'Sullivan and Ritchie 1993). On gleyed mineral soil, such trees are often described as 'pumping' (Armstrong *et al.* 1976; Booth and Mayhead 1973) as soil under high hydraulic pressure (Rodgers *et al.* 1995) is forced to the surface from the cavity that forms under the moving root-soil plate (Coutts 1986). Such trees can become a large, vulnerable component of mature forest stands on shallow mineral soils. In a study of the anchorage of 46-year-old trees on gley soils (Ray and Nicoll 1998) in an upland plantation, 35% of trees showed some evidence of pumping (unpublished data) i.e. there was a smooth faced fracture in soil under part of the root system. Once the soil has failed under a tree, the tree is more vulnerable to windthrow in subsequent storms. O'Sullivan and Ritchie (1993) and Rodgers *et al.* (1995) reported a 25% reduction in anchorage resistance resulting from cyclic loading that fractured the soil under the plate. Some trees are however believed to partially recover from this destabilisation if drier and less windy conditions follow the period of soil disturbance, allowing new roots to grow through the fractured zone into deeper soil (Ray and Nicoll 1998).

Components of root anchorage

Large variability of anchorage is a common feature of 'tree pulling' experiments where trees are mechanically uprooted. The regression of critical resistive turning moment against tree size (stem mass or diameter) for trees mechanically overturned in studies conducted by the Forestry Commission, was linear, positive and significant, but, for example, values for 20 cm DBH trees on peaty gley soil ranged from 10 to 50 kNm (Nicoll, unpublished). Coutts (1986) states that "the magnitude of this variation on a single soil type indicates the possible scope for improving stability if a clearer understanding of the causes can be obtained".

Coutts (1986) separated the resistance of a shallow root system to overturning into four components (Figure 1-1); weight of the root soil plate, tensile strength of the windward 'guy' roots, tensile strength of the soil, and resistance to bending of roots at the hinge. The force needed to overturn the tree is this overall resistance multiplied by the length of the lever arm, that is, the distance from the tree centre to the hinge point on the root system.

As a tree starts to overturn, roots on the lee-side act mechanically as a lever-arm, while those under tension on the windward side anchor in a similar way to guy lines (Figure 1-1). The length of the lever-arm is determined by the position of the largest structural roots and the variation in rigidity along their length (Coutts *et al.* 1999). Commonly the lever-arm structural roots fail at a point where they branch. This behaviour conforms to beam-theory. If a beam is circular in cross section, its second moment of area, I, is represented by the following equation (Gordon 1978):

(1.1) $$I = \frac{\pi r^4}{4}$$

The flexural stiffness of the beam is E (the Youngs modulus of the material) x I. Therefore, if a root is considered to be a beam with a circular cross-section, its stiffness will be proportional to the fourth power of its diameter (Coutts 1983b). After a branch point, even if the combined cross sectional area of branch roots remains the same as the 'parent' root, there is a considerable reduction in stiffness of the system, making it particularly vulnerable to failure at this point. The following calculation demonstrates the reduction in I for a 'parent' root with radius a that branches into two branch roots each with half the cross sectional area of the parent and with radius b. The relative cross sectional areas of the branch and parent roots are:

(1.2) $$2\pi b^2 = \pi a^2$$

therefore;

(1.3) $$2b^2 = a^2$$

and the relationship between length of radii a and b is;

(1.4) $$b = \frac{a}{\sqrt{2}}$$

As for a circle with radius a;

(1.5) $$I_a = \frac{\pi a^4}{4}$$

so;

(1.6) $$I_b = \frac{\pi\left(\frac{a}{\sqrt{2}}\right)^4}{4} = \frac{\pi a^4}{16}$$

and therefore the relative values for I for the parent and branch roots will be;

(1.7) $$I_a = 4I_b$$

Therefore, the two branch roots each have 0.25 x I of the parent root and assuming constant Young's modulus, their combined stiffness will be half that of the parent root.

Fusing of roots

Another feature of tree development that can be important for mechanical stability is the fusing of roots within and between root systems. Eis (1970) and Kozlowski (1971) describe inter and intra-specific fusing between roots of a large variety of tree species. This behaviour, as well as providing the trees with the benefits of shared nutrient and water supply, will provide a large degree of mutual support between trees (Külla and Lõhmus 1999). Conifers growing in plantations where the water-table is shallow commonly have roots that are fused to those from neighbouring trees, especially where roots are forced together, such as in the constrained space of a plough ridge. Although fusing provides mutual support, it can ultimately lead to rows of plantation trees being overturned together and thereby increase the losses to windthrow (Quine *et al.* 1995).

Root plate rigidity

Roots are approximately three orders of magnitude stronger than soil under tension (Coutts 1983b), for example, the load per unit area at failure for Sitka spruce roots is reported to be between 35 MPa (Coutts 1983b) and 43.7 MPa (Parr 1994; Parr and Cameron 2004), while the mean strength of soil in the B horizon, A horizon and peat are reported to be 51 kPa, 27.2 kPa, and 18.3 kPa respectively (Ray and Nicoll

1998). However, the area of soil broken as a tree is uprooted is three orders of magnitude greater than the cross sectional area of the broken roots. Therefore, soil strength makes an important contribution to anchorage. Roots stretch by 10 - 20% of their length before failure while most soils stretch by less than 2% before failure. A load applied to the root system will therefore break the soil before the roots.

In the study by Coutts (1986), roots broke in sequence rather than simultaneously and most roots that broke had diameters less than 0.5 cm. Coutts (1986) demonstrated that shallow root-soil plates are not rigid during overturning, but flexible, and that soil breaks first close under the base of the tree, with cracks propagating outwards. Most soil under shallow plates will be broken by lifting the centre of the plate by only 2 cm (Ray and Nicoll 1998). Therefore, soil will shear under a flexible soil-root plate with a force comparatively less than a rigid plate of the same area where a larger area must shear to start overturning.

With only a small displacement needed to fracture the soil under a root-soil plate, a particularly important function of horizontal structural roots is to provide rigidity to the plate and hence increase the force required to fracture the soil (Coutts *et al.* 1999). The form of the structural root system develops through differences in the allocation of assimilates to individual roots undergoing secondary thickening (Fayle 1975). Both the number and size of the major structural roots are important, as is the distribution of biomass around the tree (Coutts *et al.* 1999; Nicoll *et al.* 1995). As the stiffness of roots is approximately proportional to the fourth power of their diameter (described earlier), a large number of thin roots would offer considerably less resistance to bending than a few thick roots with the equivalent cross sectional area (Coutts 1983b). However, where biomass is allocated predominantly to few roots, the effectiveness of anchorage will depend on the evenness of distribution of these roots around the stem (Coutts 1983a; Coutts *et al.* 1999).

Tree adaptive growth in response to wind

The constant stress hypothesis

An important factor in maintaining mechanical support of trees in a windy environment is the acclimation or 'adaptive' development of trees in response to wind action. The effects of wind on above-ground development of trees have been studied for many years. Knight (1803) restricted the wind movement of apple trees so that they could only flex back and forward without any sideways movement. After one growing season he observed increased thickening of the stem in the plane of flexing, compared to the perpendicular plane, with a ratio of 13:11. Several other researchers have since manipulated trees by shaking or flexing the stems and have observed a reduction in shoot height growth (Jacobs 1939; Rees and Grace 1980; Stokes *et al.* 1997b). Secondary thickening has been found to be restricted in the stem and branches by wind movement but accelerated in the stem base (Telewski 1995), with again, greater thickening of the lower stem along the axis of the prevailing wind direction (Stokes *et al.* 1997b). Such developmental responses counteract increasing movement as the tree grows and will improve stability by allocating assimilate to parts of the tree where mechanical stress is greatest. Observations of tree growth responses to mechanical stress were developed by Schwendener (1874) and Mezger (1893) into the '*constant*' or '*uniform' stress hypothesis* which states that the development of stem form is optimised to give uniform bending stress over the whole stem surface. This hypothesis has recently been re-examined by many authors including Mattheck (1991), Morgan and Cannell (1994), Ennos (1995), Wood (1995), Blackburn (1997) and Dean *et al.* (2002). Although the stem form of a tree is sometimes close to representing a beam of constant resistance (Gaffrey and Sloboda 2001), the constant stress hypothesis is unlikely to hold as the forces acting on trees change. Morgan and Cannell (1994) found that the hypothesis largely held for Sitka spruce at low wind speeds, but failed when winds were greater than 10 m s^{-1}. Gaffrey and Sloboda (2001), found that constant stress was not achieved over the stems of Douglas-fir, even at low wind speeds (5 m s^{-1}). Instead of maintaining constant stress, it seems more likely that cambial growth is proportional to the mechanical stress that the stem experiences.

Root radial growth of conifer species concentrated to the lee-side of the tree relative to the prevailing wind has been reported by Mason *et al.* (1986), Nielsen (1990), Nicoll *et al.* (1995), and Nicoll and Ray (1996). Leeward roots close to the tree must in particular resist bending under compression, and therefore require greater thickening than windward roots, and those further from the tree on all sides, that act more under tension. Enhanced leeward structural root development may be associated with the increased radial growth that has been observed on the lee side of conifer stem bases (Robertson 1991).

Thigmomorphogenesis

The physiological mechanism for adaptive growth in response to mechanical stimulation has been termed "thigmomorphogenesis" (Jaffe 1973). Increased stem radial growth in response to mechanical flexure is due to stimulated cell division in the vascular cambium (Telewski and Jaffe 1986c). This increase appears to be linked to production of ethylene by mechanically stressed tissue (Goeschl *et al.* 1966), and plants experimentally treated with ethylene have shown similar development (Eklund and Little 1998; Telewski 1990).

Hydraulic and biomechanical requirements

Secondary thickening in stems has also been described using hydraulic models of tree growth (Mencuccini 2002; Mencuccini *et al.* 1997; Spicer and Gartner 1998b). The 'pipe model' hypothesis of plant form (Shinozaki *et al.* 1964a; Shinozaki *et al.* 1964b) states that the sapwood area remains in proportion to the needle mass above. However, not all authors have found this; for example, Huber (1928), Tyree and Ewers (1991) and Gaffrey and Sloboda (2001) found no such proportionality. Other hydraulic models of tree growth appear more useful, especially if considered in association with biomechanical models (Gaffrey and Sloboda 2001). If secondary thickening of tree components responds to both hydraulic and biomechanical requirements, an interaction or 'trade off' might be expected (Spicer and Gartner 1998a; Spicer and Gartner 1998b). However, Mencuccini *et al.* (1997) found that in Scots pine (*Pinus sylvestris* L.) specific hydraulic conductivity and modulus of elasticity ('Youngs modulus') were positively related to each other and that there appeared to be no trade-off between the two. Differentiating between the effects of these processes may be further complicated by a reduction of stem hydraulic conductivity induced by wind movement and damage. Fredericksen *et al.* (1993a) reported a reduction of functional xylem conducting area in wind bent trees, especially on the compression side of the stem. It will therefore be important to attempt to separate the developmental responses of the tree that maintain hydraulic function from those that maintain mechanical support.

Root responses to stand thinning

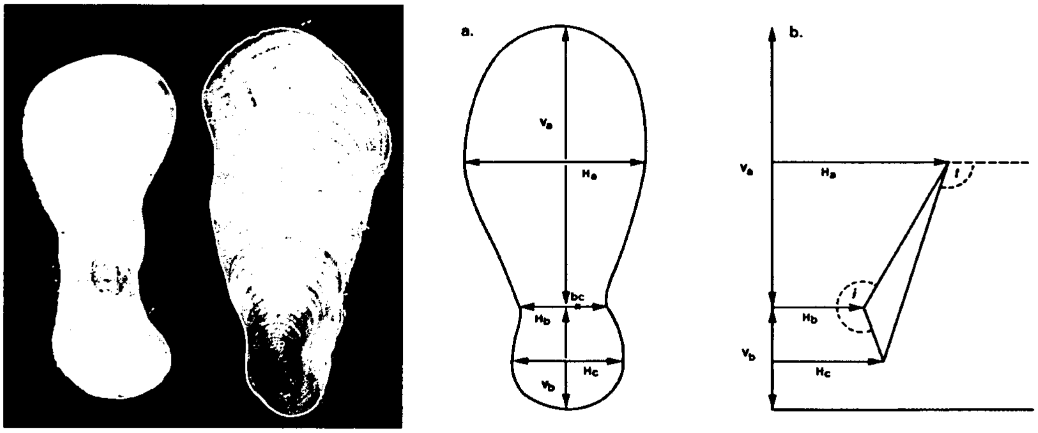
Adaptive growth may be more important below-ground than above-ground as a compensatory mechanism, but there is only limited information on the effects of mechanical stress on biomass allocation to and within the structural root systems of large forest trees (Coutts *et al.* 1999). Wilson (1975) found an increase in growth-ring width in the lower stem and in the base of structural roots of *Pinus strobus* L. trees corresponding with increased wind movement after thinning of the stand. He found considerably less secondary thickening on these parts of trees if they were guyed to prevent stem movement after stand thinning. Urban *et al.* (1994) reported an immediate increase in thickening of structural roots but a 4-year delay in the increase of diameter growth in the stem in *Picea glauca* (Moench) exposed after removal of neighbouring trees, and comparable differences between stem and root secondary thickening after thinning of *Pinus resinosa* Ait. were reported by Fayle (1983).

Cross-sectional shapes of structural roots

Resistance to bending also occurs by development of the shape of structural roots. In response to wind movement, trees with shallow structural roots have been reported to develop root cross-sectional shapes comparable in appearance to the 'I-beams' and 'T-beams' used by engineers (Banks 1973; Büsgen and Münch 1929; Hintikka 1972; Rigg and Harrar 1931; Wood 1995). Figure 1-2 shows examples of these root shapes. Engineering I- and T-beams are constructed to maximise resistance to bending or flexing using a minimum of material (Gordon 1978). Büsgen and Münch (1929) proposed that the development of such shapes in tree roots results from root movement induced by stem swaying, as an extension of the 'uniform stress hypothesis' to below-ground parts of the tree. The adaptive growth of structural roots can be analysed using a set of three descriptors of root shape (Figure 1-2), calculated from the dimensions of structural root cross sections: 'T-angle', 'I-angle', and V_a/V_b ratio, (Nicoll and Ray 1996; Ruel *et al.* 2003). The T-angle describes the difference between lateral thickening in the upper and lower parts of the root section and hence the tendency towards a T-beam shape. Angles greater than 90° show more lateral thickening in the upper part of the root than the lower part of the root; angles less than 90° show the reverse. The further the angle deviates from 90°, the more T-beam shaped the section. The I-angle describes the tendency towards an I-beam shaping of the root; angles greater than 180° indicate an I-beam shape, angles less than 180° indicate an ovoid shape. The V_a/V_b ratio compares thickening in the vertical plane, above (V_a) and below (V_b) the biological centre of the root. A V_a/V_b ratio of 1 indicates equal vertical thickening above and below the biological centre and the higher the number, the greater the upward relative to downward thickening (Nicoll and Ray 1996; Ruel *et al.* 2003).

Several studies of conifers (Deans 1981; Fayle 1968; Kozlowski 1971; Somerville 1927) report greater growth on the upper side compared to the lower side of horizontal structural roots, i.e. 'epinastic growth'. However some species of pine are reported to show the opposite behaviour. Brown (1915) found growth rings of *Pinus strobus* L. to be thickest on the lower side of roots, and Wilson (1975) reported that the greatest thickening varied between the upper and lower sides of roots of the same species. Nicoll and Ray (1996) found thickening of individual Sitka spruce roots in the vertical plane to be greater above the biological centre than below, especially close to the stem. This decreased with distance from the tree but the change in allocation pattern varied between windward and leeward sector roots. Leeward roots had greater V_a / V_b ratios than windward roots up to 1.0 m from the stem centre. The analysis of cross sectional shape by Nicoll and Ray (1996) also found that within 1.0 m of the stem centre, I-angles were larger (more 'I-beam' shaped) on windward than leeward roots. By 1.25 m from the tree, cross sectional shapes were more ovoid, i.e. they had smaller I-angles, and therefore these roots, as would be expected from Coutts (1986), appeared to be less adapted to resist flexing than to act under tension.

Figure 1-2. Analysis of root cross sectional shape. Left, Typical Sitka spruce I- and T-beam root cross sectional shapes. Right, a. A system for measurement of such sections relative to 'bc', the biological centre, and b. analysis of the development of I-beam (I angle) and T-beam shapes (T angle), from Nicoll and Ray (1996).



Buttress development

Enhanced secondary thickening between the root and the stem, resulting in the development of supporting buttresses, may also reflect growth to equalise stress (Clair *et al.* 2003; Ennos 1995). The large tabular buttresses characteristic of many tropical tree species, and the smaller more rounded buttresses often observed on temperate trees, make a rigid connection between the stem and the root system. These structures reduce bending and stress concentration at the base of the tree (Mattheck 1993). Buttresses also increase the leverage required for over-turning by moving the 'hinge' point of the root system further away from the base of the tree. The buttresses observed on coniferous trees characteristically have a 'T-beam' cross-sectional shape. Analysis of root cross sections in the Nicoll and Ray (1996) study showed T-angles to be largest (i.e. having a pronounced 'T-beam' shape) up to 0.75 m from the tree centre, and leeward roots had significantly greater T-angles than windward roots. Therefore, the development of buttresses is enhanced on the lee-side relative to the prevailing wind.

An analysis of relative strength of root cross sectional shapes

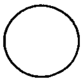
In modelling the development of structural roots systems in relation to tree stability, it is necessary to quantify the relative rigidity of various root cross sectional shapes (Coutts *et al.* 1999). Little is known about the relative strength properties of the various root shapes that have been observed. The effect on root stiffness of changing root cross sectional shape but maintaining cross-sectional area (CSA) has not previously been examined, but can be achieved by calculating second moment of area (I) of structural root transverse sections. The second moment of area of a shape measures the efficiency of that shape in respect of its resistance to bending. The magnitude of the bending moment of a beam is related to shape and the material modulus. Therefore, the magnitude of the moment M required to bend a beam to curvature K varies directly as the product of the modulus of elasticity, E (Young's modulus) and the Second moment of area I:

$$(1.8) \qquad M = E\,I\,K.$$

The product of E and I is called 'flexural stiffness' or 'flexural rigidity'.

Second moment of area I was therefore calculated for 'I-beam' and 'T-beam' root shapes from trees examined in a previous study (Nicoll and Ray 1996). These shapes (see Table 1-3) were scaled to have the same area and values and were compared to I values for an ellipse and circle of the same area. Root cross sectional shapes were broken into parallel rectangles (5 mm deep, width to fit the shape at that point) and area calculated for each. I_{xx} (i.e. second moment of area for bending around a horizontal axis) and I_{yy} (bending around a vertical axis) were calculated for each rectangle relative to the centre of mass of the whole shape and were summed to produce overall I_{xx} and I_{yy} values. Flexural stiffness EI was calculated for each of the sections assuming a mean Young's modulus in bending E for conifer roots from Fegel (1941) of 5990 MPa.

Table 1-3. Second moment of area for flexing in the vertical plane (I_{xx}) and horizontal plane (I_{yy}), and estimated flexural stiffness (for flexing in the vertical plane), for different root cross sectional shapes with the same area. The shapes are not illustrated to scale. Percentage comparisons of I_{xx} and I_{yy} were made between the shapes by assigning 100% to the 'I-beam' root shape.

Shape	I_{xx} (m^4)	I_{yy} (m^4)	%I_{xx}	%I_{yy}	**Flexural stiffness EI (Nm^2)**
1. 'I-beam' root section (12875 mm^2, depth 195 mm, width 87 mm) 	40.259	5.367	100	100	2.4 x10^5
2. 'T-beam' root shape with same area as shape 1. 	33.787	5.727	84	107	2.0 x10^5
3. Elliptical section of same area as 1. (depth 195 mm) 	30.598	5.687	76	106	1.8 x10^5
4. Circular section of same area as 1. (diameter 128 mm) 	13.191	13.191	33	246	7.9 x10^4

The analysis revealed that I_{xx} was larger than I_{yy} for all shapes except the circle (Table 1-3). The I_{xx} value was largest for the I-beam shape. The 'T-beam' shape had only 84% of the I-beam I_{xx}, but slightly larger (107%) I_{yy}. The ellipse and circle with the same area both had smaller I_{xx}, but larger I_{yy} values. The 'I-beam' root had a second moment of area (I_{xx}) that was 305% of the value for an equivalent sized circular root. The cross sectional area of a circle that would be required to give the same I_{xx} as produced by the 'I-beam' root shape was 74% larger than the 'I-beam' root section.

This analysis confirms that the 'I-beam' root shape is particularly suited to resisting vertical flexing. A root with this shape will have better flexural stiffness than would be provided by any of the other shapes (rectangular, elliptical, or circular section roots) with the same cross sectional area. These roots develop from being circular in section to being elliptical, and then 'I-beam' shaped as they thicken and therefore increase their flexural rigidity at a faster rate than would be achieved by laying down circular growth rings. The increased I_{yy} value for T-beam roots relative to I-beams would give them resistance to torsional loading while at the same time being efficient at resisting vertical bending. For the tree to develop a root as rigid as the I-beam root without having any capability for 'adaptive growth' it would have to produce a circular section root with 74% more cross sectional area. This may be an extreme example, but such an increase in allocation of assimilates to the roots would have a major impact on above-ground development. Trees used for this study had root:shoot ratios of around 0.5. Even if the average adaptive value was half of the calculated 74%, i.e. a 37% increase in root mass to compensate for a lack of adaptive growth, a tree with the same total biomass would have to increase its root:shoot ratio from 0.5 to 0.8 and allocate 18% less biomass above ground. The development of adaptive root shapes is therefore a mechanism that maintains tree stability, while allowing maximum above-ground growth. Another strategy that would improve the flexural rigidity of a root would be to increase strength and stiffness properties of the wood itself. However, tree roots would have to increase their Young's modulus in bending three-fold to provide the same flexural stiffness in a circular cross-section root of the same cross-sectional area as the adapted root (Nicoll 2000).

Problems, hypotheses and objectives

Our understanding of the biological, meteorological and mechanical processes involved in the windthrow of forest trees has progressed considerably since the early work on windthrow and tree stability conducted in the 1960s. Analyses of results from each strand of research have over the years been incorporated into a variety of models and decision support systems. Early tree pulling experiments provided data that were combined by Fraser and Gardiner (1967) into a comparison of anchorage of Sitka spruce on a variety of soils. Observations and surveys of windthrow in relation to site factors and exposure were developed into a windthrow hazard classification of British conifers by Booth (1977) and Miller (1985). Investigations of the mechanical components of tree anchorage by Coutts (1986) were developed by Blackwell *et al.* (1990) into a mechanical model of tree anchorage that allowed comparison of the relative importance of each component. Further analysis of data from tree pulling experiments and a detailed investigation of the wind climate in the British Isles using 'tatter flags' (Quine and White 1994) were combined into a computer based decision support system for forest managers 'ForestGALES' (Dunham *et al.* 2000; Quine and Gardiner 1998) that provided an assessment of how the risk of windthrow changes as a forest stand develops.

However, despite these substantial steps forward in understanding and modelling tree stability and windthrow, there remain a number of important unanswered questions. Firstly, although the tree pulling experiment data were analysed first by Fraser and Gardiner (1967) and then for incorporation in ForestGALES by Dunham *et al.* (2000), neither analysis included the complete set of tree pulling experiments conducted in Britain, or provided an adequate statistical analysis of the data. An analysis is required that compares anchorage of the most commonly planted coniferous species in Britain, in relation to tree size, the soil types found in the British Isles, and rooting depth. Secondly, models of tree anchorage and tree stability have, up to now, assumed a simplified system where trees are assumed to be on horizontal terrain. However, much of the forested land in the British Isles consists of complex terrain and no attempt has previously been made to compare the structural root development or stability of trees grown on slopes with trees grown on horizontal ground. Thirdly, although thinning and respacing of forest stands are commonly practised management techniques, used to improve forest productivity and in the transformation to CCF systems, the ways in which trees adapt both above- and below-ground to the changed light and wind regimes are not understood. A detailed investigation of the growth responses of coniferous trees to stand thinning is required to improve the way that post-thinning stability is modelled.

The following hypotheses will be tested:

(1) Anchorage varies between tree species and soil type and increases with rooting depth.

(2) The anchorage of trees is reduced on steep terrain and varies with direction of overturning.

(3) The architecture of the structural root system is modified by the terrain on which the tree grows.

(4) Above- and below-ground cambial growth is modified by wind action on the tree and is greatest in parts of the tree that experience the most mechanical stress.

The anchorage of trees will be examined in relation to species, soil type and root depth, by performing a meta-analysis of data from tree-pulling experiments conducted in the British Isles. Then, the effect of terrain on tree stability will be examined by mechanically overturning trees on a steep slope. The effect of the slope on aspects of structural root architecture that are important for tree anchorage will be described. Finally, changes in above- and below-ground development of trees in response to changes in wind movement will be quantified, and the mechanical implications of these changes will be discussed.

2. Anchorage of coniferous trees in relation to species, soil type and rooting depth

Abstract

A database was constructed of tree anchorage measurements from experiments conducted on thirty-four sites in Britain between 1960 and 2000. The database contained results from almost 2000 trees from twelve conifer species; Corsican pine *(Pinus nigra* var. *maritima*), Douglas-fir (*Pseudotsuga menziesii*), European larch (*Larix decidua*), grand fir (*Abies grandis*), Japanese larch (*Larix kaempferi*), lodgepole pine (*Pinus contorta*), noble fir (*Abies procera*), Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), and western red cedar (*Thuja plicata*). Each tree was assigned to a soil group and root depth class. The soil groups were; freely-draining mineral soils, gleyed mineral soils, peaty mineral soils, peat soils. Root depth classes were; <40 cm (shallow rooting), 40–80 cm (medium rooting) and >80 cm (deep rooting). A meta-analysis of these experiments was conducted to compare anchorage between species, soil groups and root depth classes using regressions of critical turning moment against stem mass. As Sitka spruce formed the largest part of the database, with 1155 trees, and was the only species to have trees in all soil group and root depth class combinations, it was used as a benchmark. For Sitka spruce, the best anchorage was found on peat soils, and the poorest anchorage was on gleyed mineral soils. Trees with root depths deeper than 80 cm had critical turning moments that were 10 to 15% larger than trees of equivalent mass with shallower root depths. Significantly better anchorage was observed for grand fir than Sitka spruce with various rooting depths on free-draining and gleyed mineral soils, and for Douglas-fir on medium depth mineral soil. Poorer anchorage was observed over a range of soil groups and root depth classes for lodgepole pine, for shallow rooted Norway spruce on gleyed mineral soil, and for Corsican pine on medium depth mineral soil. Other combinations of tree species, soil group and root depth classes had similar anchorage

to the equivalent Sitka spruce. The implications of these results are discussed with respect to the development of wind risk models for forest management.

Introduction

Windthrow of trees is a major disturbance factor in forested areas of the world (Clinton and Baker 2000; Cremeans and Kalisz 1988; Ennos 1997; Jane 1986; Pontailler *et al.* 1997; Putz *et al.* 1983; Rebertus *et al.* 1997; Schaetzl *et al.* 1989). The gaps created by wind are important for forest structural dynamics, and influence the diversity of tree species, structure and age. In addition, overturning of trees accelerates the mixing of soil horizons, and provides micro-sites with improved soil aeration and nutrition that favour tree regeneration (Beatty and Stone 1986; Schaetzl *et al.* 1990). However, windthrow reduces profitability in forest stands managed for timber production through reduced economic value of windthrown timber (Nieuwenhuis and Fitzpatrick 2002; Savill 1983) and increased harvesting costs (Quine *et al.* 1995). In addition, stands in particularly windy regions are commonly harvested before their age of optimum economic return to reduce the risk of windthrow (Gardiner and Quine 2000). The British Isles are located in the track of most north Atlantic depressions, and as a result have a windier climate than other parts of Europe (Troen and Peterson 1989). Within Britain, a large proportion of forest cover is located in the windiest parts of the country (Miller *et al.* 1987), and windthrow remains one of the most important problems that the forest industry must deal with.

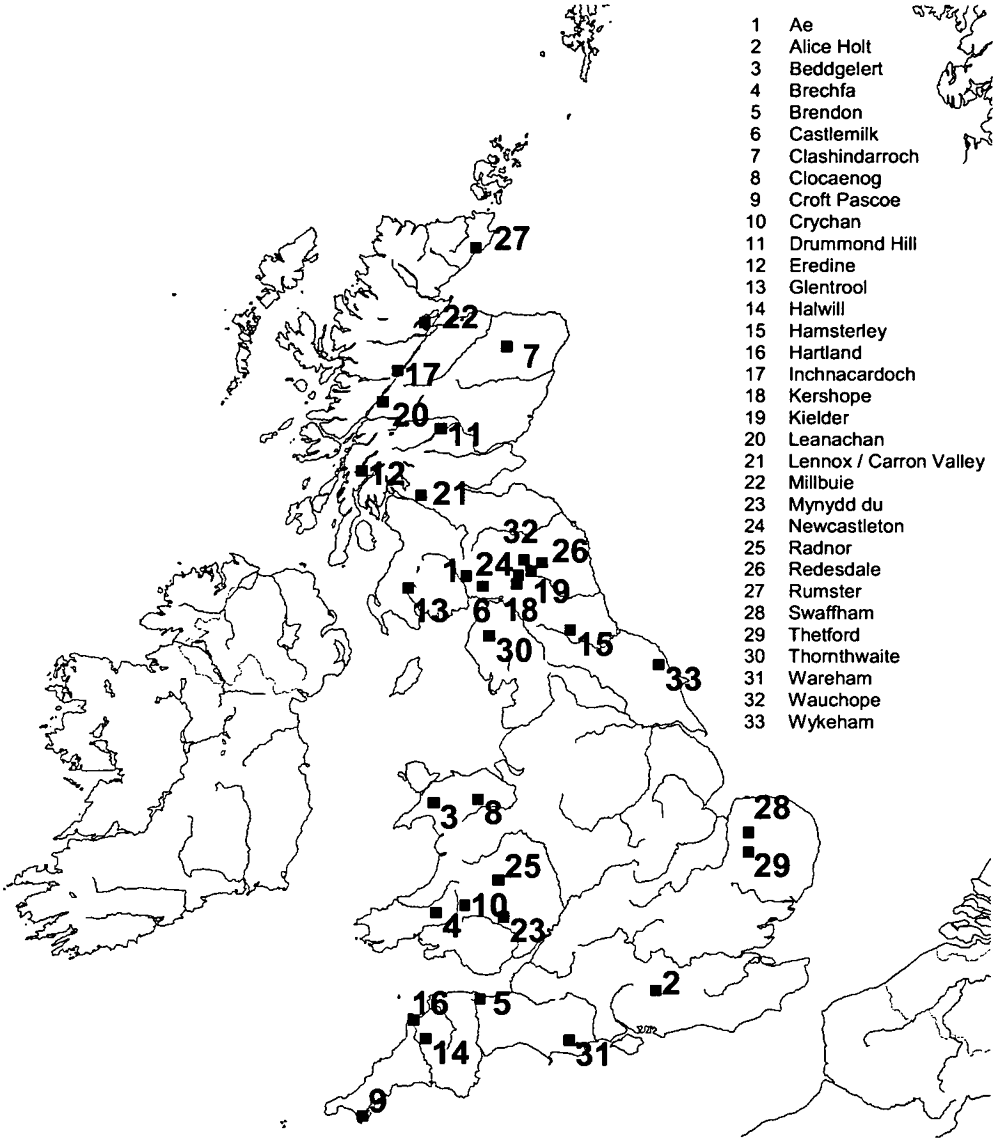
In order to predict and reduce forest losses due to windthrow, it has long been recognised that data are required that describe the stability and anchorage of trees in relation to species, tree characteristics, site, soil, climate and forest management techniques. 'Stability' is defined here as the overall resistance of the whole tree to overturning in the wind, and 'anchorage' as the resistance of the root system of the tree to uprooting. In 1960, A. I. Fraser and co-workers at the British Forestry Commission started investigations into factors that affect tree stability. They developed techniques for mechanically overturning trees, and gathered information on soils, tree dimensions, rooting and tree anchorage (Fraser 1962). Trees were pulled over on the range of soil and cultivation types common to British forest plantations. Above- and below-ground tree dimensions, applied loads, and details of the pulling operation necessary for calculation of turning moment, were recorded for each tree. Sampled trees were from a variety of conifer species, the majority being Sitka spruce (*Picea sitchensis* (Bong.) Carr.). In total, 1809 trees had been pulled by 1974, 969 of which were Sitka spruce. Sitka spruce was then, and remains, the most economically important tree species in Great Britain, presently accounting for around 29% of woodland tree cover and 49% of the conifer area (Anon 2003). The results of tree-pulling experiments conducted between 1960 and 1966 were described by Fraser (1967). Subsequent tree-pulling work up to 1974 was described in a series of brief progress reports (Booth 1974; Booth and Mayhead 1972; Booth and Mayhead 1973; Everard *et al.* 1970; Everard and Taylor 1969; Fraser and Henman 1966; Fraser and Neustein 1967; Pyatt and Booth 1973; Pyatt and Booth 1974) but no overall analysis of the data-set was published. Tree anchorage investigations recommenced in the early-1980s when Blackburn (1986) examined the effects of tree spacing on anchorage. The relationships between architecture of tree root systems and the biomechanics of tree stability were investigated by Coutts (1983b; 1986) and the stability of relatively mature trees was examined in relation to root architecture, rooting depth and root-soil plate flexibility by Ray and Nicoll (1998).

A new impetus for gathering tree anchorage data was provided in the 1990s by the development of a predictive model of windthrow for the British forestry industry “ForestGALES” (Quine and Gardiner 1998). An anchorage module, that would be a central component of this model, was identified as a necessity. It was apparent that the existing tree pulling data-set would form a useful basis for this, but was inadequate in its current form. Most noticeably, at that time, there were few data describing the anchorage of trees larger than 20 m height and 30 cm diameter (DBH) at breast height (1.3 m) on most soils, and few data for trees of any size on deep peat soils. Although only 45% of data were for species other than Sitka spruce, the decision was made to continue to concentrate on this species due to its commercial importance. A new programme of tree pulling was initiated that concentrated on anchorage of larger Sitka spruce trees, on various soil type and cultivation combinations. Experiments conducted as part of this programme added another 130 trees to the data-set. Data from these tree pulling experiments have now been compiled into a database containing almost 2000 trees. Figure 2-1 shows the location of all tree-pulling experiments conducted in Britain between 1960 and 2000.

The anchorage of trees can be expressed as the critical (maximum) resistive turning moment at the base of the stem during overturning. Turning moment is defined simply as force x length of a lever arm. Fraser and Gardiner (1967) provided equations relating anchorage, expressed as turning moment, to stem mass, for trees on a variety of soil types, and a number of subsequent studies, for example Blackburn (1986), Ray and Nicoll (1998), Moore (2000), Meunier *et al.* (2002) and Achim *et al.* (2005a) have characterised anchorage using the same approach. Other authors have described relationships based on related stem characteristics, including stem volume and DBH (Fredericksen *et al.* 1993b; Papesch *et al.* 1997). For example, Peltola *et al.* (2000) found significant correlations between maximum resistive turning moment and several above-ground characteristics of Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst.) and birch (*Betula* sp). Meunier *et al.* (2002) used linear regressions to compare critical turning moment with a variety of above-ground characteristics and found the best regression with stem mass. Regressions of maximum resistive turning moment against stem mass therefore provide an effective means of making anchorage comparisons, for example between trees of different species or between different soils.

This chapter describes a meta-analysis of the combined tree-pulling data-set from tree-pulling experiments conducted in Britain between 1960 and 2000, in order to test the hypothesis that root anchorage of conifers varies between species and soil group, and increases with rooting depth. The aim was to provide empirical models of the anchorage of a variety of conifer species in relation to tree size, soil group and rooting depth, that may be used in the development of wind risk decision support systems for forest managers.

Figure 2-1. Location of tree-pulling experiment sites. Details of trees pulled on each site are given in Table 2.4.



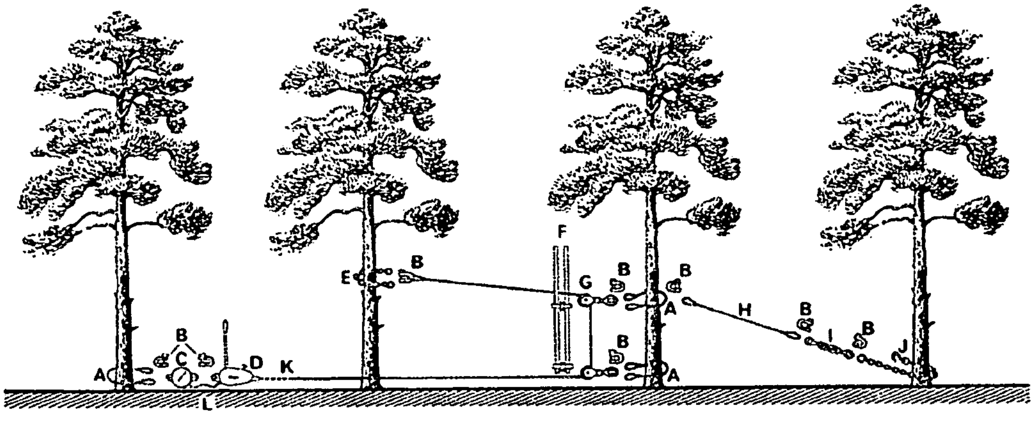
Methods

Tree pulling methodologies

Original method

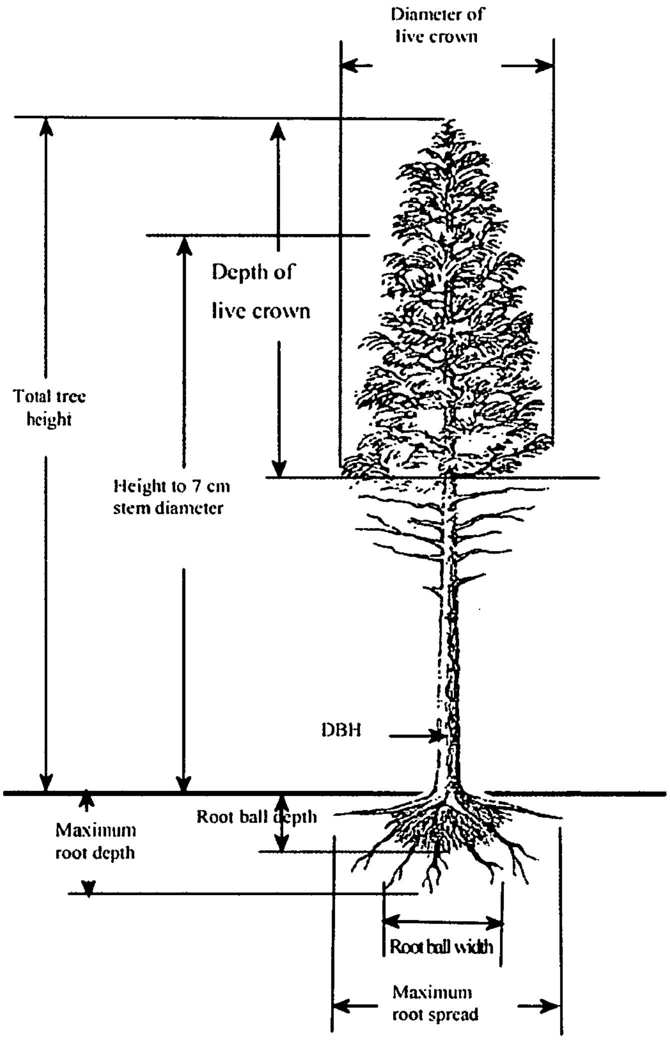
In the tree-pulling experiments that commenced in 1960, a sample of at least eight trees were selected at random for each soil type and silvicultural treatment examined. To overturn a tree, an almost horizontal force was applied at one third of the tree's height (Fraser and Gardiner 1967). This was achieved using a hand winch, a system of pulley blocks, and an adjustable pulley block spacer that raised a block to close to the pull height (Figure 2-2). Trees that obstructed the line of pull were removed before work started. As trees were pulled over, the force applied was recorded, by reading from the dial on a dynamometer, for every degree of movement of the tree.

Figure 2-2. Original tree–pulling method. A – wire rope slings, B – D-shackles, C – Dynamometer, D – Hand winch, E - Chain sling on pull-tree, F – Adjustable pulley block spacer, G – Single sheave swivel snatch-blocks, H - Backstay wire ropes, I – Rigging screw, J – Chain sling with shortener hook, K – White paint marks on rope for measurement of pull-tree angle, L – end of wire rope. Illustration from Fraser and Gardiner (1967).



Once the tree had been pulled over, the dimensions of the stem, the crown and the root plate were measured (Figure 2-3). Further details of the early tree pulling sites and methodology are given by Fraser and Gardiner (1967). This methodology was used with only minor changes until the 1980s, and a modification where the top of the stem was removed before pulling was used by Ray and Nicoll (1998).

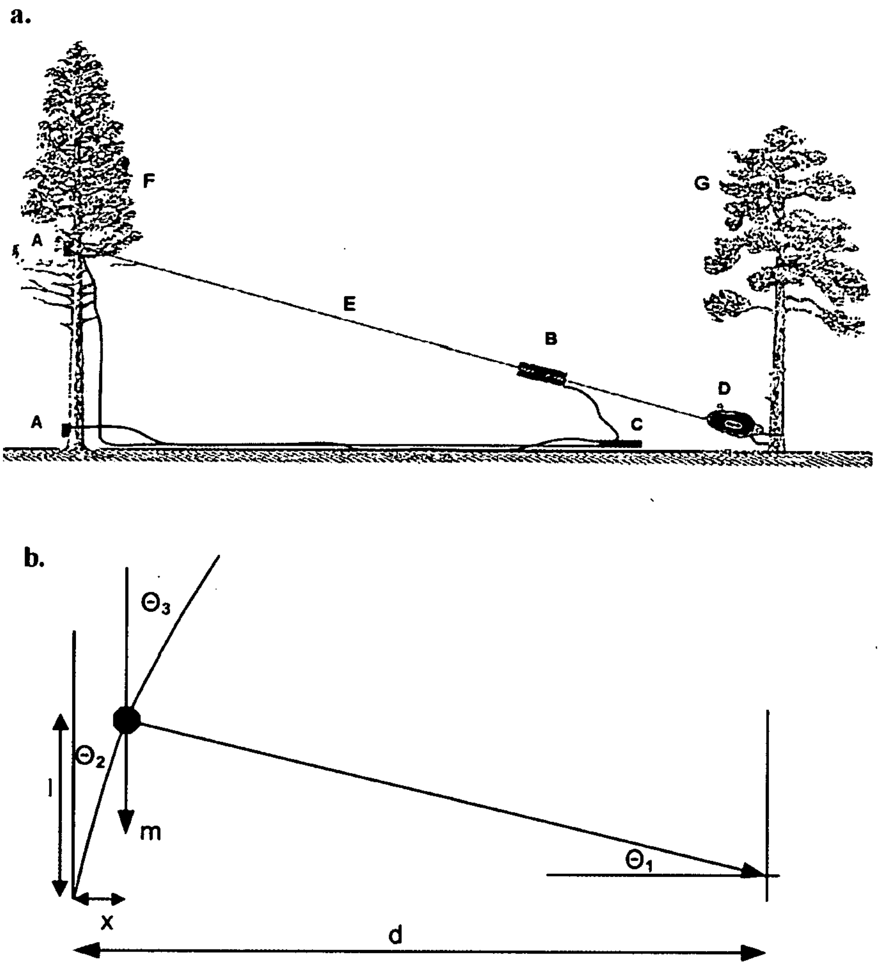
Figure 2-3. Standard measurement of the overturned trees in tree-pulling experiments (adapted from Fraser and Gardiner (1967)).



Current method

In tree pulling experiments conducted from 1997 onwards, eight subdominant, eight co-dominant and eight dominant trees were overturned, where possible, on each site. These trees were selected randomly from within diameter ranges based on quartile data from tariff plots. The direction of pull was as random as possible within the practical constraints of the tree-pulling operation. If trees were on a ploughed site, they were pulled in a direction perpendicular to the plough furrow. Neighbouring trees were felled to avoid obstruction of pull or crown interference.

Figure 2-4 a). Current tree-pulling method. A, inclinometers fixed at tree base and ½ tree height; B, load cell; C, datalogger; D, powered winch attached by nylon sling to the anchor tree; E, cable between the winch and a nylon sling on the pull-tree at ½ tree height; F, pull-tree; G, anchor tree. b). Measurements used in the calculation of critical turning moment: m, tree mass; F, force applied by the winch; d, distance between the anchor and pull-trees; x, horizontal displacement of the pull tree; l, the height of the centre of mass at time of maximum load; θ_1, angle of the winch cable relative to horizontal θ_2, angle of the tree base at time of maximum load; θ_3, angle of the tree above the attachment point at time of maximum load.



Digital biaxial clinometers (Applied Geomechanics, Santa Cruz, California, USA) were fixed to the stem near the base (1.3 m above soil level) and at half tree height. A chainsaw powered winch (Habegger, Thun, Switzerland) was attached to the anchor tree using a 2 m polyester webbing round-sling (safe working load 5 t), and a load-cell (0 – 5 t) was positioned between the anchor tree and the winch (Figure 2-4a). The clinometers and load-cell were connected to a datalogger. The pulling cable was fixed to a polyester round-sling placed at half tree height on the pull-tree. Distance was recorded between the anchor tree and the pull tree, and the angle (relative to horizontal) was recorded from the winch (or offset tree) to the attachment point on the pull-tree using a hand held clinometer (Suunto, Vantaa, Finland). After taking a zero reading from the load-cell and both clinometers, the strain was taken up, and the tree was pulled slowly using the winch. The datalogger was programmed to record maximum load from the load-cell, and angles from both clinometers at the time of maximum load (Figure 2-4b). Once the tree was on the ground, the crown width was measured, and instrument and cable attachment points were marked, as was the position of the lowest live branch and the lowest complete live branch whorl. Live and dead branches were removed and weighed in bundles by hanging them from a balance under a 3 m high steel tripod erected in the forest. After branches were removed, the height of the cable attachment point, height of both clinometers, lowest live branch, lowest live branch whorl position, height to 7 cm stem diameter (timber height) and tree height were recorded. These measurements were comparable with those described in the original method. Stem diameter was measured at 1 m intervals from the base to the top for calculation of stem volume as a series of truncated cones. A 1 m central section was cut from the stem, and diameters at each end were measured, before weighing for calculation of stem green density and mass.

Soil grouping

As there were insufficient data to compare tree anchorage between all of the soil types and phases that have been identified on British forest sites (Kennedy 2002; Pyatt 1982), it was necessary to combine soils into four groups with broadly similar physical properties, i.e; free-draining mineral soils “A”, gleyed mineral soils “B”, peaty mineral soils “C” and deep peat soils “D” (Table 2-1).

Table 2-1. Soil groupings used for tree anchorage comparisons.

Rootable depth	Free-draining mineral soils	Gleyed mineral soils	Peaty mineral soils	Deep peats
Shallow < 40 cm	A1	B1	C1	D1
Medium 40 – 80 cm	A2	B2	C2	D2
Deep > 80 cm	A3	B3	C3	D3

The soil groups from A to D have increasing moisture on the soil moisture regime scale devised for the UK Ecological Site Classification (Pyatt *et al.* 2001). Free–draining mineral soils (A) include brown earths, podzols, ironpan soils, calcareous soils, rankers and skeletal soils. Gleyed mineral soils (B) include ground-water and surface water gleys as well as gleyed brown earths, gleyed podzol and gleyed ironpans. Peaty mineral soils (C) are peaty gley soils, as well as peaty podzols and peaty ironpans. Deep peats, are defined as being >45 cm of organic matter, and include *Juncus* (flushed basin) bogs, *Molinia* (flushed blanket) bogs, sphagnum (flat or raised) bogs and unflushed blanket bogs (Kennedy 2002).

Root depth is known to have a large influence on tree anchorage (Blackwell *et al.* 1990) and comparisons in this chapter are therefore based on a separation of soil groups into ranges of potential or actual rooting depths; <40 cm, 40 – 80 cm, and >80 cm (see Table 2-1). These were chosen as rooting depth ranges as they were broad enough to allow for variation across a site and to make prediction possible based on soil classification. Trees were assigned a root depth class, based on actual measurements where they were available, or by using default rooting depths for individual soil types provided by Ecological Site Classification (Ray, D. and Rayner, B. *personal communication*).

Table 2-2. Tree stability database fields.

Site and tree	Soil, cultivation and stand management	Stem	Crown	Below-ground	Anchorage
Tree Number	Planting date	Tree height	Crown weight	Root weight	Pulling date
Age	Soil type	Timber height	Crown diameter	Maximum root depth	Root/stem rot
Species	Cultivation	DBH	Height to lowest live whorl	Root plate depth	Mode of failure: snap / overturn
Forest	Stability soil group	Stem weight	Crown depth	Root plate spread mean	Attachment height
Country	Rootable depth code	Taper	Crown angle	Root plate surface area	Maximum load
Location	Thinning	Stem volume	Crown volume	Root plate volume	Applied max. turning moment
Expt. number	Spacing	Stem density	Crown area		

Standardisation of data

Data from tree-pulling experiments conducted between 1960 and 2000 were compiled into a database (Table 2-2) that included dimensions and anchorage of 12 tree species (Table 2-3), aged between 15 and 56 years old. As the experimental method had been modified over the years, and parameters were measured in varying units, all data were checked against the original experimental records and units were standardised to SI. Written experimental and site records (Table 2-4) were explored to find soil type, tree dimensions, anchorage data and other available information. Critical turning moments were recalculated for all trees. Critical turning moments were calculated at the stem base as follows:

$$(2.1) \quad M_{critical} = M_{applied} + M_{mass}$$

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. M_{mass} and $M_{applied}$ were calculated from measurements shown in Figure 2-4b using the following equations;

(2.2) $M_{mass} = m * x$

(2.3) $M_{applied} = F \cos\theta_1 * l$

For the purposes of this calculation, the centre of mass of the tree was placed at half tree height (the pull height), and the stem was assumed to be a straight beam rotating around its base. For pre-1998 experiments where trees were pulled at ⅓ tree height, a single stem angle measurement was taken between the tree base and the pull height, and this measurement was taken to be the inclination of the beam between the stem base and the centre of mass. For experiments conducted from 1998 onwards, the inclination of the beam was taken as being the average of θ_2 and θ_3, the angles relative to vertical at the stem base and half tree height (Figure 2-4b). The lengths x and l were derived using simple trigonometry.

Table 2-3. Tree species, and codes of trees pulled in tree-anchorage studies in Britain between 1960 and 2000. The number of trees pulled, the number that overturned and snapped, mean height and mean DBH are shown for each species.

Species	Latin name	Code	# pulled	# over-turned	# snapped	Mean height (m)	Mean DBH (cm)
Corsican pine	*Pinus nigra* var. *maritima* (Ait.) Melville.	CP	88	83	5	13.4	21.9
Douglas fir	*Pseudotsuga menziesii* (Mirbel) Franco.	DF	40	40	0	16.0	22.8
European larch	*Larix decidua* Miller.	EL	24	24	0	13.5	18.0
Grand fir	*Abies grandis* (Douglas ex D.Don) Lindley	GF	40	37	3	17.5	22.1
Japanese larch	*Larix kaempferi* (Lindley) Carriere.	JL	44	44	0	14.7	21.3
Lodgepole pine	*Pinus contorta* Douglas ex Loudon.	LP	244	208	36	13.1	18.6
Noble fir	*Abies procera* Rehder.	NF	16	16	0	13.8	20.3
Norway Spruce	*Picea abies* (L.) Karsten.	NS	144	139	5	13.3	20.6
Scots pine	*Pinus sylvestris* L.	SP	137	130	7	13.5	21.1
Sitka spruce	*Picea sitchensis* (Bong.) Carriere	SS	1155	1045	110	14.6	21.0
Western Hemlock	*Tsuga heterophylla* (Raf.) Sarg.	WH	44	42	2	13.7	19.0
Western red cedar	*Thuja plicata* Donn ex D.Don	RC	8	8	0	12.6	21.4

Statistical analysis

Data from trees that snapped during overturning (8.4% of the total dataset) or for which visible root or stem rot was recorded (1.5% of the total dataset) were excluded from the analysis. A series of mixed linear models were used to compare the effects of the soil and root depth factors, as well as tree species, stem mass and all 2-way interactions, on critical turning moment. Fixed and random effects were modelled using residual maximum likelihood (REML) and included a function (the reciprocal of the variance) to down-weight trees with large stem mass to account for the greater variation in turning moments required to overturn such trees. Fixed effects were soil type, root depth and stem mass, and the random effect was 'forest' within each soil/depth class combination.

Analyses for Sitka spruce were made using data from this single species, whilst differences in critical turning moments between Sitka spruce and the other tree species, were examined by fitting a series of linear mixed models to the full dataset and comparing parameter estimates for individual species. Rather than the usual R^2 statistic, estimated standard errors of the regression lines were calculated as they were considered to be more informative. Not only do they take into account the highly variable number of trees used to estimate the slope but also the variation between forests in which the trees were sampled.

Results

Anchorage of Sitka spruce

Sitka spruce was the only species with sufficient data to model the effects of all four soil groups (free-draining mineral, gleyed mineral, peaty mineral, deep peats) at three rooting depths (<40 cm, 40–80 cm, >80 cm). Stem mass.soil group and stem mass.rootable depth were both significant factors ($p < 0.001$) and the best estimate of critical turning moment, containing only significant effects, is given by the model in Table 2-5. Stem mass was the single most important variable in determining the critical turning moment required to overturn a tree. The intercept term in the model was not significantly different from zero and was therefore removed, forcing all regression lines to pass through the origin. On similar soils, trees with rootable depths >80 cm required 10 to 15% more force to overturn them, than trees with root depths less than 80 cm. For trees of similar mass, those growing on deep peats required the greatest force to overturn them. Trees growing on gleyed mineral soils were most easily overturned, requiring only two-thirds of the turning moment of those growing on deep peats.

The interaction term stem mass.rootable depth.soil type, although not included in the initial model above, was considered for inclusion as it had a level of significance of $p = 0.06$. To provide regressions for use in windthrow risk models, critical turning moments were subsequently compared with stem mass for each soil group, root depth combination (Figure 2-5, Table 2-6) using the fully parameterised model. Sitka spruce on deep peats, at all rooting depths, had greater resistance to overturning than on other soil types. There was little difference in anchorage between trees with shallow and medium rooting depth on deep peats (Figure 2-5). Sitka spruce on gleyed mineral soils had similar anchorage when rooting within shallow and medium depth ranges, but when deep rooted they were better anchored and had similar anchorage to deep-rooted trees on mineral soils. On peaty mineral soils, anchorage of Sitka spruce was similar within the shallow and medium rooting depth ranges.

Anchorage of other species

There were considerably fewer data available for species other than Sitka spruce (Table 2-3), and commonly there was a poor spread of data between soil group and depth combinations. Therefore, data from each available species, soil group and root depth combination were compared with data from Sitka spruce using regression analysis. Table 2-6 shows the estimates of slope coefficients 'C_{reg}' for regression lines and p-values that indicate the significance of similarities with equivalent lines for Sitka spruce. Medium rooting depth (40–80 cm) Douglas-fir and deep rooted (>80 cm) grand fir on free draining mineral soils had significantly better anchorage (indicated by a larger C_{reg} value) than Sitka spruce (both $p < 0.01$). Shallow (<40 cm) and medium root depth grand fir on gleyed mineral soils were also significantly better anchored than Sitka spruce ($p < 0.05$). Species, soil group and root depth combinations that had significantly poorer anchorage than Sitka spruce on the same soil with the same rooting depth were: medium root depth Corsican pine on free draining mineral soils ($p < 0.01$); shallow rooted Norway spruce on gleyed mineral soils ($p = 0.01$); deep rooted grand fir on peaty mineral soils ($p < 0.001$); medium depth lodgepole pine on mineral soil; and deep rooted lodgepole pine on peaty mineral and deep peat soils ($p < 0.01$). For other combinations of species, soil group and root depth, the comparison showed no significant difference, or there were no data (Table 2-6).

Table 2-4. Tree pulling sites, species, tree height and DBH range, number of trees pulled, and pulling year (see Figure 2-1 for forest locations).

Forest	Species	Tree height range (m)		DBH range (cm)		No. trees	Expt. years
		Min	Max	Min	Max		
Ae	NS	9.14	14.94	13.34	29.72	48	1963
	SS	10.97	18.90	10.80	41.91	152	1960, 61, 69
Alice Holt	CP	12.19	15.54	15.49	20.32	8	1968
	DF	11.89	14.63	16.26	20.32	8	1968
	GF	18.29	20.12	18.54	24.38	8	1968
	RC	11.89	13.72	18.54	22.61	8	1968
	WH	12.80	15.24	15.49	19.30	8	1968
Beddgelert	SS	10.66	20.42	16.97	29.10	48	1962
Brechfa	SS	13.10	22.00	10.60	26.50	20	1982
Brendon	CP	13.41	15.85	17.78	27.43	8	1966
	DF	16.46	19.51	21.84	29.21	8	1966
	LP	9.75	12.50	17.78	24.38	8	1966
	NS	14.63	16.46	17.02	23.37	8	1966
	SS	9.14	18.90	16.26	23.37	16	1966
Carron Valley	SS	8.53	13.41	12.95	22.61	44	1965
Castlemilk	SS	18.60	23.65	21.40	31.80	24	1998
Clashindaroch	EL	9.45	12.19	13.34	17.37	12	1962
	JL	10.36	12.19	13.34	17.37	12	1962
	LP	9.14	11.89	12.93	17.78	12	1962
	SP	8.84	10.67	12.93	14.96	7	1962
Clocaenog	NS	9.75	12.95	15.36	24.25	32	1963
	SP	10.66	11.88	19.40	22.63	2	1963
	SS	6.71	17.37	10.16	27.48	122	1962, 63, 68
Croft Pascoe	LP	5.60	8.70	8.00	13.00	31	1972
Crychan	SS	8.23	11.28	10.92	16.51	16	1968
Drummond Hill	EL	13.41	18.29	16.18	23.85	12	1962
	JL	15.54	18.29	18.19	25.07	11	1962
	LP	13.72	14.63	15.37	24.26	7	1962
	SP	11.89	12.50	17.79	22.63	5	1962
Eredine	SS	13.41	15.85	15.49	26.67	8	1969
	WH	13.41	16.15	17.02	24.89	8	1969
Glentrool	SS	24.00	30.08	28.50	55.50	22	1998
Halwill	GF	14.33	17.98	17.78	27.43	8	1968
	NS	12.19	22.50	18.54	31.00	16	1968, 73
	SS	11.28	23.00	14.48	34.00	36	1965, 68, 73
	WH	12.50	14.02	17.78	25.91	8	1968
Hamsterley	LP	13.10	16.50	14.50	27.00	8	1972
	SS	12.60	15.30	13.50	25.00	16	1972
Hartland	SS	13.72	16.46	16.26	31.52	32	1965
	WH	12.80	13.72	19.30	25.15	4	1965
Inchnacardoch	LP	10.50	21.60	11.43	40.50	92	1968, 71
	SP	13.20	19.00	18.00	28.50	17	1971
	SS	9.50	15.20	14.00	24.00	28	1971
Kershope	SS	11.58	27.90	18.54	42.00	70	1966, 93, 94
Kielder	GF	12.50	18.29	15.75	27.18	16	1964, 69
	LP	10.00	16.50	11.50	29.50	52	1969, 71
	NF	9.80	14.50	15.00	24.50	8	1972
	NS	9.70	11.60	13.40	20.30	8	1969
	SS	9.00	17.00	10.00	35.50	196	1961, 64, 69, 71, 72,
Leanachan	SS	10.00	27.70	16.00	46.50	36	1998
Lennox	NS	10.36	13.72	14.48	25.40	8	1965
	SS	11.58	13.11	14.48	23.37	8	1965
Millbuie	LP	13.50	15.50	14.50	23.00	10	1974
	SP	11.00	13.50	15.50	26.00	10	1974
	SS	12.50	13.50	19.50	25.00	2	1974
Mynydd ddu	DF	15.85	20.12	24.38	32.26	8	1968
	GF	21.95	24.08	19.30	26.67	8	1968
	NF	14.33	15.24	17.78	25.91	8	1968
	NS	13.72	15.85	19.30	23.37	8	1968
	WH	16.46	19.20	18.54	26.67	8	1968
Newcastleton	NS	11.58	20.12	18.60	32.00	16	1964
	SS	10.06	24.69	14.48	35.56	72	1964
Radnor	SS	9.75	16.46	13.72	28.96	32	1963
Redesdale	SS	6.71	10.97	11.43	21.08	36	1964
Rumster	SS	20.21	27.30	24.50	40.10	15	1998
Swaffham	DF	11.13	18.29	12.12	32.33	16	1960
Thetford	SP	10.97	17.07	14.48	27.43	24	1966
Thornthwaite	SS	9.45	11.28	13.72	18.29	8	1968
	WH	8.23	9.75	12.45	14.48	8	1968
Wareham	CP	9.45	15.85	14.48	23.37	40	1969
Wauchope	SS	9.30	13.10	11.90	24.60	32	1998
Wykeham	CP	12.50	15.85	21.84	30.23	32	1968, 70
	JL	13.41	16.76	21.08	35.56	21	1968, 69, 70
	LP	14.02	16.15	19.30	27.43	24	1968, 69
	SP	11.28	18.29	16.51	30.73	72	1968, 70
	SS	10.36	17.07	14.99	27.94	64	1969, 70

Table 2-5. Solution for fixed effects of stem mass.root depth and stem mass.soil type for Sitka spruce critical turning moment[1].

Effect	Soil type	Root depth	Estimate	Standard error
stem mass . root depth		<40 cm	167.48	8.19
stem mass . root depth		40-80 cm	167.83	6.97
stem mass . root depth		>80 cm	186.98	8.13
stem mass . soil type	Free-draining mineral		-18.94	8.37
stem mass . soil type	Gleyed mineral		-55.69	7.51
stem mass . soil type	Peaty mineral		-39.85	8.78
stem mass . soil type	Deep peats		0	

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[1] To find the slope of the regression line (C_{reg}) for critical turning moment against stem mass for a particular soil type and root depth combination, the relevant stem mass.root depth estimate should be added to the stem mass.soil type estimate. As regression lines were fitted through zero, the critical turning moment is simply the slope estimate multiplied by stem mass.

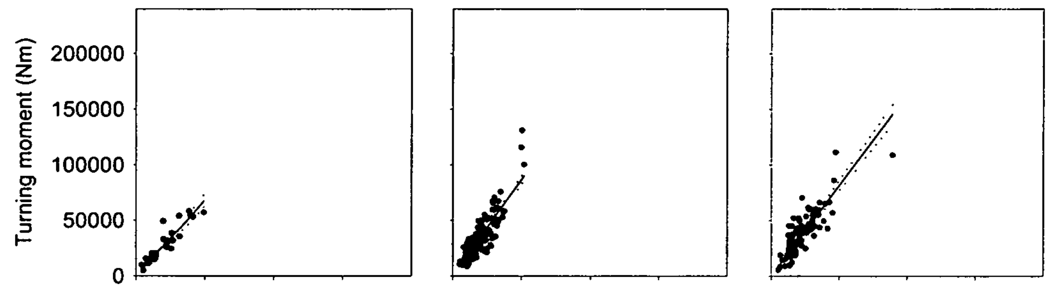
Table 2-6. Coefficient of regression line (C_{reg}), number of samples (number of sites in brackets), p-value for the comparison with the equivalent regression for Sitka spruce, and standard error (s.e.), for each species, soil group and rooting depth. Coefficients significantly different ($p < 0.05$) from Sitka spruce are indicated with an asterix. Trees were excluded if they snapped during tree pulling, or if root rot was recorded. Soil groups and root depth codes are described in Table 2-1.

Species	Root depth / Soil group	C_{reg}			n samples (sites)			*p*-value			s.e.		
		1	2	3	1	2	3	1	2	3	1	2	3
CP	A	105.1	125.5*	131.0	1(1)	31(2)	24(3)	0.17	<0.01	0.10	24.8	10.3	12.7
	B		129.5			27(2)			0.39			21.9	
	C												
	D												
DF	A		197.9*	165.6		16(2)	15(2)		<0.001	0.39		10.1	11.9
	B	197.4	156.9		2(1)	6(1)		0.22	0.17		70.3	51.8	
	C												
	D												
EL	A		177.5	147.7		1(1)	23(2)		0.65	0.77		33.4	21.4
	B												
	C												
	D												
GF	A			212.9*			10(2)			<0.001			15.3
	B	166.0*	193.0*	173.1	8(2)	8(2)	3(1)	<0.05	<0.05	0.66	24.4	25.4	27.7
	C		135.2	128.5*		2(1)	6(1)		0.77	<0.001		31.9	9.0
	D												
JL	A	177.1	182.8	168.2	1(1)	12(1)	31(3)	0.29	0.19	0.35	30.9	14.7	13.6
	B												
	C												
	D												
LP	A	137.9	142.6*	140.1	6(4)	63(6)	25(6)	0.77	<0.05	0.33	12.8	7.3	12.8
	B		137.8	148.5		15(2)	5(2)		0.31	0.61		26.3	21.4
	C	94.1	119.0	123.2*	1(1)	12(1)	6(1)	0.72	0.78	<0.001	95.7	24.9	9.7
	D		141.3	132.2*		7(1)	19(2)		0.73	<0.001		42.9	15.6
NF	A			107.5			8(1)			0.07			24.7
	B												
	C	78.5	105.6	195.8	2(1)	5(1)	1(1)	0.34	0.48	0.78	51.9	28.1	20.9
	D												
NS	A	127.8	154.6	160.9	7(1)	22(2)	22(4)	0.67	0.72	0.63	32.7	19.2	12.4
	B	62.9*	114.2		24(3)	64(5)		<0.001	0.73		9.5	9.9	
	C												
	D												
RC	A												
	B		171.7	193.9		6(1)	2(1)		0.13	0.41		40.2	38.9
	C												
	D												
SP	A	124.1	146.4	141.3	5(3)	71(5)	40(5)	0.31	0.17	0.27	15.4	9.6	9.6
	B												
	C												
	D												
SS	A	142.4	162.0	154.0	31(8)	149(12)	101(13)	—	—	—	8.6	6.1	6.4
	B	111.0	110.6	160.2	109(12)	191(14)	24(7)	—	—	—	6.4	3.7	8.9
	C	129.0	126.0	202.4	120(7)	137(8)	8(3)	—	—	—	8.6	6.6	9.5
	D	180.6	156.7	189.9	19(5)	50(7)	13(6)	—	—	—	20.2	10.4	11.8
WH	A	109.9	141.2	168.7	5(2)	7(1)	8(1)	0.14	0.36	0.52	19.5	21.6	22.1
	B	126.0	152.2		12(2)	10(3)		0.70	0.13		36.6	27.2	
	C												
	D												

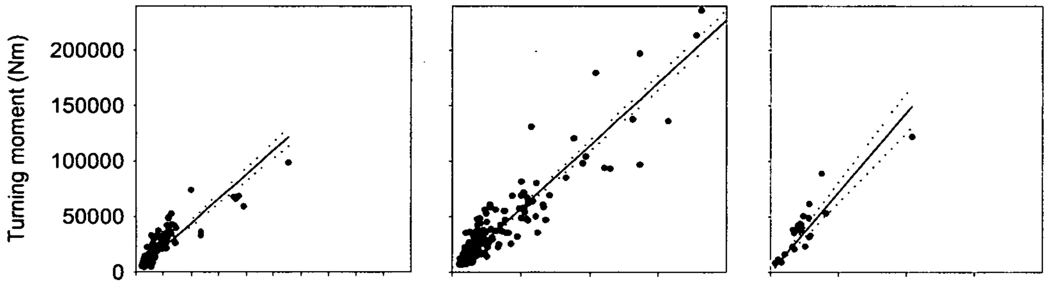
Figure 2-5. Relationship between critical turning moment and stem mass for Sitka spruce in each soil and root depth grouping. The model fitted contains the stem.soil.root interaction terms and the dotted lines give the 95% confidence interval for this estimate.

Root depth class: < 40 cm 40 - 80 cm > 80 cm

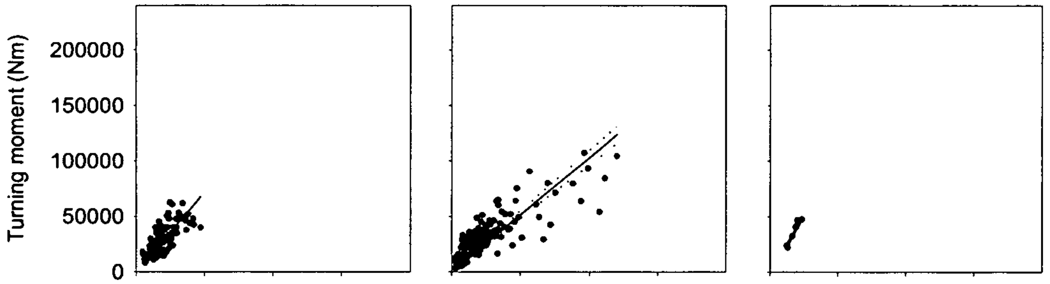
a. Free-draining mineral soils



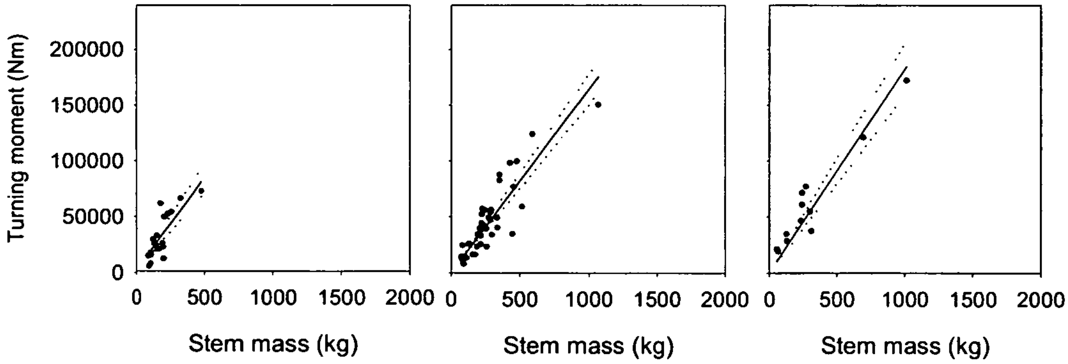
b. Gleyed mineral soils



c. Peaty mineral soils



d. Deep peats



Discussion

This study gives the first objective comparison of anchorage between a wide range of conifer species. The comparison has revealed important, yet complex differences between species, and their interactions with site conditions. Of conifer species commonly grown in the British Isles, grand fir was found to be the best anchored on deep, freely draining mineral soils and had significantly better anchorage than Sitka spruce. However, on peaty mineral soil it had significantly poorer anchorage than Sitka spruce. Sitka spruce was particularly well anchored on deep peat soils and had significantly better anchorage than lodgepole pine, the only other species examined on deep peat soils. On shallow rooted gleyed mineral soils, Sitka spruce had poor anchorage, and although most other species behaved similarly, Norway spruce had significantly poorer anchorage. Anchorage comparisons between species are therefore not simple, and depend on soil physical properties and rooting depth.

It is important to remember that this study provides comparisons of root anchorage rather than tree stability. Modelling or measurement of crown characteristics, and hence wind-loading, is required to relate the former to the latter. However, anchorage may be expected to be a reasonable predictor of conifer tree stability if conifer species are assumed to have similar crown characteristics. There are comparisons in the literature of stability between some of the conifer species examined here, but most of these comparisons are based on windthrow records after storms, rather than experimental studies. For example, Neustein (1965) examined windthrow after a storm and reported better stability of Norway spruce compared to Sitka spruce. In the analysis presented in this chapter, Norway spruce had significantly poorer anchorage than Sitka spruce on one soil group, root depth combination, and similar anchorage on the remaining combinations, so the differences in the Neustein study may have resulted from stands being on different soils. Ruth and Yoder (1953) found that western hemlock had poorer stability than Sitka spruce and Douglas-fir, although this may have been associated with butt rot (*Heterobasidium annosum*) infection of the roots in the western hemlock. In the present analysis western hemlock was similarly anchored to Sitka spruce, but trees in the data-set with recorded root rot were not included. Similarly, Busby (1965) described greater vulnerability of Japanese larch to wind damage compared to Sitka spruce, while in the present study anchorage of Japanese larch was not significantly different to Sitka spruce on mineral soils.

In a tree-pulling experiment conducted on mineral soil in Finland (Peltola *et al.* 2000), Scots pine was found to be better anchored than Norway spruce, while in the present investigation these species had similar anchorage. The difference between these results may reflect deeper rooting depths of Scots pine compared to Norway spruce in the Finnish study, in agreement with the finding that anchorage of Norway spruce is comparatively poorer on sites with restricted rooting depth. However, regressions in the Finnish study are based on critical turning moment against tree height x DBH^2, rather than stem mass as used in the present study. Results of tree-pulling studies where stem mass is the predicting variable, and can therefore be more directly compared to this study, are described in Table 2-7. In the present study, Douglas-fir showed better anchorage than Sitka spruce for one soil group; i.e. medium depth mineral soil. Similarly, in a study conducted in New Zealand, Douglas-fir grown on a mineral soil was better anchored than radiata pine (Moore and Gardiner 2001). However, when the regression coefficient (C_{reg}) is compared between Douglas-fir in the British and New Zealand tree-pulling experiments, this species appears to be considerably better anchored in Britain. Other conifer species described in the table are different from the species investigated in the present study, but again have lower C_{reg} values for equivalent soil group and root depth, except for maritime pine, a tap-rooted species, on deep mineral soil. Better anchorage of conifers in the British Isles, compared to other parts of the world, may be expected as they experience higher average wind speeds than many other forested areas (Troen and Peterson 1989), and tree root anchorage is known to be strengthened in response to wind movement (Nicoll and Ray 1996; Stokes *et al.* 1997a; Urban *et al.* 1994).

The finding that Sitka spruce has better resistance to overturning on deep peats than on other soils is perhaps surprising but reinforces some observations in the literature. Pyatt (1966) reported negligible windthrow of Sitka spruce on deep peats after a storm, despite 6% damage on surface-water gley and 2% damage on peaty gley. Rigg and Harrar (1931) reported that windthrow of conifers was rare on natural peat bogs, although it was common on adjacent mineral soils. One explanation for this phenomenon is that the extraction force for Sitka spruce roots has been found to be nine percent greater in peat than in mineral soils (Anderson *et al.* 1989). An additional factor may be the tendency for conifer roots on peaty soils to develop eccentric 'I-beam' cross sectional shapes (Büsgen and Münch 1929). This behaviour is important to tree stability because a root with such a shape can have 300 % of the flexural stiffness of a circular root with the same cross sectional area (see Chapter 1). Roots that are held rigidly in mineral soils would be expected to have a smaller stimulus for adaptive development in response to wind (Nicoll and Ray 1996) than that experienced in more plastic peat soils. However, during a storm, as the soil at the base of the root plate starts to fracture, anchoring roots are pulled from the soil, and the stiffness of the lateral structural roots becomes particularly important (Coutts 1986). Therefore, if roots of a tree on deep peat flex more as the tree sways than roots of a tree on mineral soils, they will adapt better to the wind environment and be better prepared to resist bending in the strongest winds when they occur.

Table 2-7. Slopes of regression lines (C_{reg}) for critical turning moment (Nm) against stem mass (kg) compared between species from studies described in the literature.

Species	Name	Soil	Soil group	C_{reg}	Reference
Abies balsamea L.	Balsam fir	Podzol	A3	100.9	Achim *et al.* (2005b)
Picea glauca (Moench) Voss	White spruce	Podzol	A3	100.9	Achim *et al.* (2005b)
Picea mariana (Mill.) B.S.P.	Black spruce	Podzol -shallow/stony	A1	105.2	Elie and Ruel (2005)
		Podzol -deep/no stone	A3	108.9	
Pinus banksiana Lamb.	Jack pine	Mineral soil -deep/no stone	A3	130.9	Elie and Ruel (2005)
Pinus pinaster Ait.	Maritime pine	Podzol -shallow/hard pan	A1	125.8	Cucchi *et al.* (2004)
		Podzol -deep/no hard pan	A3	168.8	
Pinus radiata D. Don.	Radiata pine	Orthic Pumice soil	A3	83.0	Moore (2000)[2]
Pseudotsuga menziesii (Mirb.) Franco	Douglas-fir	Orthic Pumice soil	A3	91.0	Moore and Gardiner (2001)[2]

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[2] C_{reg} calculated using regression of critical turning moment against stem volume, and stem green density data.

Conclusions

The analysis described here has provided linear relationships between critical turning moment and stem mass that can be used to predict tree anchorage within windthrow risk models. Despite the analysis being based on a large number of tree-pulling experiments conducted over a 40-year period and with almost 2000 data points, there are still a number of gaps in the database. Ideally, tree-pulling experiments would continue until each possible combination of species, soil grouping and rooting depth range had been investigated. However, the practical difficulties and high cost of tree-pulling experiments will limit work of this kind and it is likely that any similar work in the future will be small-scale studies to answer particular topical questions about tree anchorage. For example, as the importance of tree species diversity increases in commercial forestry, a better understanding may be required of the anchorage of trees that are currently considered to be minority species. This could be achieved by the development of critical turning moment regressions based on tree pulling experiments, or through the development of improved mechanical models of tree anchorage. However, Sitka spruce is now well understood in terms of anchorage, and the anchorage of other species commonly appears to be similar on comparable soils. It would therefore be acceptable for wind risk models to use the relevant Sitka spruce regression lines for other conifer species until better data become available.

3. Does steep terrain influence tree stability? – A field investigation

Abstract

The anchorage of 40-year-old Sitka spruce (*Picea sitchensis* (Bong.) Carr.) trees grown in a plantation on a steep (ca. 30°) slope was compared with that of trees grown on an adjacent horizontal area. There was similar gleyed mineral soil on the sloping and horizontal areas. Trees were mechanically overturned using a winch, and anchorage was quantified by measuring load, stem angle and tree dimensions. Trees on the slope were overturned upslope, downslope or across-slope. Critical turning moments were calculated around the tree base and the actual hinge point. Critical wind speeds required to uproot or snap trees in this stand were modelled to compare the vulnerability of trees to upslope and downslope winds.

No overall difference was found in anchorage between trees grown on the horizontal and sloping parts of the site. However for trees on the slope, those pulled upslope showed significantly more resistance to overturning for a given stem mass than those pulled downslope. Critical turning moments calculated at the hinge point were smaller than those calculated at the stem base, but differences were small and had no effect on the comparison between treatments. Critical wind speeds for uprooting were estimated to be 28 m s^{-1} for an upslope wind and 24 m s^{-1} for a downslope wind on this site. The implications of these results are discussed in relation to windthrow risk modelling and forest soil conservation.

Introduction

Problems of managing forest stands in areas vulnerable to wind damage have necessitated the development of predictive models of windthrow, such as ForestGALES (Gardiner *et al.* 2004; Quine and Gardiner 1998), HWIND (Peltola *et al.* 1999; Peltola *et al.* 1997) and WINDA (Blennow and Sallnäs 2004). Although in the development of these models local wind climate has been adjusted to allow for topography (Peltola *et al.* 1999; Suárez *et al.* 1999), the assumption is made that there is no difference in anchorage between trees growing on horizontal and sloping sites. However, aerial photographs of wind damage to forest plantations taken after storms have shown more damage to trees on slopes and valley sides in some areas compared with trees grown on more horizontal sites (Quine, C.P. *personal communication*). It is not clear if these observations result from localised variation in wind exposure, funnelling of wind in valleys (Savill 1983), mechanical differences in anchorage resulting from variation in root architecture, or a combination of these effects. A number of studies of tree anchorage, including the analysis in Chapter 2 of this thesis, have related tree critical turning moments to measurable tree characteristics. All have shown good linear relationships between critical turning moment and stem mass, stem volume, or stem diameter for trees on particular soil types (Blackburn 1986; Fraser and Gardiner 1967; Fredericksen *et al.* 1993b; Meunier *et al.* 2002; Moore 2000; Papesch *et al.* 1997; Peltola *et al.* 2000; Ray and Nicoll 1998). These simple relationships are used within windthrow models to predict tree vulnerability based on measured or predicted tree dimensions for particular defined soil and site conditions. In improving the accuracy of forest windthrow models, it is important that we test whether the anchorage of trees is reduced on slopes compared to those grown on horizontal sites.

Understanding the stability of trees on slopes is also important for the development of models to predict soil loss through erosion and landslides. Trees have a positive effect on soil stability of vulnerable slopes (O'Loughlin 1974; Swanston 1974), reducing soil losses through erosion and shallow landslides. The network of coarse and fine tree roots close below the surface binds soil together, while sinker roots anchor the surface layers to the deeper, more stable, soil mass (Zhou *et al.* 1997). However, windthrow of trees has a negative effect on soil stability and may be the most important factor in downslope movement of soil on many forested slopes (Schaetzl 1986). Soil from upturned root-soil plates on steep slopes is frequently deposited downslope of the original tree position as windthrown trees are harvested or as the roots decompose (Beatty and Stone 1986). Recently disturbed, unconsolidated, soil that is unprotected by vegetation can easily be eroded by surface water flow (Schaetzl *et al.* 1990), and water penetrating into deeper soil horizons from craters formed under overturned root-soil plates may trigger shallow slides on unstable slopes (Swanston 1974). Increasing pressure on the forest industry to conserve soil and to minimise sediment input to streams and water courses, has led to calls for better assessment of risk of soil loss from forested sites (Montgomery and Dietrich 1994).

Understanding the mechanics of tree anchorage on slopes will improve the accuracy of predicting of both economic loss and soil loss that result from windthrow events. An important development in our understanding of tree stability on sloping terrain will be to describe anchorage in relation to the direction in which wind blows during a storm, that is, upslope, downslope or across-slope. Two hypotheses were tested in a field investigation: (1) trees on slopes are less stable than trees on horizontal terrain and (2) the stability of trees on slopes will vary with the direction of overturning. Trees on a steep (ca. 30°) slope were mechanically overturned either upslope, downslope or across-slope and their resistance to overturning was compared with that of trees grown on a horizontal part of the site with similar soil. Critical wind speeds required to overturn these trees were calculated using a version of the GALES method (Gardiner *et al.* 2000) modified for forest stands on slopes. Wind stability was compared among wind directions and a sensitivity analysis was performed to examine the relative influence of changes in parameters influenced by slope. In addition, measurement of uprooted root-soil plate dimensions allowed us to quantify the soil that could become available for erosion following windthrow of trees on sloping terrain.

Methods

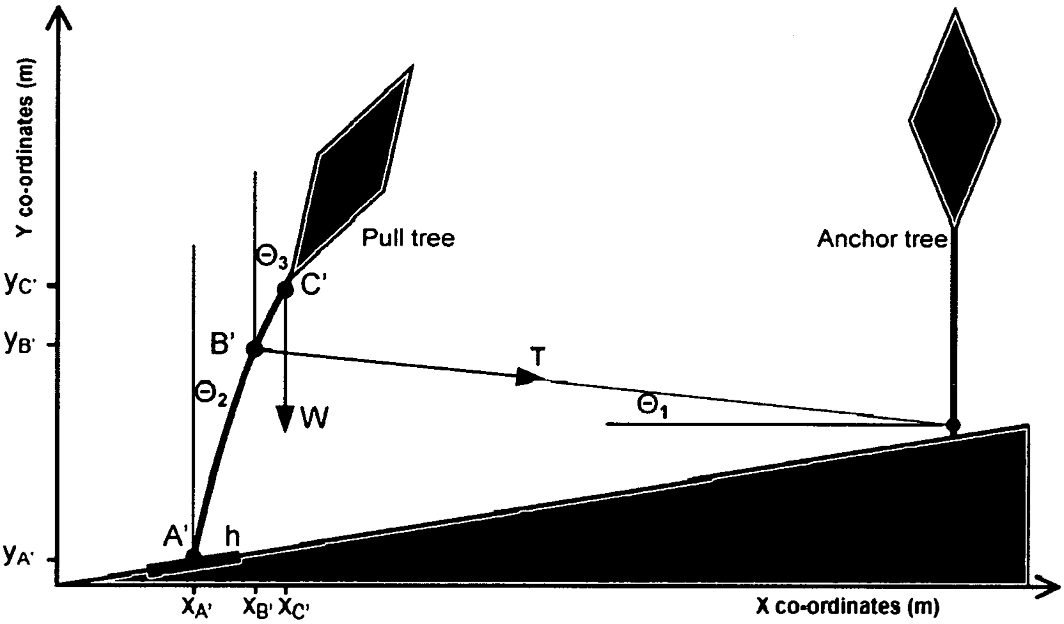
Site details

Thirty-six Sitka spruce (*Picea sitchensis* (Bong.) Carr.) trees were mechanically overturned in Leanachan Forest near Fort William, west Scotland (56° 51.95' N, 4° 58.40' W). The site was an almost uniform north-facing slope, 300 m wide and 25 m deep, with an inclination of between 26° and 33°, and with horizontal areas at top and bottom. Trees were planted on the site in 1962 as 2-year-old '1+1' transplants. At the time of the investigation (November 2001), the mean tree height was 22.3 m, and mean diameter at breast height (DBH) was 23.4 cm. Trees were spaced on average 2.66 m apart, representing 1415 stems ha^{-1} in plan view, which equated to 2.86 m between trees and 1225 stems ha^{-1}, parallel to the slope. Weather before and during the field investigation was wet, with periods of light to moderate rainfall. The soil on both the sloping and the horizontal areas was a mineral soil, classed as a surface water gley (Kennedy 2002) with some induration in places. Typically, the soil profile consisted of a thin leaf litter over a gleyed humic loamy A horizon (15-25 cm thick), over a well drained loamy B horizon (40-100 cm thick), that extended down to an induration or to rock (A. Kennedy, unpublished report, 2005). The soil had a predominantly silty loam texture. Wind, monitored on open moorland 1 km from the experiment site between 1988 and 1999, had a prevailing direction of 255° from north.

Treatments

A total of nine trees were selected for each of four pulling treatments: pulled across-slope, pulled downslope, pulled upslope, and pulled on the horizontal part of the site. In the across-slope treatment, four trees were pulled east, and five were pulled west. In the horizontal treatment, trees were overturned in random directions. To obtain a consistent range of tree sizes in all pulling treatments, three dominant, three codominant and three sub-dominant trees were selected for each treatment. For the purpose of sample selection, dominant trees were defined as being close to the upper quartile of DBHs of trees measured in tariff plots, sub-dominant trees had DBHs close to the lower quartile, and co-dominant trees had DBHs close to the median. Trees were selected randomly within these constraints from across the site.

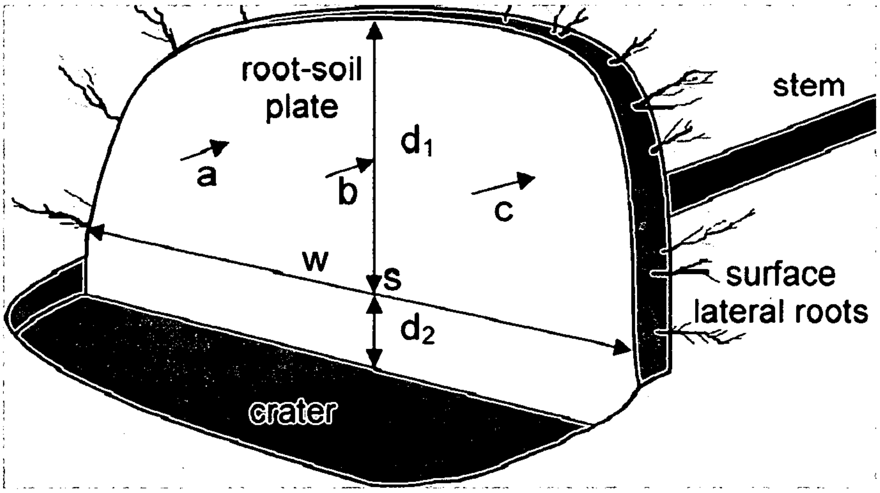
Figure 3-1. Tree pulling on a slope, showing an example of a tree being overturned upslope (not to scale), and the method for calculation of turning moment using a co-ordinate system. A , B and C are the stem base, cable attachment point and centre of mass on the pull tree, respectively. T is the applied force. θ_1 is the angle of the pull cable, θ_2 is the stem base angle, and θ_3 is the stem angle at half tree height.



Measurements and instrumentation

The site slope angle was measured around each selected tree, and digital biaxial clinometers (Applied Geomechanics, Santa Cruz, California, USA) were fixed to the stem at 1.3 m above the base and at half tree height. Neighbouring trees were felled where necessary to avoid crown interference during tree-pulling. A chainsaw-powered winch (Habegger, Thun, Switzerland) was attached to an anchor tree using a 2-m long polyester round-sling (safe working load 5 t). Each anchor tree was selected to be more than one tree length in the selected direction from the pull tree. A load-cell (3 t maximum load) was positioned on an 8.2-mm diameter steel cable between the winch and the pull tree. Both clinometers and the load-cell were connected to a data logger. To protect the safety of the operator when the tree was pulled downslope, the winch was offset by up to 90° by attaching a pulley block to another tree in the pull direction. The pulling cable was fixed to the pull tree with a polyester round-sling placed on the tree at approximately half tree height. The distance between the anchor tree and the pull, or offset, tree was recorded. The angle of the cable was measured from the winch attachment point (or pulley on the offset tree) to the attachment point on the pull tree (Figure 3-1).

Figure 3-2. Measurement of the root-soil plate; plate width (w), distance from stem centre (s) to windward edge (d_1), distance from s to hinge (d_2), and plate thickness at three points (indicated by arrows, a, b and c) across the plate.



After a zero reading was taken from the load-cell and both clinometers, the strain was taken up, and the tree was pulled over using the winch. The tree stem angles, measured from the clinometers, were recorded by the data logger when the maximum load was reached. Once the tree was on the ground, crown spread was measured, and instrument and cable attachment points were marked on the stem, as was the position of the lowest live branch whorl. Live and dead branches were removed and weighed in bundles by hanging them from a weighing balance suspended under a 3-m high steel tripod. The height of the winch-cable attachment point, height of attachment of both clinometers, position of the lowest live branch whorl, and height of the tree were then measured on the de-branched stem. Stem diameters were measured at 1-m intervals up the stem from the base using measuring callipers with 1-mm resolution. A 1-m central section of the stem was removed for green density (i.e., fresh mass per unit green volume) determination. The dimensions of the root-soil plate were then measured as shown in Figure 3-2, that is, 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 soil depth at 3 points in a line across the plate at 0.5 x d_1. The edge of the plate was defined as being where soil was no longer held by the roots (see Figure 3-2). The volume of the root-soil plate was estimated from these measurements, using the mean plate depth, and assuming a half ellipse shape for the area above the stem centre, and a rectangular shape below the stem centre.

Calculation of the critical turning moment

The relative positions (x, y co-ordinates in the vertical plane) of the base of the anchor tree, the hinge, the attachment point, and the centre of gravity of the pull tree were all determined for the moment in time when the maximum load was reached (Figure 3-1). From these, the length of the complete lever arm (stem plus part of the root-soil plate) and an accurate measurement of the angle of the pull-cable at maximum load (θ_1) were calculated. The stem and root-soil plate were considered to be rigid for the purpose of this calculation. Critical turning moments were calculated at the stem base and at the hinge point (h), excluding trees that snapped as they overturned. The inclination of the stem was taken to be the mean of angles at the tree base (θ_2) and at half tree height (θ_3), when the maximum load was reached. The average hinge distance was used for three trees for which the hinge distance could not be measured on site. Critical turning moments were calculated as follows:

$$(3.1) \quad M_{applied} = T_x\left(y_{B'} - y_{A'}\right) + T_y\left(x_{B'} - x_{A'}\right)$$

$$(3.2) \quad M_{total} = M_{applied} + W\left(x_{C'} - x_{A'}\right)$$

where $x_{A'},y_{A'}$, represents the coordinates (m) of the stem base or hinge position, $x_{B'},y_{B'}$ the cable attachment point, and $x_{C'},y_{C'}$ the centre of gravity of the tree at the time when the maximum force was reached. $M_{applied}$ (Nm) is the critical turning moment applied by the winch. T_x (N) and T_y (N) are the horizontal and vertical components of the applied force respectively, calculated from the wire pull angle at the time when the maximum applied load was reached (Figure 3-1). M_{total} (N m) is the total critical turning moment of both the force applied by the winch cable and the force resulting from the overhanging weight of the leaning tree. W (N) is the total weight of the tree. The centre of gravity of each tree was calculated from the mass data from the tree sections, with the crown mass added at half crown depth.

Calculation of critical wind speed

Critical wind speeds at which average trees in a stand would uproot (U_{uproot}) or snap (U_{snap}) were calculated using the GALES method (Gardiner *et al.* 2000), for the treatments that showed significant differences in anchorage. This analysis was based on mean site conditions, that is, 22.3 m tall Sitka spruce with DBH 23.4 cm, at a spacing of 2.86 m on a slope of 30°. These calculations assumed that only anchorage parameters varied between treatments. The equations given by Gardiner *et al.* (2000) for trees on flat ground were modified for slopes, and an idealised slope was assumed where the wind flowed parallel to the ground and was not influenced by topographic obstacles. The maximum bending moment applied to the base of the average stem in a stand by an hourly-averaged top wind speed in the canopy (u_h, m s^{-1}) was calculated using the following equation:

$$(3.3) \qquad M_{\max} = d\rho G\left[\frac{Du_h k}{\ln\left(\dfrac{h-d}{z_0}\right)}\right]^2$$

where d (m) is the zero plane displacement height, ρ (=1.226 g m^{-3}) is air density, G (dimensionless) is a wind gust factor (the ratio of maximum to mean bending moment), D (m) is the average spacing between trees, k is Von Karman's constant (= 0.41), h (m) is canopy height, and z_0 (m) is the aerodynamic roughness (Gardiner *et al.* 2000).

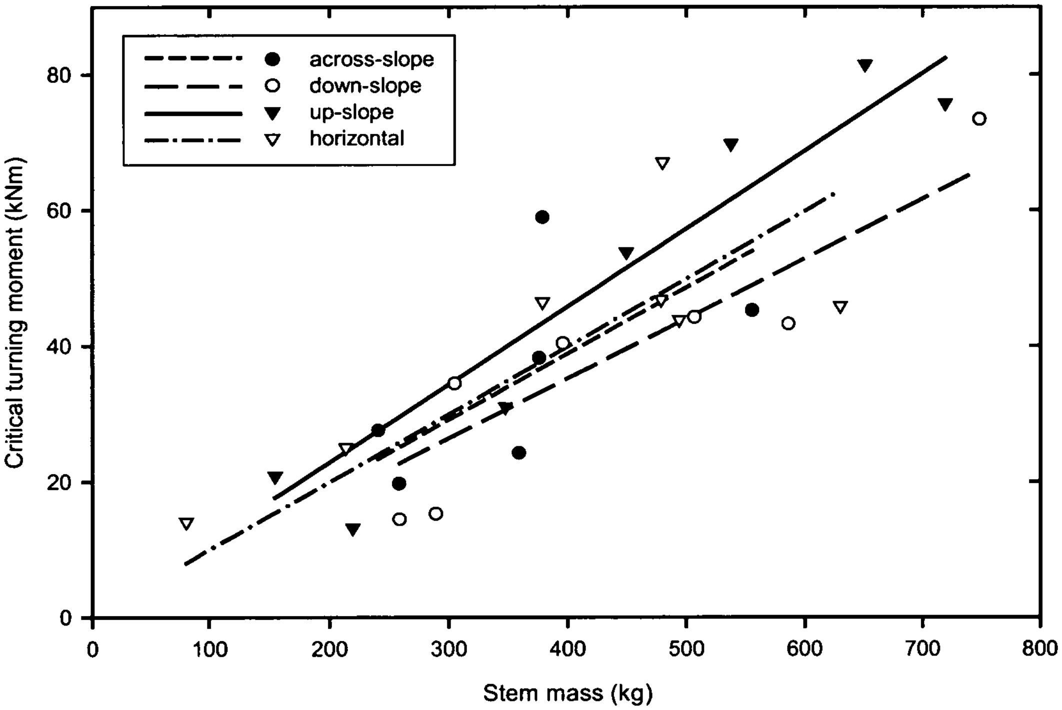
The constants k and ρ are not influenced by slope conditions. D is usually obtained from assessments of the number of trees per hectare, either from field surveys or aerial photography and assumes the ground to be horizontal. The calculation of D was therefore adjusted to make it representative of spacing across the real surface area of this sloping site. G may be expected to vary between horizontal and sloping terrain, and between parts of a slope, but as this variation has not been quantified, G was calculated as described by Gardiner *et al.* (1997) for horizontal terrain, assuming an airflow that is parallel to slope. The values of z_0 and d were derived from h and a frontal area index (λ, dimensionless) with simple analytical expressions developed by Raupach (1994). Rather than being the mean height of the trees, h_{slope} was the distance, perpendicular to the slope, between the top of the canopy and the ground. λ was calculated by dividing the crown area of the average tree, assuming a diamond-shaped crown profile (Gardiner *et al.* 2000), by the area of the surface the tree occupied on the ground.

A sensitivity analysis was performed to examine the percent changes in U_{uproot} and U_{snap}, predicted using the GALES method, that result from variations in parameters that may be affected by slope, that is, slope inclination, G, crown area, stand density and stem deflection at maximum turning moment. Each parameter was increased and reduced by 20% as in Gardiner *et al.* (2000). Changes in crown area (± 20%) were calculated using a proportional change in width and depth. Changes in stem deflection were increases or decreases in the tree's deflection from vertical at the time when the maximum load was reached.

Statistical analysis

Means of above- and below-ground tree components were compared using one-way analysis of variance with 'across-slope', 'downslope', 'upslope' and 'horizontal' as the treatment structure. Critical turning moments were compared between treatments (excluding snapped trees) using linear regression analysis, with stem mass as the covariate. Regression lines were compared as *a priori* contrasts between trees pulled upslope, downslope and across-slope, and between trees grown on the slope and on the horizontal.

Figure 3-3. Linear regressions of critical turning moment at stem base against stem mass. Data excludes trees that snapped during overturning, and all regression lines were fitted through zero.



Results

Most trees in all treatments were uprooted, exposing a well-defined root-soil plate, but the stems of three trees pulled across-slope, and two from each of the other treatments (upslope, downslope and horizontal,) snapped as they were winched over. Above-ground characteristics were similar among trees subjected to the different pull treatments (Table 3-1). The root-soil plate depth of trees pulled downslope was greater than the depth of those in the other treatments (p = 0.02). The estimated volume of the root-soil plate (Table 3-1) was greatest for trees pulled downslope and smallest for trees pulled upslope ($p = 0.04$). The overall mean root-soil plate volume was 1.44m^3.

The effect of the treatments on the relationship between critical turning moment, calculated at the stem base, and stem weight is shown in Figure 3-3 and Table 3-2. The intercept terms of the regressions were not significantly different from zero and were removed to correspond with the convention in previous tree anchorage studies (for example, see Chapter 2, Peltola *et al.* 2000 and Achim *et al.* 2005).

For a given stem weight, no significant difference in the critical turning moment was found between trees on horizontal ground and those on slopes; that is, the average of across-slope, downslope, and upslope ($p = 0.98$). However, significantly smaller moments (Figure 3-3, Table 3-2) were required to uproot trees downslope than upslope ($p < 0.05$). The critical turning moments calculated at the hinge point of the root-soil plates were slightly smaller than those calculated at the base of the stem for all treatments, but the ranking remained the same with the upslope treatment having the largest moments, and the downslope treatment having the smallest moments. The hinge:stem base ratio of critical turning moments for the average tree was 0.91, 0.96, 0.90 and 0.97 for across-slope, downslope, horizontal, and upslope treatments, respectively.

Table 3-1 Mean and standard error (s.e.) of tree characteristics and mean critical turning moments (t.m.) calculated at the stem base (F-test *p*-values from ANOVA are given for the comparison between means; n = 9 per treatment for above-ground characteristics and n for other characteristics are as in Table 3.2).

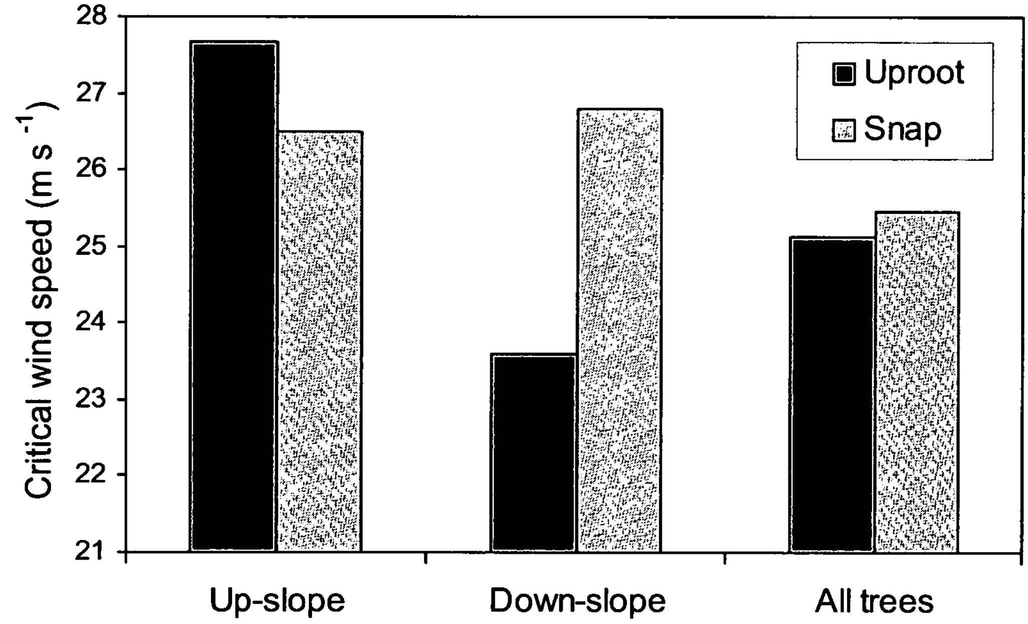
treatment	**Across-slope**		**Downslope**		**Upslope**		**Horizontal**		***p***
characteristic	**mean**	*s.e.*	**mean**	*s.e.*	**mean**	*s.e.*	**mean**	*s.e.*	
Above-ground									
Tree height (m)	22.69	*0.50*	22.89	*0.47*	22.95	*0.84*	20.82	*1.02*	0.16
DBH (cm)	23.0	*1.5*	22.9	*1.6*	22.4	*1.3*	23.4	*1.5*	0.96
Crown Diameter (m)	3.08	*0.29*	3.07	*0.14*	3.01	*0.28*	3.29	*0.21*	0.85
Crown Depth (m)	11.98	*0.75*	12.86	*0.70*	12.22	*0.81*	11.24	*0.71*	0.50
Stem volume (m^3)	0.45	*0.07*	0.46	*0.07*	0.46	*0.07*	0.42	*0.06*	0.97
Total stem mass (kg)	422.9	*63.7*	405.6	*60.7*	421.5	*64.7*	368.2	*57.0*	0.91
Crown mass live (kg)	66.7	*13.7*	69.5	*14.4*	68.3	*13.7*	69.9	*15.4*	1.00
Crown mass dead (kg)	15.1	*1.9*	19.2	*3.9*	21.0	*4.0*	25.5	*4.4*	0.27
Shoot mass total (kg)	504.6	*77.1*	494.3	*75.8*	510.8	*79.3*	463.6	*73.6*	0.97
Stem wood density (kg m^{-3})	945.2	*24.9*	880.0	*28.0*	907.3	*25.0*	849.3	*36.1*	0.13
Below-ground									
Max root depth (m)	0.94	*0.10*	1.24	*0.14*	0.92	*0.07*	0.89	*0.07*	0.06
Root-soil plate depth (m)	0.66	*0.11*	0.78	*0.11*	0.43	*0.04*	0.48	*0.04*	**0.02**
Root soil plate area (m^2)	2.40	*0.47*	2.52	*0.22*	1.90	*0.37*	3.05	*0.49*	0.25
Root soil plate volume (m^3)	1.42	*0.21*	2.01	*0.36*	0.82	*0.18*	1.51	*0.28*	**0.04**
Hinge dist. from stem centre (m)	0.57	*0.06*	0.48	*0.04*	0.59	*0.07*	0.70	*0.08*	0.17
Critical turning moments									
Applied critical t.m. at stem base (kNm)	38.818	*7.452*	28.992	*5.444*	38.640	*6.567*	34.249	*4.632*	0.64
Total critical t.m. at stem base (kNm)	46.987	*8.763*	36.501	*6.390*	47.933	*8.427*	40.152	*5.065*	0.64

Table 3-2. Number of trees uprooted (excluding snapped trees), coefficient of the linear regression of critical turning moment against stem mass, and R^2 for each treatment.

Pull treatment	n_{uprooted}	coefficient	R^2
Across-slope	6	89.4	0.24
Downslope	7	83.7	0.84
Upslope	7	110.4	0.91
Horizontal	7	88.6	0.39

As the only significant difference between critical turning moments was between trees pulled up- and downslope, critical wind speeds for overturning were calculated separately for trees pulled in these directions, and for all treatments combined (Figure 3-4). Although there was predicted to be little difference in the wind speed required to snap trees upslope (26.5 m s^{-1}) and downslope (26.8 m s^{-1}), a considerably greater wind speed would be required to uproot trees upslope (27.7 m s^{-1}) than downslope (23.6 m s^{-1}). For all treatments combined, U_{uproot} was predicted to be 25.1 m s^{-1} and U_{snap} to be 25.5 m s^{-1}.

Figure 3-4. Critical wind speed required to uproot and snap average trees on the site, compared between those pulled upslope, downslope and all treatments combined, calculated using the modified GALES method.



The sensitivity analysis (Table 3-3) predicted a relatively small (<3%) increase or decrease in U_{uproot} and U_{snap} from +/- 20% changes in crown area and stem deflection. Changes of +/- 20% in the slope angle were predicted to cause a <7% increase or decrease in critical wind speed. The method was most sensitive to changes in G and stand density, and +/- 20% changes in these parameters were predicted to alter critical wind speed by up to 11 %.

Table 3-3. Sensitivity of the prediction of critical wind speed for uprooting (U_{uproot}) and stem snap (U_{snap}) to +/- 20% changes in factors that may be affected by slope, using the modified GALES method and based on mean characteristics for the site.

Variable	Change	% change in U_{uproot}		% change in U_{snap}	
		upslope	downslope	upslope	downslope
Slope	+20%	6.0%	5.9%	6.4%	6.4%
	-20%	-4.4%	-4.3%	-4.7%	-4.6%
Gust factor (G)	+20%	-8.1%	-8.1%	-8.2%	-8.2%
	-20%	11.0%	11.0%	11.0%	11.0%
Crown area	+20%	2.5%	2.5%	2.4%	2.4%
	-20%	-2.9%	-3.0%	-2.8%	-2.8%
Stand density	+20%	10.6%	10.6%	10.5%	10.5%
	-20%	-11.4%	-11.4%	-11.3%	-11.3%
Stem deflection	+20%	1.8%	1.8%	1.9%	1.9%
	-20%	-2.0%	-2.0%	-1.9%	-1.9%

Discussion

There was no overall difference in the critical turning moment of trees on horizontal and steeply sloping terrain. Based on these findings, there is therefore evidence to reject the first hypothesis and confirm the implicit assumptions in predictive models of windthrow (Blennow and Sallnäs 2004; Gardiner *et al.* 2000; Gardiner *et al.* 2004; Peltola *et al.* 1999; Quine and Gardiner 1998) that regressions of critical turning moment against stem mass remain unaltered by the terrain on which the stand is located, provided that soil type is constant.

Trees in this study were significantly more vulnerable to overturning downslope than upslope, and the difference in critical turning moment was of the order of 25%. This supports the second hypothesis, that the stability of trees on slopes will vary with the direction of overturning. Increased anchorage of trees when a force is applied in an upslope compared with a downslope direction provides trees with better resistance to the more commonly experienced winds. Mean wind speeds on sites on hilly terrain will tend to be less in a downslope than in an upslope direction, owing to the shelter effect on the lee side (Finnigan and Brunet 1995). Airflow tracks the slope closely on the windward side of a hill as the wind travels upslope, but the flow commonly separates from the slope on the lee side. As a result, wind speeds are reduced in the 'wake' region and wind direction can sometimes be reversed if a 'separation bubble' forms below the separated flow on the lee side (Finnigan and Brunet 1995).

Root plate volume and root plate depth was less for trees overturned upslope than for those pulled downslope, directly reducing two of the components of tree anchorage defined by Coutts (1986): root-soil plate mass and soil strength. The increase in resistive turning moment of upslope trees must therefore result from increases in either, or both, of the remaining two components identified by Coutts (1986), that is, the pull-out resistance of roots, and the resistance to bending of structural roots at the 'hinge'. Therefore, the observed difference between upslope and downslope anchorage could result from increased root growth on the down-hill side of the tree, providing better combined pull-out resistance of roots on the windward side of the tree. Alternatively the difference may result from relatively less structural root development on the downslope side, that would move the hinge point closer to the tree and hence reduce the downslope resistive turning moment (Achim *et al.* 2003; Coutts *et al.* 1999; Stokes *et al.* 1997b). As structural root mass has been found to be greater on the lee side of wind exposed trees (Nicoll and Ray 1996), we might expect to find more root mass on the upslope side of exposed trees on slopes. Therefore, adaptations of the root system in response to wind could explain the higher resistance to upslope overturning. However, the study described here examined the stability of trees on only one site, that was north facing and may therefore have been relatively sheltered. Future studies should examine trees grown on sloping sites that have more exposed aspects.

The small decrease in critical turning moment calculated at the hinge point compared with the stem base results from differences in the length and angle of the lever arm induced by repositioning of the rotation point. Ideally, tree anchorage should be calculated at the position of the hinge, rather than at the stem base, because this most accurately represents the moment resulting from soil and root resistance. However, when determining critical wind speeds it is important that turning moments are compared at a standard point, and turning moments calculated at the tree base (as in Figure 3-3) are most useful for comparison in models such as ForestGALES.

In this study, U_{snap} was the same for trees pulled up- and downslope, but U_{uproot} upslope was greater than downslope. This result indicates that in storms where critical wind speeds are reached, more trees on this site may be snapped than overturned in an upslope wind, while more may be overturned than snapped in a downslope wind. However, an improved understanding of tree breakage and further modelling of the mechanics of tree stability on slopes are required to confirm these findings.

The sensitivity analysis, presented here, used the GALES method (Gardiner *et al.* 2000) to reveal the relative importance of each input parameter that is affected by slope. The smallest effect on critical wind speed was caused by changes in stem deflection at the time of maximum load. This indicates that there was little effect of rotating the stand on the sloping site to be horizontal for the purpose of calculating critical wind speed. Equally, the simple estimation of crown area, using a diamond shape, appeared to be adequate, as a 20% change in crown area resulted in a change of <3% in critical wind speed. Of the remaining parameters, slope and stand density were relatively important in the calculation, but should be measurable with a high level of precision. The other remaining parameter, *G*, the gust factor, made the most important contribution to the calculation, with a change of up to 11% in critical wind speed resulting from a 20% change in *G*. As the calculation assumed *G* to be the same on a slope as on horizontal terrain, the sensitivity analysis indicates that measurement or modelling of *G* on complex terrain should have the highest priority in future tree stability research.

The findings of this study also have implications for soil conservation and for the prediction of soil loss from forest sites, during and following storm events. In some forest areas, the greatest loss of soil from forest sites is reported to result from root-plate overturning during windthrow (Schaetzl 1986; Schaetzl *et al.* 1990). On this experimental site, average root-soil plate volume was calculated to be 1.44 m^3. The average calculated root volume of trees on this site was 0.11 m^3 (see Chapter 4), that is 7.6% of the total root-soil plate volume, leaving 1.33 m^3 soil per root-soil plate. Therefore, the potential volume of soil displaced on this sloping site with 1415 stems ha^{-1} if all trees were overturned is in the order of 1882 m^3 ha^{-1}. This is the maximum volume of soil that could be displaced downhill from root-soil plates if all trees were uprooted downslope during a storm, and if the slope was steep enough for none of the soil to fall back into the craters. However, the volume of soil lost from the site may be expected to be greater if the initial disturbance was to lead to further erosion or slope instability, as described by Swanston (1974). The average soil dry bulk density for this site was 950 kg m^{-3}, so soil displaced from the root-soil plates would be in the order of 1800 tonnes ha^{-1}. This compares to a 0.2 tonnes ha^{-1} increase in soil loss reported from sloping forest sites in the year following clear felling and an increase of between 0.03 and 1.3 tonnes ha^{-1} during site cultivation (Carling *et al.*, 2001). Therefore, a catastrophic windthrow event on a steep slope theoretically has the potential to initiate soil loss at a rate in the order of 1000 times greater than harvesting and site cultivation combined.

Displacement of soil as root-soil plates overturn will have some benefits for subsequent regeneration and growth of stands, in that the inversion of plates and mixing of soil (Schaetzl 1986) can provide nutritional benefits to trees planted or grown from seed on the site (Clinton and Baker 2000; Ruel and Pineau 2002). Overturning of root-soil plates can also contribute to accumulation of carbon in mineral soil horizons (Kramer *et al.* 2004). However soil conservation is a vital part of sustainable forestry practice (Carling *et al.* 2001), and the loss of large quantities of soil from forest stands on sloping terrain, with related damage to the ecology of water courses (Nisbet 2001; Stott and Mount 2004), should be avoided if at all possible (Forestry Commission 1993). The potential for increased soil erosion associated with extensive windthrow indicates that less risk of overturning should be tolerated on steeply sloping terrain, which in turn has implications for the structure of forests that should be maintained in such areas.

4. Development of the structural root systems of trees on horizontal and sloping terrain

Abstract

The coarse root systems of twenty-four Sitka spruce (*Picea sitchensis* Bong (Carr.)) trees, from a 40-year-old plantation in west Scotland, were extracted, digitised in three dimensions, and root topology was recorded. Roots were from trees grown on a steep (ca. 30°) north-facing slope, or from an adjacent horizontal area. The prevailing wind was across the slope and trees were growing on a gleyed mineral soil on both the sloping and horizontal parts of the site.

Analysis of below-ground parts of the trees in comparison with those above-ground revealed a positive linear relationship between coarse root volume and stem volume. Most non-directional characteristics of root architecture were similar between trees on the slope and flat terrain. Allocation of root mass around trees was examined in relation to the slope and the prevailing wind direction. Trees on the horizontal area had more root mass in leeward sectors than other sectors, but trees on the slopes had more root mass in the windward sectors than other sectors. Centres of mass of the root systems from the horizontal part of the site were not significantly clustered in any direction, but root systems of trees on the slope had centres of mass significantly clustered across the slope in the windward direction. For trees on the slope, the mean direction of the largest sector without structural roots was 4° from north, i.e. downslope. The results are discussed in relation to soil characteristics and the biomechanical requirements of trees on slopes.

Introduction

The architectural pattern of plant root systems is a product of the number of roots, their position of origin, initial growth direction, deviation in direction, branching pattern and turnover (Coutts *et al.* 1999). The form of woody structural root systems of trees and shrubs results from a pattern of secondary thickening superimposed on this framework. Despite genetic variation in architecture and allocation of biomass within tree root systems (Nicoll *et al.* 1995; Parr and Cameron 2004), the restrictions imposed on development by features of the soil environment appear to be a stronger determinant of root form (Drexhage and Gruber 1998; Gruber and Nick 1999; Stokes and Mattheck 1996; Wagg 1967). For example, roots of most species are capable of growing to several metres depth where the soil is easily penetrable, and is well aerated. However, root depth is commonly restricted by soil constraints such as: high bulk density (Moffat *et al.* 1998); indurations or restrictions such as iron-pans (Coutts 1989); limited water availability or nutrient supply; a water-table or bed-rock close below the soil surface (Armstrong *et al.* 1976); or a combination of these (McMinn 1963; Sainju and Good 1993). Similarly, root system symmetry is strongly influenced by factors such as uneven nutrition (Coutts 1987; Coutts and Philipson 1976) or water supply (Coutts *et al.* 1999; Coutts and Philipson 1987), and the flexing of the roots during wind action on the tree (Nicoll and Ray 1996; Stokes *et al.* 1995a; Stokes *et al.* 1997b).

Another aspect of the soil environment that must influence the development of root architecture is the topography of the soil surface. The largest proportion of tree root mass is commonly found within a few centimetres of the soil surface, regardless of whether the tree is on horizontal or sloping terrain (Coutts 1989). Surface roots develop from lateral roots that grow plagiogravitropically, i.e. they maintain their growth direction at an angle relative to gravity (Rufelt 1965). Some surface roots have been shown to be inherently negatively gravitropic (Coutts and Nicoll 1991), allowing them to grow upwards and then track below an undulating surface. As they grow upwards and approach the surface they are deflected downwards or parallel to the surface by changing soil environmental conditions such as reduced moisture content and increasing light (Coutts and Nicoll 1993). A balance between upward growth and downward deflection appears to keep roots at an optimum depth below the soil surface for growth, and prevents them from emerging into the atmosphere. As surface roots commonly experience conditions more suitable for growth in terms of aeration, nutrition and soil density, they develop into the largest roots within a structural root system (Fayle 1968). Despite a developing understanding of the physiological processes involved in development of tree roots on slopes, comparisons of root architecture between trees on sloping and horizontal terrain are limited (McMinn 1963), and the few root architecture studies of trees on slopes have provided inconsistent results in terms of asymmetry in relation to slope, (Di Iorio *et al.* 2005; Marler and Discekici 1997). Data on root architecture on sloping terrain are required to allow modelling of the contribution of soil holding by roots to slope stability (Ekanayake *et al.* 1997; Sakals and Sidle 2004; Watson *et al.* 1997; Zhou *et al.* 1997) and to develop models of tree stability on slopes (Achim *et al.* 2003; Nicoll *et al.* 2005).

The hypothesis tested in this chapter is that trees grown on steep slopes show greater root architecture asymmetry than trees grown on horizontal terrain. Coarse root architecture is compared between trees described in Chapter 3, i.e. trees grown on a steep slope and on an adjacent horizontal area, on a uniform soil in a plantation of Sitka spruce (*Picea sitchensis* (Bong.) Carr.). The site had a prevailing wind across the slope, which allowed a comparison of the effects of slope and wind action on tree root system development.

Methods

Sample and site details

Sitka spruce root systems were removed from a mature plantation on a steep slope (26°-33°), and from a horizontal area at the bottom of the slope. The site was in Leanachan Forest, west Scotland (56° 51.95’ N, 4° 58.40’ W). The aspect of the slope was due North. Trees were planted on the site, without cultivation, in 1962. At the time of the investigation in November 2001, the mean tree height was 22.3 m, and mean diameter at breast height (DBH) was 23.4 cm. The final average spacing of trees was 2.66 m, with 1415 stems ha^{-1} in plan view, which equated to 2.86 m spacing and 1225 stems ha^{-1} on the slope surface.

Soil characteristics

The soil on both the slope and the horizontal areas was a gleyed mineral soil, defined using the Forestry Commission soil classification (Kennedy 2002) as a surface-water gley. The soil had a sequence from an Ah horizon with abundant animal activity to a B horizon that was underlain by a stony layer at the transition to the C horizon (van Beek 2004). The stony layer formed a barrier to root penetration and large roots were observed to be deflected by it. The B and C-horizons were gleyed, indicating the occasional presence of a water-table. The soil structure became more massive with increasing depth, and fewer pores were found between and in the soil peds. Stoniness and stone size increased with depth. The topsoil was finer textured than deeper soil and contained the largest amount of clay and silt. The clay content decreased with depth, whilst the relative proportions of silt and sand remained the same throughout.

The dry bulk density of soil increased with depth from 540 kg m^{-3} in the A horizon to 1270 kg m^{-3} in the C horizon (Table 4-1). The stones formed a soil fabric that was locally filled with finer material, and there were many interstitial pores. Total porosity in the A horizon was 69% and close to 80% in the B and C horizons. Near the surface, the macro-pores were more uniform in size but included many that had originated as root conduits and animal burrows. Consequently, the upper soil layers had a high saturated hydraulic conductivity, in the order of several metres per day. Infiltrated water would be expected to cause waterlogging in the soil horizons above the underlying bedrock of this site. The organic carbon content was 22.5% in the A horizon and <1% in the B and C horizons (Table 4-1). The A and B horizons had mean shear strengths of 11.52 kPa and 28.44 kPa respectively (Table 4-1).

Table 4-1. Soil characteristics for A, B and C soil horizons at the Leanachan site (from van Beek 2004). Horizon depth, dry bulk density (given as mass over total volume), soil porosity, volumetric shrinkage after drying, saturated hydraulic conductivity, Volumetric water content (VWC) at saturation, field capacity and wilting point, with drainable and effective pore space, undrained shear strength, and % organic carbon.

Horizon	A	B	C
Depth below surface (cm)	3-13	13-34	34-90
Dry bulk density (x 1000 kg m^{-3})	0.54	0.88	1.27
Porosity ($m^3 \cdot m^{-3}$)	0.69	0.81	0.78
Shrinkage (%)	33	0	0
Saturated hydraulic conductivity (m day^{-1})	5.85	1.46	0.54
VWC Saturation	0.69	0.81	0.78
VWC Field capacity	0.54	0.52	0.51
VWC Wilting point	0.22	0.16	0.09
Drainable pore space	0.15	0.29	0.27
Effective pore space	0.32	0.36	0.43
Undrained shear strength (kPa)	11.52	28.44	-
Organic Carbon %	22.5	<1	<1

Wind climate

Wind was monitored using a 3-cup switching cup anemometer and windvane (A100R and W200G, Vector Instruments, Rhyl, North Wales, UK) mounted on the top of a 10 m guyed mast, between 31 October 1988 and 24 June 1999. The mast was located 1 km north from the experiment site (56° 52' 28" N, 4° 59' 02" W) at a similar altitude on moorland that was clear of trees. The anemometer gave 1 count for a passage of 0.8 m of air. The threshold of the anemometer was 0.2 m s^{-1} with a maximum speed of >75 m s^{-1} and an accuracy of 1% between 10-55 m s^{-1}. The windvane had a resolution of 22.5° ±3° with a threshold of 0.3 m s^{-1}. Output from the anemometer and windvane were logged every 8 seconds and stored every 30 minutes in a datalogger (Holtech Associates, County Durham, UK) as frequency distributions.

Tree uprooting

Three dominant, three co-dominant and three sub-dominant trees were mechanically overturned on the slope, in each of three directions, upslope, downslope and across-slope, i.e. nine trees per direction. On the horizontal part of the site, nine trees were overturned; three dominant, three co-dominant, and three sub-dominant, in random directions. These trees were all overturned as part of the tree stability experiment, described in Chapter 3 and Nicoll *et al.* (2005). The slope angle was measured around each selected tree, and a numbered label was fixed to the base the tree on the upslope side, before overturning by pulling at half tree height using a chainsaw-powered winch (Habegger, Thun, Switzerland). After uprooting the tree, stem diameters were measured at 1 m intervals up the stem from the base using measuring callipers with 1 mm resolution. A 1 m central section of the stem was cut and removed, and diameters at each end were measured before weighing for calculation of green stem density. All study trees were uprooted on this site during November 2001. Soil was removed from roots using hand picks, to leave the coarse root system. Root systems were extracted from the site using a tractor before returning them to the laboratory for architectural analysis.

Root architecture measurements

Time constraints prevented architectural analysis of all root systems, so a sub-sample of 24 root systems was examined. These were selected randomly from trees from each pull direction on the slope, and from horizontal treatment trees, leaving similar numbers of root systems from each of these treatments.

Root systems were cleaned on return to the laboratory, inverted for measurement and levelled to make the stem point vertically downward. Coarse root architecture was digitised using a Fastrack 3-D digitiser with a LongRanger transmitter (Polhemus Inc, Colchester, VT, USA) (Sinoquet and Rivet 1997). The 3D digitiser generates near-field, low-frequency, magnetic field vectors, from three orthogonal coils in the transmitter and detects the field vectors with a small triad of electromagnetic receiver coils in a hand held stylus. The signals are input to a mathematical algorithm that computes the receiver position (x, y, z co-ordinates) and orientation relative to the transmitter. The LongRanger sphere was placed within 3 m of the root system with the X+ arrow pointing towards the root system. Electromagnetic sources and metallic objects were removed from the work area, as they could have interfered with the electromagnetic field from the 3-D digitiser. The root system was positioned so that the reference direction marked on the root system pointed towards the sphere. The reference direction was the same for all trees in the experiment. Care was taken to avoid moving the sphere during digitising, but when it was necessary to move it, such as for storage at night, the sphere was replaced afterwards in exactly the same position and orientation. This position was checked by digitising the same reference points before and after storage. Data from the digitizer and root topology were logged using Diplami software (Sinoquet *et al.* 1997). Points were digitised and diameters recorded on roots until their diameter tapered down to 5 mm and after that only the end point of the root was digitised. Roots greater than 5 mm diameter are defined, for the purpose of this investigation, as 'coarse roots'. A measurement was taken approximately every 20 cm along each root when the root was straight and every 2 cm when it deviated. By digitising points on the root surface with the digitizer stylus pointing towards the root centre and inputing the root diameter (measured on the vertical and horizontal axes) at this point, the software calculated the x, y, z co-ordinates of the root central axis. The topological order of each root was recorded using tree graph coding (Godin 2000), modified for root topology as described by Danjon *et al.* (2005; 1999b), with the system updating the order for each ramification.

Root architecture analysis

Data were transformed into 'mtg' files as required by AmapMod software (CIRAD, Montpellier, France). Amapmod routines were written and run to analyse characteristics of root architecture, and root volume, depth, extension, length and direction were extracted from the data using these routines. Total volume of the coarse root system was calculated assuming that roots were oval in cross sectional shape, and included the stump volume. Total depth of the system was calculated as being the maximum depth measured perpendicular to the soil surface. Maximum radial extension was taken to be the mean distance from the stump centre to the ends of extracted roots. The mean number of 1st order lateral roots, and 1st order lateral roots with diameter >10 cm, were extracted from the data to indicate the number of structural roots around trees in each treatment. Directional root deviation was calculated for each root as being the change in root azimuth angle between the origin and the end point. The size and azimuth (degrees) of the largest sector of the root system without 1st order lateral roots was calculated to give an indication of asymmetry of the structural root system. The total length of measured 1st order lateral roots and the total length of all measured roots including ramifications were calculated. The sum of 1st order lateral root mean cross sectional areas (CSAs) was calculated, assuming cross sectional ovality, as the sum of length x CSA for all root sections divided by total root length. The total surface area of all measured roots and ramifications was calculated for each tree to give an indication of the area of interface between coarse roots and soil.

Statistical analysis

For comparisons of non-directional root architectural characteristics, trees from all pull directions on the slope were combined into a single slope treatment and compared with trees from the horizontal treatment. Means were compared using a Mann-Whitney test. For analysis of directional data, means were first compared between pull-direction treatments to examine if loss of roots during extraction had affected the balance of root mass. Data from all treatments on slopes were then combined for comparison with horizontal treatment trees.

Directional data were analysed using 'Oriana' software (KCS, Wales, UK), following the circular statistical techniques described by Mardia and Jupp (2000). The Watson-Williams non-parametric F-test was used to compare azimuths of centre of mass between pairs of treatments to determine if their mean angles differed significantly. This was applied to each combination of pairs of the groups of trees pulled in each direction, upslope, downslope and across-slope, and trees on the horizontal site, to investigate if loss of roots during the extraction process had influenced the balance of the root system. The resulting F statistic is equivalent to Fisher's variance ratio statistic, commonly used in linear statistics. Means were considered to be significantly different when the *p*-value was less than 0.05. The test was then used to compare the direction of the centre of mass and the centre of the largest sector without 1st order 'structural' roots between trees from the slope and trees from the horizontal part of the site. The Rayleigh's Uniformity Test was used to calculate the probability that azimuths were distributed uniformly. A probability less than 0.05 was taken to indicate that data were not distributed uniformly, i.e. there was evidence of a preferred azimuth. Rao's Spacing Test was used to test the null hypothesis that the azimuths were uniformly distributed. This test is appropriate if directional data are bimodal. The null hypothesis of uniformity was again rejected if $p < 0.05$. The V-test (Mardia and Jupp, 2000) was used to test if the distribution was non-uniform in specified mean directions. In this case, the azimuth of centre of mass was tested against the westerly wind direction for the site and the largest sector without roots was tested against north.

Figure 4-1. Wind at Leanachan forest recorded between October 1988 and June 1999. a. Wind rose of frequency of mean hourly wind directions at Leanachan forest. The solid line from the centre indicates the mean wind direction at 255° from north. b. Scatter plot of mean hourly wind speed against direction, showing peaks of wind speed from east, south and west. The density of the plot obscures many hidden points, especially under the scatter between 220 and 280°.

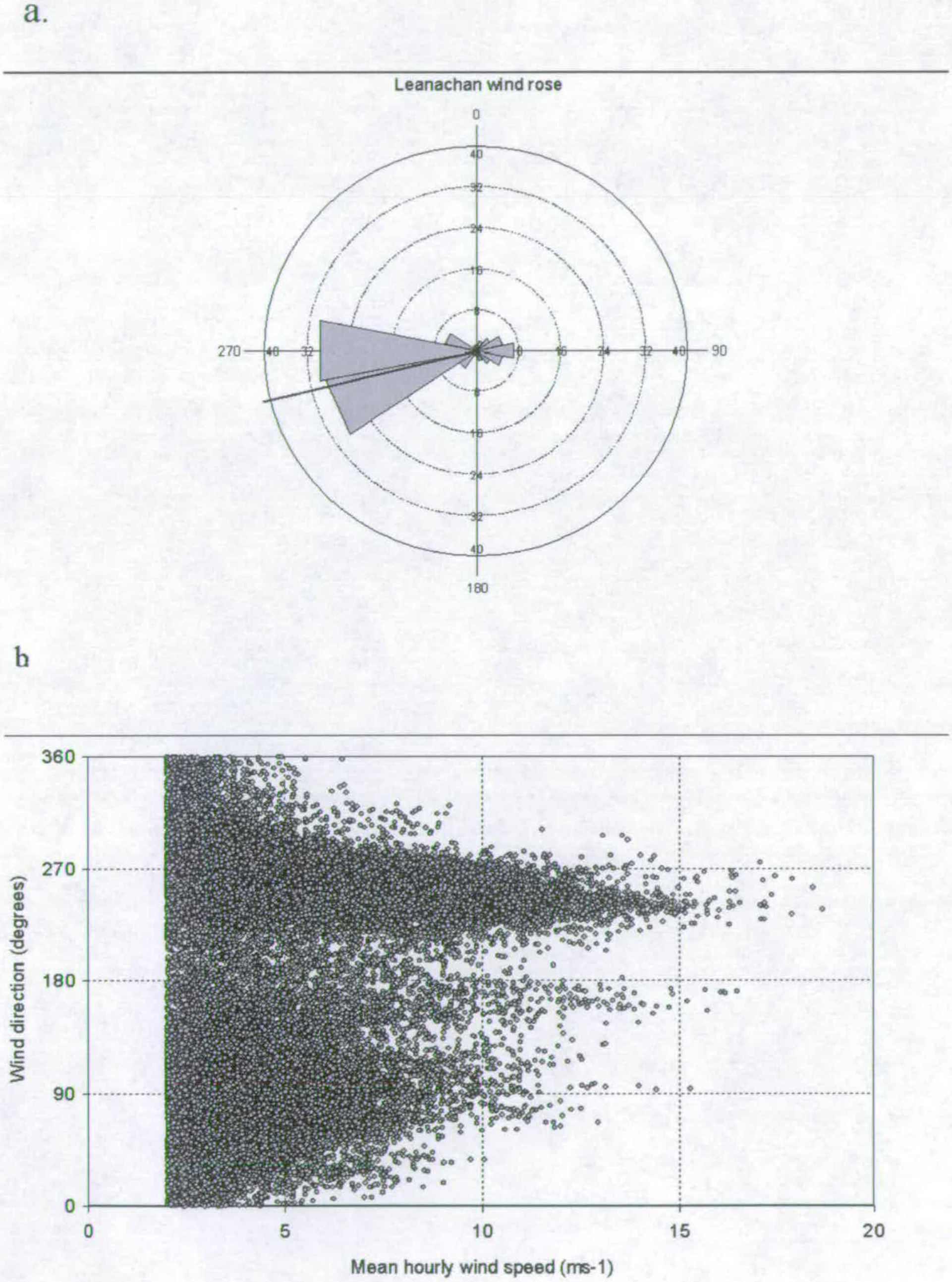


Figure 4-2. Example plot from Amapmod of a root system from the Leanachan site. Side view (above) and plan view (below). Grid squares have 12-cm sides.

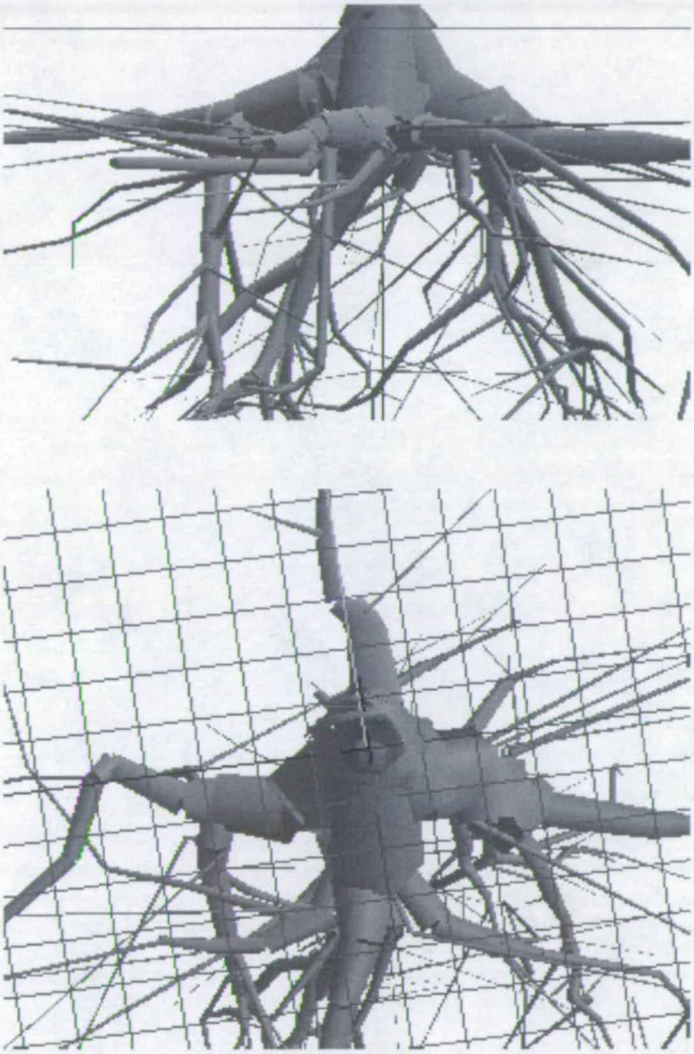


Table 4-2. Mean root architecture characteristics of woody roots of trees on the horizontal and sloping sites, based on analysis using Amapmod, n $_{\text{(horizontal)}}$ = 7, n $_{\text{(slope)}}$ = 17. The *p*-value for comparison of means is based on a Mann-Whitney test.

Characteristic	**Horizontal treatment** Mean	**Slope treatment** Mean	*p*-value
Total volume of all roots and stump (m^3)	0.120	0.105	0.62
Root system depth (m)	1.04	1.14	0.42
Maximum radial extension (m)	2.04	1.93	1.00
Number of 1st order lateral roots	7.9	10.1	0.05
Number of 1st order lateral roots with diameter > 10cm	5.1	4.9	0.85
Mean root deviation (°)	24	25	0.62
Largest sector without roots (°)	134	163	0.49
Total length of 1st order lateral roots (cm)	995	1330	0.09
Total length of 1st order lateral roots and ramifications (cm)	6035	6938	0.49
Sum of mean cross sectional area of 1st order lateral roots (cm^2)	617	509	0.42
Total surface area of 1st order lateral roots and ramifications (m^2)	4.59	5.02	0.26
Total volume of 1st order lateral roots and ramifications (cm^3)	94362	90656	0.76

Table 4-3. Circular statistical analysis of the azimuth of centre of mass and of the largest sector without 1st order lateral roots.

	Centre of mass					Largest sector without roots	
Variable	across	down	up	horizontal	slope	horizontal	slope
Number of Observations	6	5	6	7	17	7	17
Mean Azimuth (μ) (°)	315	277	292	115	294	10.5	3.8
Median (°)	309	273	279	100	288	1.5	358
Standard Error of Mean (°)	26	13	20	37	10	25.4	15
Rayleigh Uniformity Test (Z)	2.93	4.32	3.96	1.45	10.29	2.39	5.89
Rayleigh Uniformity Test (P)	<0.05	<0.01	<0.05	n.s	<0.001	n.s	<0.01
Rao's Spacing Test (U)	177.7	223.9	206.8	129.8	206.3	140.6	182.6
Rao's Spacing Test (P)	n.s	< 0.01	< 0.01	n.s	< 0.01	n.s	< 0.01
V Test (V; expected mean 270°)	0.49	0.92	0.75	-	0.71	-	0.59
V Test (P)	<0.05	<0.001	<0.01	-	<0.001	-	<0.001

Results

Analysis of approximately 10 years wind data from the anemometer and wind vane to the north of the experimental site showed the average wind direction to be 255° from north (Figure 4-1). The mean wind speed was 4.14 m s^{-1}. As the slope of the experimental site ran almost exactly east-west, the prevailing wind may be expected to be diverted to flow across the slope and therefore to be from due west, although this was not confirmed. Although most wind was from the west, there were also strong winds from other directions although at much lower frequencies, and mean hourly wind speeds greater than 15 m s^{-1} were recorded from west, south and east (Figure 4-1b).

An example Amapmod plot (Figure 4-2) illustrates typical coarse root architecture on this site. Comparisons of root architecture characteristics (Table 4-2) indicate that root systems were largely similar between slope and horizontal sites. Root volume, including the stump, varied between 0.05 m^3 and 0.25 m^3. The effect of the treatment was non-significant, and slope and horizontal trees were therefore combined for the final regression. There was a strong positive linear relationship (Figure 4-3) between root volume and stem volume ($R^2 = 0.74$) for both treatments combined. The average ratio of root volume:stem volume was approximately 0.35. Root system depth was similar between treatments with slightly greater average depth on the slope (1.14 m) than on the horizontal (1.04 m). Maximum radial extension was close to 2 m for both treatments, but as most roots had broken before the tip, this reflected the amount of root retrieved from the site rather than actual root spread. The number of roots defined as 1st order laterals was on average eight on trees from the horizontal part of the site and ten on trees from the slope. This difference was significant ($p = 0.05$). However, when only roots greater than 10 cm diameter were counted (as an indication of the number of major structural roots that support the tree), there were on average five on trees from both treatments. Roots had grown away from the stump with little deviation from a straight line, the mean deviation being 23.6° and 25.1° for horizontal and slope trees respectively (difference not significant). Root systems of slope treatment trees appeared to have slightly poorer radial symmetry, indicated by larger sectors without roots, than horizontal treatment trees, but the difference was not significant. Total lengths of all 1st order roots, and of all roots including ramifications were similar between treatments. The total lengths of measured roots, the sum of CSA of 1st order lateral roots, and the surface area (area of interface between root and soil) were also similar between treatments (Table 4-2).

Root taper plotted as a decrease in coarse root volume with distance from the tree (Figure 4-4) was similar between slope and horizontal treatments. Root volume decreased exponentially with distance, with almost no root volume at a greater distance than 2 m from the trees. Root volume also decreased rapidly with depth (Figure 4-5) with almost no mass deeper than 1.26 m below the soil surface, although this may partly reflect the loss of smaller roots at the base of the root-soil plate during root extraction. Roots originating close below the surface within the A horizon and the upper part of the B horizon tended to grow parallel to the surface. Roots that grew into or through the C horizon, either from the stump or from the surface laterals, tended to grow steeply or vertically downwards (see example in Figure 4-2). Very few roots were observed to penetrate into the stonier parts of the C horizon or the R horizon below it. This architecture resulted in 86% of root volume of slope trees being within the top 36 cm of the soil surface in the A and B horizons, 13% being between 36 cm and 70 cm in the C horizon and 1% penetrating deeper than 70 cm into the stony R horizon. Similarly, trees grown on the horizontal part of the site had 81% of root volume within the top 36 cm of the soil (A and B horizons), 18% between 36 cm and 70 cm (C horizon) and 1% deeper than 70 cm (R horizon). There was no significant difference between horizontal and slope treatment trees in root volume depth distribution. The decrease in volume appeared to coincide with the observed increase in soil bulk density, stoniness, and periodic waterlogging, with depth.

Centres of mass of root systems of horizontal treatment trees (Figure 4-6) had randomly directed azimuths. Table 4-3 shows results from Rayleigh's Z test, Rao's spacing test and Kuiper's V test, for horizontal treatment trees, indicating that there was no evidence of any clustering of centre of mass directions. In contrast, these tests all gave significant p-values (<0.05) for trees on the slope (Table 4-3), indicating that centres of mass were significantly clustered. These results were not affected by the pulling direction. The V test was applied to compare the clustering direction with 270°, the expected prevailing wind direction for the site. The highly significant results indicate that root centres of mass were significantly clustered in this direction.

To investigate if the direction of root extraction had altered the centres of mass through root loss in the pull direction, the Watson-Williams F-test was used to compare azimuths of centres of mass between pairs of treatments (Table 4-4). All comparisons between pull directions on the slope were non-significant, indicating that roots extracted in the different directions retained a similar directional asymmetry. Comparisons of each slope treatment with the horizontal treatment gave significant *p*-values of between 0.001 and 0.003, indicating different directions of asymmetry between horizontal treatment root systems and root systems from all pull directions on the slope. When the pull directions were again combined and all slope trees were compared against horizontal treatment trees, there was a very highly significant difference in direction of centre of root mass. Figure 4-7 shows the root volume distribution between 45° sectors relative to north, compared between slope and horizontal treatment trees. The sector with the greatest root volume was 225-270° in the slope treatment and 45-90° in the horizontal treatment. Overall, more root volume was in sectors toward the westerly prevailing wind direction on the slope and away from the prevailing wind on the horizontal, compared to other sectors. However, on the horizontal, root systems also had a relatively large volume in a sector directly towards the prevailing wind (Figure 4-7).

The largest sectors of the root systems without 2nd order roots (Table 4-3) were not significantly clustered in any direction for trees grown on the horizontal part of the site. For trees on the slope, however, the directions of the largest sector without roots was significantly clustered. The mean size of this sector was 163° (standard error 27°) and the mean azimuth was 3.8° from north (standard error 15°). The V-Test (Mardia and Jupp, 2000) was used to test the null hypothesis of uniformity against the alternative hypothesis that the distribution was non-uniform with a mean direction of 0° (north and downslope). The *p*-value for this test was <0.001, indicating a highly significant downslope clustering of sectors without roots.

Table 4-4. Watson-Williams F-tests for azimuths of centre of mass compared between pairs of treatments. The 'all slope' treatment is across, down and up combined and was only compared against the 'horizontal' treatment. F scores are shown in the lower half of the matrix and probabilities are shown in the upper half. *P*-values less than 0.05 are considered to indicate a significant difference between treatments in azimuth of centre of mass.

treatment	across	down	up	horizontal	all slope
across	-----	0.157	0.402	0.003	-----
down	2.39	-----	0.475	0.002	-----
up	0.767	0.556	-----	0.001	-----
horizontal	14.541	17.563	17.752	-----	<0.001
all slope	-----	-----	-----	22.137	-----

Figure 4-3. Coarse root volume against stem volume for trees from slope and horizontal treatments. The regression line y= 0.354x – 0.014 is for both treatments combined (n=24, R^2=0.74).

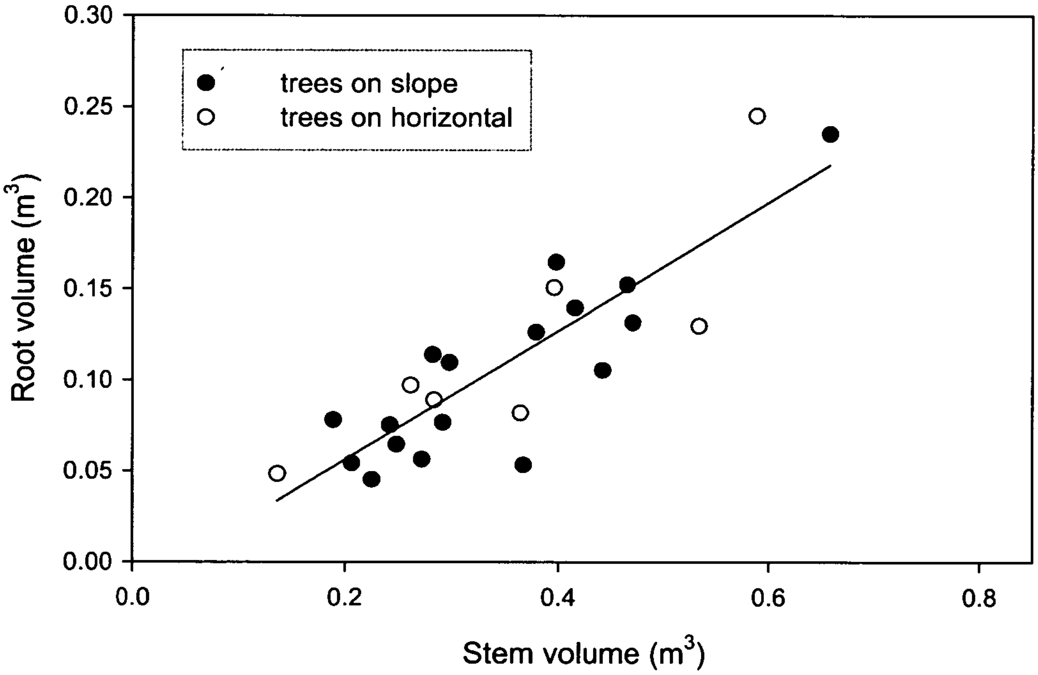


Figure 4-4. Distribution of coarse root volume with distance from the tree, shown for horizontal and slope treatments. The bars are means, with standard errors above and below the means.

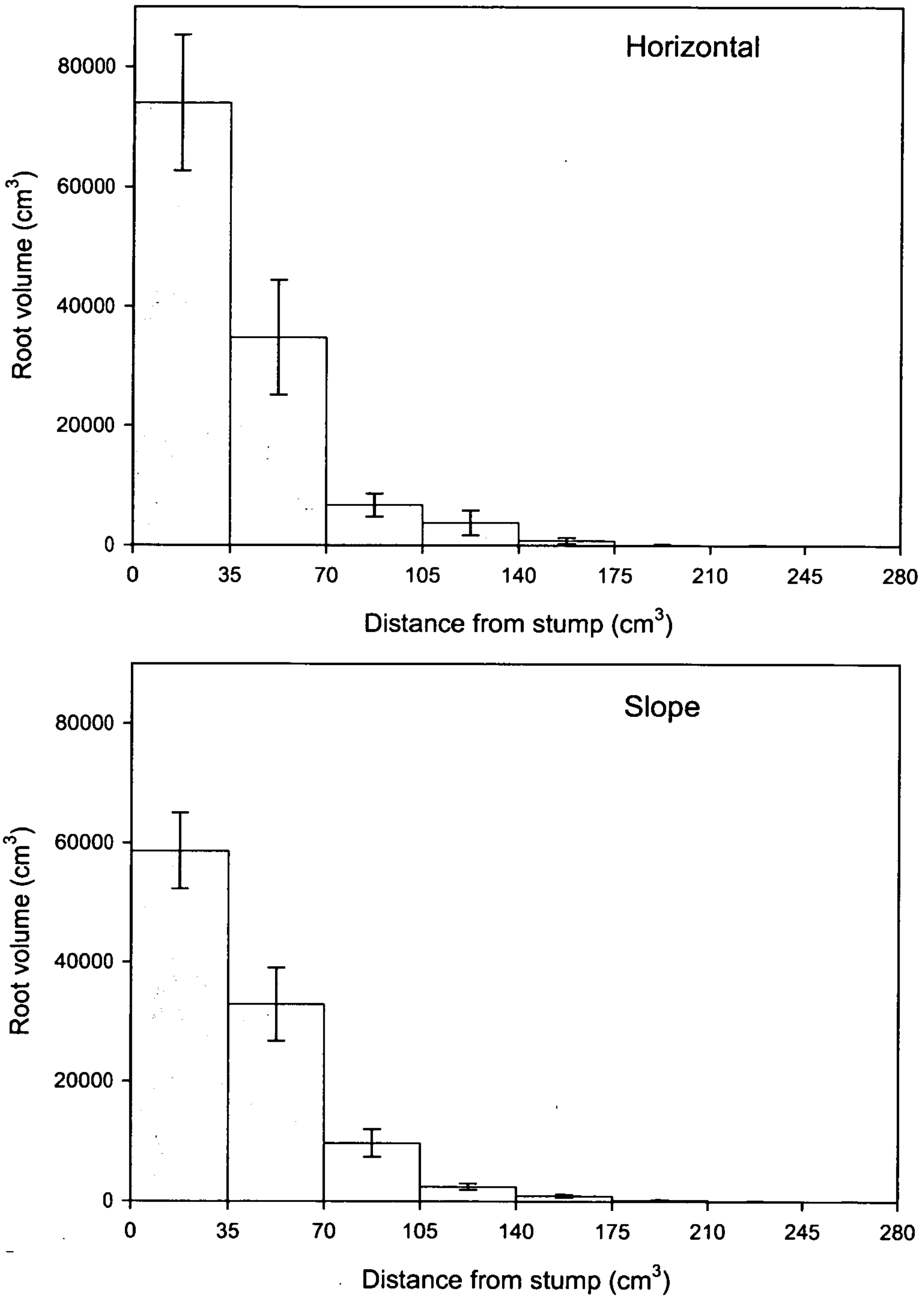


Figure 4-5. Distribution of coarse root volume with depth below the soil surface, shown for horizontal and slope treatments. The bars are means, with standard errors above and below the means.

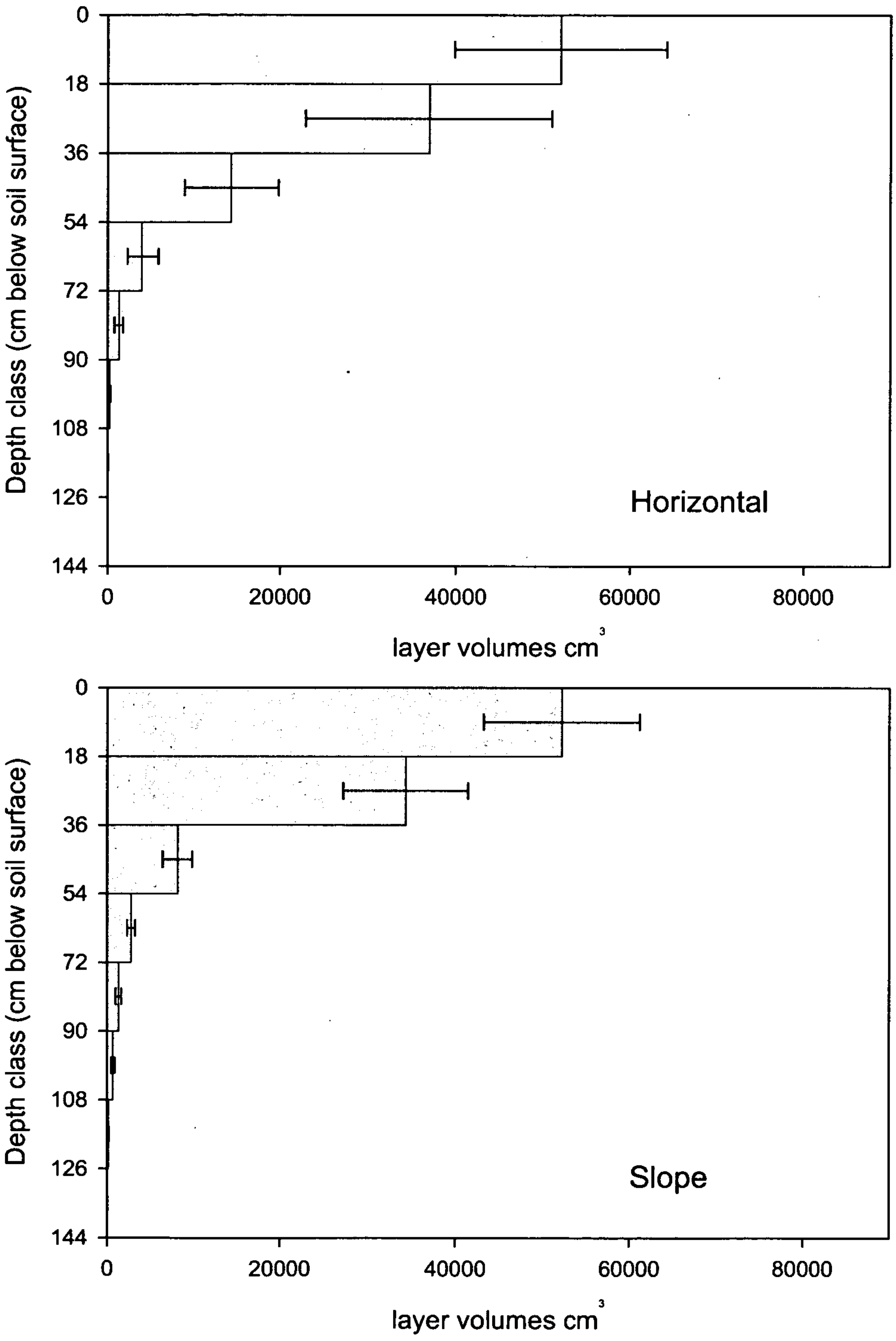


Figure 4-6. Vectors to root system centre of mass for each tree relative to north (downslope = 0°). A mean direction (with 95% confidence intervals) is shown for the slope treatment, which has significant clustering of centres of mass.

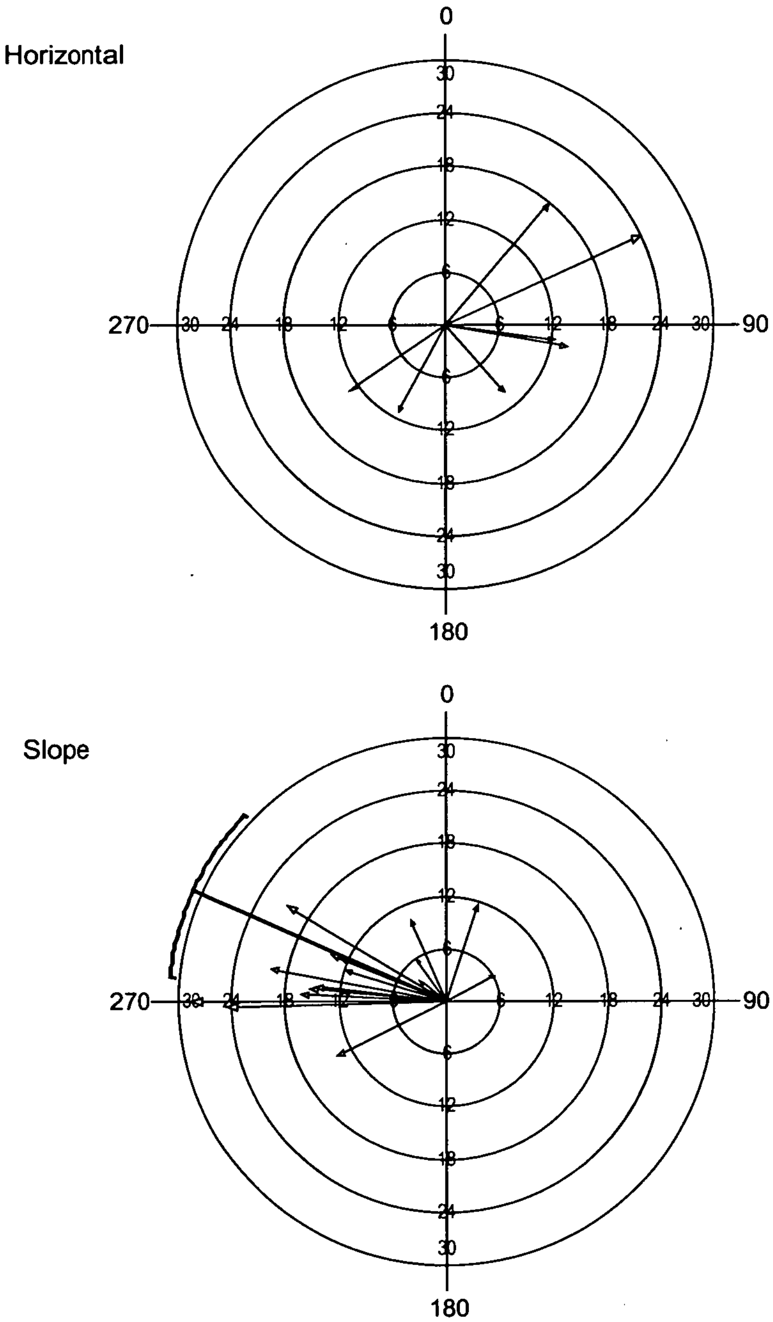
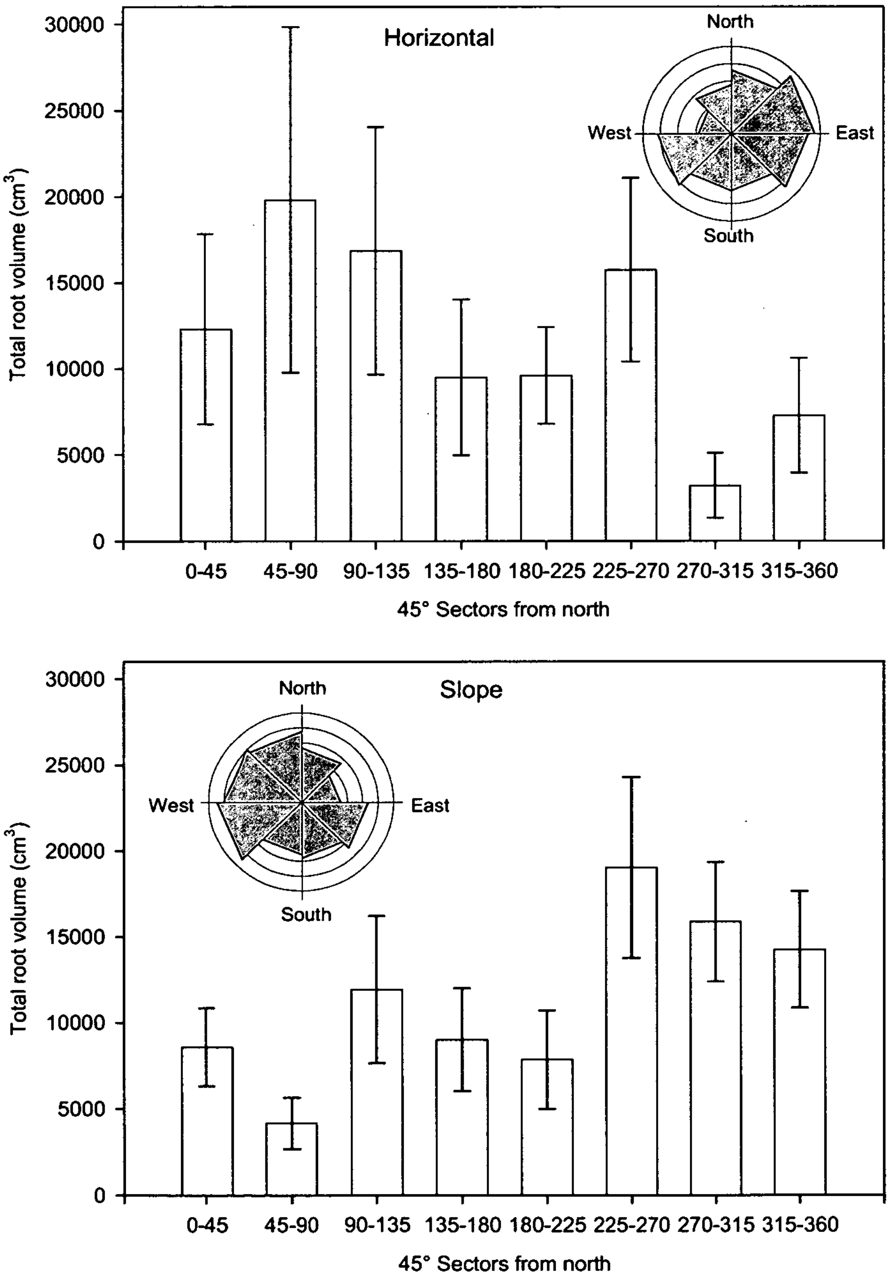


Figure 4-7. Distribution of root volume in 45° sectors from north (mean and standard errors above and below the means) for trees on the slope and horizontal treatments. The circular insert on each graph illustrates the distribution relative to north. Upslope on this site was 180°, and the prevailing wind was from 255°.



Discussion

The few previous studies of tree root development on steep slopes have provided inconsistent results. McMinn (1963) examined the characteristics of roots of twenty-five year-old trees on level terrain, and ten- and forty-year-old Douglas fir (*Pseudotsuga menziesii* (Mirbel) Franco) trees grown on 25° to 35° slopes. On the horizontal terrain, lateral roots extended in approximately equal distances around trees. On sloping ground, downslope roots descended into the soil and did not extend far from the base of the tree, but roots growing upslope or across the slope followed under the soil surface for considerably greater distances. Marler and Discekici (1997) found that around 70% of roots of papaya (*Canica papaya* L.) plants growing on a 30° hill slope had formed on the downslope side of the plants by 17 weeks after planting. Di Iorio (2005) found a tendency for roots of *Quercus pubescens* Willd. to cluster predominantly in the upslope direction on 14 to 34° slopes. Watson *et al.* (1995) examined root development of kānuka (*Kunzia ericoides* (A. Rich.) J. Thompson) and radiata pine (*Pinus radiata* D. Don.) trees grown on 15° to 32° slopes in New Zealand. Lateral roots of 6-, 16-, and 32-year-old kānuka trees were distributed unevenly around the stumps, growing predominantly up and across-slope. In the 16-year-old trees, this asymmetry was observed to relate to increased branching and taper of roots on the downslope side. The lateral roots of radiata pine on slopes were also distributed asymmetrically around the stump. The roots of 8-year-old trees were predominantly across and upslope, while 16- and 25-year-old trees on less steep slopes had more lateral root growth in the across and downslope direction. Sundström and Keane (1999) examined the symmetry of root systems of Douglas fir grown for 10 years on a shallow slope (7°- 12°) with easterly to north-easterly aspect where the prevailing wind was from the south-west. They found least root mass downslope, and root growth concentrated across the slope, parallel with the contour.

Previous studies of Sitka spruce also showed no consistent effect of a shallow (<15°) slope on coarse root architecture, with concentrations of root mass in different investigations being either on the upslope (Nicoll and Ray 1996) or downslope side (Nicoll *et al.* 1995) of trees. On a steeper (ca. 20°) slope, Quine and Burnand (1991) reported that the root system centres of mass were strongly clustered upslope. However, wind direction may be a more important factor in root system asymmetry of Sitka spruce. In both the Nicoll *et al.* (1995) and Nicoll and Ray (1996) studies, more structural root mass appeared to be clustered on the down-wind side of the tree relative to the prevailing wind. Stokes *et al.* (1995a, 1995b) found responses in the form of uneven radial development of lateral roots in seedlings of European larch (*Larix decidua* P. Mill.) and Sitka spruce that were exposed to continuous wind in a wind tunnel. In another study, Stokes *et al.* (1997b) described similar development of roots of young trees that were subjected to mechanical flexing as they grew. In both of these studies, roots thickened more on the sides of the tree in the direction of flexing and showed an increase in vertical compared to horizontal diameter. Mickovski and Ennos (2002) described a similar development of *Pinus sylvestris* L. seedling roots in response to unidirectional flexing of the stem. In the present study, trees were grown on a steep (ca. 30°) slope on a site with the prevailing wind across-slope. Roots had their centres of coarse root mass and largest amounts of mass clustered towards the upwind direction, with sectors with most root mass and length in the same direction. The direction of clustering of centres of mass was also slightly downslope, although the largest sector without structural roots indicates that structural roots seldom grew directly downhill. Roots grown on the adjacent horizontal part of the site on the same soil had no significant clustering in any direction, but overall they had more root mass in sectors towards and away from the prevailing wind. The largest amount of root mass and length was in a downwind sector. Therefore, for trees grown on the horizontal part of the site, these results appear to conform with previous studies, but on the steep slope the results were surprising in that roots concentrated in the opposite direction, towards the prevailing wind. The possibility of an interaction between the effects of slope and wind should be investigated in further experiments. Interestingly, a re-examination of the data presented by Quine and Burnand (1991) indicates that the root centres of mass were on average obliquely upslope, towards the west. As the prevailing wind where Quine and Burnand (1991) conducted their study was from the west, their results appear to correspond with the finding of the present study.

Why trees would put a larger allocation of assimilates into windward roots on slopes but leeward roots on the horizontal remains to be explained, but the mechanical characteristics of trees on steep slopes will undoubtedly be different to those on the horizontal. A possible cause of the difference would be the motion of the above-ground part of the tree in the wind. Tree crowns do not flex back and forth in a straight line in the wind, but have a more complex motion that on average tends to resemble an ellipse (Gardiner 1995; Mayer 1987). The shape of this movement will be influenced by the root architecture as well as wind direction, and the interaction with crowns of other trees. However, the development of root secondary thickening may in turn be influenced by the pattern of motion. For a tree to remain upright on a slope, the mechanical requirements of roots will be different to those on the horizontal, and roots on the upslope side of a tree may be expected to act under tension more often than those downslope, while the roots downslope may commonly be under compression. The mechanical function of these roots will be further complicated by swaying of the tree that will alternately load roots under tension and then under compression (Hintikka 1972; Stokes and Mattheck 1996). Detailed modelling of the anchorage mechanics of trees on sloping and horizontal terrain may help to explain these results.

Of course, the possibility remains that clustering of root centres of mass is related to factors other than wind on the site. Root system development may be expected to be influenced by variation in planting method, however Coutts *et al.* (1990) found that in Sitka spruce the original transplant root system is replaced rapidly by a new adventitious system and therefore initial root distortions tend not to be maintained. Henderson *et al.* (1983) suggested that the structural root system of Sitka spruce is inherently regular, but that heterogeneity of the soil environment causes the observed variability in the final pattern. Factors that may be expected to have an effect on the symmetry of a tree root system include; incidence of light on the crown (Coutts *et al.* 1999), unevenness of nutrition and soil water (Coutts 1983a; Mou *et al.* 1997), site cultivation (Coutts *et al.* 1990; Quine and Burnand 1991; Quine *et al.* 1991; Savill 1976), and variation in soil physical properties (Fayle 1980; McMichael and Quisenberry 1993). Trees on this site were planted without cultivation, and there was no evidence of pronounced unevenness of any of the other factors around the study trees, except for light on the crown. Uneven exposure to light of the crowns of edge trees may be implicated in the development of large structural roots (Cucchi *et al.* 2004) that grow outward from the forest stand. Edge trees of conifer plantations have pronounced crown asymmetry with branches from ground level to tree top on one side and branches only near the tree top on the other, and this imbalance would be expected to result in an unevenness of assimilate supply to the root system. However, as the stand used for the present study was dense, with crowns only slightly more exposed to light from the north, and with similar amounts of foliage on all sides of the trees, unevenness of assimilate was not expected to be a factor in the observed development of root asymmetry.

The direction of the largest sector without structural roots on root systems may be particularly important for tree anchorage and would be expected to indicate a direction of increased vulnerability to windthrow (Coutts *et al.* 1999). The combined reduction in stiffness of roots at the hinge point and reduction of the length of the lever arm would be expected to result in a substantial reduction in anchorage if a tree is overturned in this direction (Coutts 1986). The highly significant clustering of azimuths of sectors without roots almost directly downhill in this investigation corresponds well with measurements of anchorage of the same trees reported previously (see Chapter 3). These trees were mechanically overturned in contrasting directions and were found to have significantly poorer resistance to overturning when they were overturned downslope than when overturned upslope.

The pattern of root development in relation to depth corresponds with changes in soil characteristics. Soil bulk density and stoniness increased rapidly with depth on this site. The tendency of trees to produce large 1st order lateral roots of structural importance near the surface, with 2nd order 'sinker' roots emerging and growing downwards from them is similar to the architecture of a number of forest tree species studied on mineral soils. For example, Strong and La Roi (1983) found a similar pattern of root architecture of white spruce (*Picea glauca* (Moench) Voss), aspen (*Populus tremuloides* Michx), jack pine (*Pinus banksiana* Lamb.) and balsam fir

(*Abies balsamea* (L.) Mills.) growing on mineral soil. This root form can be defined as a 'sinker system' (Drexhage and Gruber 1998). Although plant roots can exert maximum axial and radial growth pressures of around 500 Pa (Misra *et al.* 1986), allowing them to penetrate highly compacted soil, their growth rate decreases as compaction increases (Gruber and Nick 1999; Materechera *et al.* 1991). For example, root elongation rate of radiata pine (*Pinus radiata* D. Don) decreased exponentially as soil strength increased from 0 to 3.0 MPa (Zou *et al.* 2000). Day and Bassuk (1994) suggested that the approximate soil strength critical limit for root growth is 2.3 MPa, when measured by a penetrometer, above which there will only be some very restricted growth. Tree roots can also grow through rock fissures, and although this behaviour allows roots to exploit an additional source of water and nutrients and provide improved anchorage for the tree, growth rates in rock are very slow compared to roots growing in soil (Zwieniecki and Newton 1995). Therefore, the rapid decrease in root mass with depth on the site described here may be predicted from the increasing soil bulk density and stoniness.

The tendency for 1st order lateral roots to follow the A and B soil horizons also conforms to the known behaviour of tree roots in relation to changes in soil properties. Lateral roots of trees growing at a slightly downward angle can be deflected upwards to grow horizontally when they encounter a more compacted soil horizon (Wilson 1971). Similarly where lateral roots grow at an upward angle they can deflect downwards as they encounter changes such as a reduction in soil moisture near the surface (Coutts and Nicoll 1991; Coutts and Nicoll 1993), but then resume their upward growth. These mechanisms together can maintain lateral roots in the soil horizons close to the surface. Some second order roots that emerge as branches of surface laterals will be directed downward (Coutts 1989) and develop into sinker roots that grow almost vertically downwards into the deeper soil horizons. The increased branching observed on these sinker roots with depth may result from increased stoniness and increased soil compaction in the deeper horizons (Deans 1983; Materechera *et al.* 1991). Wilson and Horsely (1970) found that a reduction in the growth rate of root apices stimulates the production of lateral root branches. An additional factor limiting root depth under some trees on this site may have been occasional waterlogging of the deeper soil horizons (Armstrong *et al.* 1976; Coutts and Nicoll 1990b). Root depth therefore appeared to be ultimately limited on this site by solid bedrock and in some parts of the site by periodic waterlogging in the C horizon.

Root architecture of Sitka spruce has long been known to vary with soil type (Fraser and Gardiner 1967; Laing 1932; Yeatman 1955) but further studies of tree root architecture in relation to soil physical conditions will be required to improve models of below-ground carbon allocation (Hoffmann and Usoltsev 2001; Levy *et al.* 2004). The strong linear relationship found in the current study between stem volume and coarse root volume was similar to the relationships between stem diameter and root mass found in Norway spruce (*Picea abies* (L.) Karst.) and Douglas-fir by Drexhage and Colin (2001) and Thies and Cunningham (1996) respectively, and will be useful in prediction of below-ground biomass of Sitka spruce. However, the allocation of mass to roots growing in each soil horizon will have different impacts on long-term below-ground carbon storage. Root decomposition and carbon cycling below-ground varies with depth and soil aeration, and deeper roots will make a greater contribution to the accumulation of soil organic matter in mineral horizons (Kramer *et al.* 2004). The improved understanding of root architecture development in relation to terrain and climate provided by this experiment may also be used in models of soil holding and slope stability (Sakals and Sidle 2004; Wu *et al.* 1988), and for models of tree biomechanics and anchorage in relation to wind (Achim *et al.* 2003; Deans and Ford 1983; Nicoll *et al.* 2005).

5. The effects of wind action on radial growth of tree stems and structural roots

Abstract

When forest stands are thinned, trees are exposed to increased light availability at the same time as increased wind movement, and are particularly vulnerable to windthrow during subsequent storms. The radial growth response of tree stems and structural roots to changes in wind action were examined in two experiments.

In the first experiment, dendrochronological techniques were used to explore the relationships between wind loading on the tree and annual radial growth of the stem base and structural roots of 46-year-old Sitka spruce. Growth-ring chronologies constructed using measurements of annual growth ring widths from stem sections and from the largest structural roots, were compared to climate data (wind, temperature and rainfall) for the life of the trees. Separate chronologies were constructed from structural root growth-ring measurements from each quadrant around the trees relative to the prevailing wind direction, and at 0.5 m, 0.75 m, 1.0 m and 1.25 m horizontal distance from the tree centre. No significant correlations were found between detrended stem chronologies and wind speed. However, detrended chronologies based on root radial growth at 0.75 m from the tree centre on the lee-side were strongly correlated with mean wind speeds in the previous autumn. Regression analysis revealed a positive relationship between root growth indices from this part of the structural root system and autumn wind speeds.

In the second experiment, wind movement, light and photosynthate supply of 10-year-old Sitka spruce trees were manipulated for 4 years before harvesting. The treatments applied were: 'Thinned' - Light and wind movement were increased by thinning to remove neighbouring trees; 'Thinned and Guyed' – Light availability was increased by thinning to remove neighbouring trees (as in the thinned treatment) and movement was decreased by guying the stem at half tree height; 'Pruned and

Girdled' – photosynthate supply was reduced by removing or girdling 50% of branches on each tree; and 'Control' – no treatment. Cross-sectional samples were removed from the stem at 0.1 m, 1.3 m, 3.0 m and 4.5 m above the base, and from the structural roots at 0.25 m, 0.5 m and 0.75 m horizontal distance from the stump centre. Growth rings were measured on these samples for an analysis of radial growth responses to the treatments.

The response to the 'thinned' treatment was a small immediate radial growth increase below-ground followed by a much larger increase in the second year, and a growth decrease in the stem above 0.1 m in the first year, followed by a large growth increase in all parts of the stem in the second year. In the first year following application of the 'thinned and guyed' treatment, there was no response below-ground, but there was a decrease in stem growth. In the second year, there was a large growth increase both above- and below-ground. The responses to the 'pruned and girdled' treatment was a large immediate growth reduction both above- and below-ground. The response to the 'thinned' treatment was greater than to the 'thinned and guyed' treatment, in both the stems and structural roots. The response to the 'thinned' treatment was considerably greater in the structural roots than in the stems. Therefore, although trees responded immediately to a reduction in photosynthate supply, the response to increased photosynthate supply after stand thinning was most pronounced in the second year following treatment. Allocation appeared to be greatest to the parts of the tree that would have experienced the most mechanical stress.

Introduction

Schwendener (1874) and Mezger (1893) formulated a hypothesis that the cambium in the tree stem produces new wood in a way that equalises the mechanical stress on the outer surface – the '*uniform stress hypothesis*' (see Chapter 1). Although this hypothesis still generates debate, for example see Morgan and Cannell (1994), a number of authors (reviewed by Telewski 1995) have described increased above-ground cambial growth as a direct response to mechanical stress. Plant growth responses to wind movement and other mechanical stress, termed 'thigmomorphogenesis' (Jaffe 1973) were described in a series of studies by Jaffe (1980; 1984) and Telewski and Jaffe (1981; 1986a; 1986b; 1986c). These responses include reduced height growth, greater stem taper, and development of smaller branches. There is however less information on the growth of roots in response to mechanical stress. Roots move in the soil as a tree sways in the wind; for example, Hintikka (1972) described spruce roots in a clay soil lifting the surface by 13.6 mm for 3° of stem displacement, and by 3.1 mm for 1° of stem displacement. Rizzo and Harrington (1988) found that movement of surface lateral roots was significantly and positively correlated with wind speed, and with soil rootable depth. Conifers have been observed to allocate a larger proportion of total biomass below-ground when they experience increased wind loading (Fritzsche 1933; Nielsen and Mackenthun 1991), and Sitka spruce (*Picea sitchensis* (Bong.) Carr.) growing on exposed sites with shallow soils have been reported to allocate a larger proportion of root biomass to the lee-side relative to the prevailing wind direction (Nicoll *et al.* 1995; Nicoll and Ray 1996). Ruth and Harris (1979) also described the largest supporting buttresses as being on the lee-side of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Sitka spruce trees. This development on gymnosperm species contrasts with observations that buttresses develop predominantly on the windward side of angiosperm tree species (Baker 1973; Grace 1977; Henwood 1973; Navez 1930). Seedlings and newly planted trees show similar behaviour with increased thickening of roots on both windward and leeward sides, i.e. the roots along the axis of flexing (Stokes *et al.* 1995a; Stokes *et al.* 1997a).

Reduction of root secondary thickening has been induced in a number of experiments by preventing stem sway (Fayle 1968; Fayle 1976; Jacobs 1939; Jacobs 1954; Wilson 1975). Seedlings of Sitka spruce and European larch (*Larix decidua* (Mill.) grown in a wind tunnel responded to flexing with greater stem radial growth on the windward and leeward sides, compared to non-moving controls (Stokes *et al.* 1995b). Two-year-old Sitka spruce trees that were flexed back and forward in a machine during the growing season increased the vertical, compared to horizontal, diameter of their lateral roots (Stokes *et al.* 1997b). These studies indicate that there is a localised response to mechanical stress that results in a reallocation of assimilates between, along and around individual roots. What remains unclear is if tree responses, and in particular root responses, to wind action are related to general patterns of movement throughout the life of a tree, or if the tree responds proportionally in each year to varying levels of stress as it grows in a variable wind climate.

Dendrochronology techniques have been used to analyse root growth in a number of previous studies (Fayle 1976; Jacoby *et al.* 1995; Krause and Eckstein 1993; Schulman 1945; Urban *et al.* 1994). However, these techniques have not previously been used to correlate root secondary growth with measured wind intensity from corresponding years. Measurement of root growth rings is sometimes reported to be difficult due to the unevenness of growth around the root, and occasional missing rings (for example, Schulman 1945). However, in sections removed from the root systems of 46-year-old Sitka spruce trees described by Nicoll and Ray (1996), growth was characteristically greatest on the upper side of structural roots, regardless of shape, with clear, wide, well differentiated growth rings that were suitable for measurement (see Figure 5-1). As the upward ('epinastic') thickening of spruce roots close to the stem is believed to be partly an adaptive response to wind movement (Nicoll and Ray 1996), this part of the root is particularly suitable for an investigation of secondary growth responses to changes in wind movement.

If trees exposed to increasing mechanical stress show an exponentially declining growth response, as in the dose-response curve for *Ulmus americana* L. described by Telewski and Pruyn (1998), trees already exposed to considerable wind movement on an exposed site may show little response to the increased movement associated with stand thinning. Thinning normally results in a large observable above-ground growth response, due to increased light availability and photosynthetic activity. However, the tree must quickly stabilise itself against the greater vulnerability to overturning from increased exposure and above-ground mass. Without faster below-ground growth at this time, the tree would remain vulnerable to windthrow, and it is therefore important that its response mechanism is not already saturated. Previous studies of above- and below-ground responses to stand thinning have not included control treatments that increase light without increasing wind action. Therefore, to understand tree responses to thinning in terms of C allocation and wind stability, it will be important to characterise dose response curves for conifer species, and to separate tree responses to increased light from the responses to increased mechanical stress.

Aims and hypotheses

This chapter describes two experiments that test the hypotheses that structural roots thicken by an amount that is related to the wind movement experienced in any year, and that trees can respond to sudden, large changes in their movement, such as after thinning, to stabilise themselves by adapting their root and stem growth. The species investigated in both experiments was Sitka spruce. The first experiment was a dendrochronological analysis of structural root growth rings of 46-year-old trees in comparison with wind records for the corresponding years. The second experiment examined secondary thickening of stems and structural roots of ten-year-old trees, in response to treatments in which wind movement, and assimilate supply, were modified.

Methods

Experiment 1

Site details

Structural root cross-sectional samples were analysed that had been extracted as part of an earlier investigation (Forest Research experiment Kershope 49) (Nicoll and Ray 1996; Ray and Nicoll 1998). Roots were from Sitka spruce trees selected from a 24-ha upland plantation, planted in 1948, at Crookburn hill in Kershope Forest, Cumbria, North England (200–230 m altitude, south-east aspect; latitude 55° 06', longitude 2° 47', OS grid reference NY495790). The trees had been planted at 1.8 m spacing on manually spread turfs next to shallow furrows that were approximately 30 cm deep and 3.6 m apart. Soils varied from surface-water gley, classified as 'stagno-orthic gley' soil (Avery 1990) to peaty-gley 'humic stagno-orthic gley' soil (Avery 1990), and were drained as part of a large drainage experiment (Forest Research experiment Kershope 10/65) described in detail by Pyatt *et al.* (1985). Drainage ditches were installed across the site at 10, 20 and 40 m spacing in 3.5-m wide racks that were cut through this part of the stand in 1966 and 1967 when trees were approximately 10 m tall. The site had a mean yearly rainfall of approximately 1300 mm (Anon 1977).

Table 5-1. Above and below-ground dimensions of trees from Expt. 1 at harvesting.

	Tree height (m)	DBH (cm)	Stem weight (kg)	Stem volume (m^3)	Crown weight (kg)	Crown diameter (m)	Crown depth (m)	Root weight (kg)	Root depth (m)	Root:shoot ratio
Mean	24.3	32.02	801.8	0.76	118.5	6.90	10.31	457.7	0.562	0.513
Standard error	0.36	0.81	42.9	0.05	8.15	0.21	0.33	32.2	0.018	0.019
Standard deviation	2.292	5.066	264.5	0.29	50.9	1.343	2.04	184.7	0.112	0.108
Minimum	20.4	22.8	366.3	0.33	28.5	4.6	6.15	134.2	0.298	0.307
Maximum	27.9	42.0	1365.8	1.38	298.5	11.1	15.1	950.9	0.796	0.720

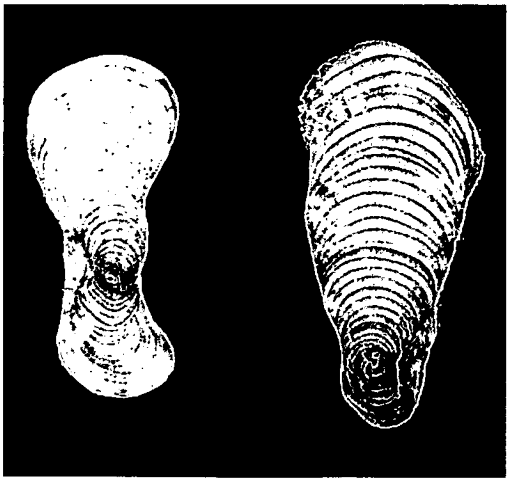
Experimental details

Thirty-nine trees selected to have a range of potential root depths (based on underlying soil water-table depth) were felled leaving a 3 m high stump. These trees had a mean height of 24 m and mean stem diameter at 1.3 m ('DBH') of 0.32 m (other dimensions are given in Table 5-1). To overturn the trees, a nylon sling was attached to the tree stump, 2 m above the soil surface, and connected to the steel cable from a hydraulic winch on a tractor. All trees were pulled in a direction away from (perpendicular to) the plough furrow at a constant pull rate of approximately 2 cm s^{-1}. Each tree was pulled over completely, and the stem was anchored to the ground to allow safe measurement of the root-soil plate. Complete details of the tree-pulling method were described by Ray and Nicoll (1998) and the present study is a re-analysis of the cross-sectional samples removed from root systems and stem bases of trees, described previously by Nicoll and Ray (1996).

Annual growth ring measurements

Sections were examined that had been cut from the stem base and from the four largest roots on each of ten trees selected randomly from the original sample. Sitka spruce trees usually have between 3 and 11 structural roots, with most trees having at least four (Coutts 1983a; Nicoll *et al.* 1995). The four largest roots were therefore expected to have the most structural importance and hence be most adapted to wind action. Root sections had been cut at 0.5, 0.75, 1.0, and 1.25 m from the tree centre. The distance from the tree centre, and direction relative to north to the section location, were recorded for each root section, and a mark indicated its original vertical orientation. Annual growth ring widths were measured from the upper outer surface of each section to the biological centre. Growth rings were often indistinguishable around the base and sides of root sections (see examples in Figure 5-1). The rings were measured by placing the section on a motorised, movable table, under a microscope. The position was recorded electronically each time a growth ring was advanced under the microscope cross-hairs, producing a set of ring widths for each section.

Figure 5-1. Examples of root cross sectional samples from Kershope used for the dendrochronological study.



Constructions of root growth ring chronologies

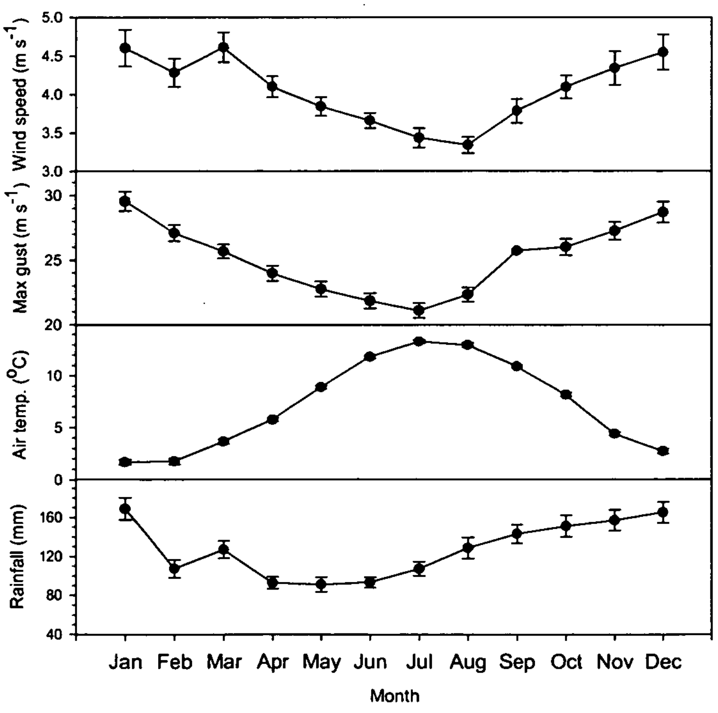
Variation in growth ring widths can be separated into low-frequency variation that results from changes related to tree age, and high frequency variation that represents large year to year changes in ring width due to environmental factors (Cook and Kairiukstis 1990; Fritts 1970). To construct chronologies, growth curves were fitted through the data, and low frequency variation was removed to leave only the high frequency variation. Chronologies were constructed from growth ring data using the 'ARSTAN' program (Cook and Holmes 1986), a subroutine of ITRDBLIB (Grissino-Mayer *et al.* 1992). Procedures in ARSTAN designed to eliminate non-climatic variation were applied to the data. All data-sets were single detrended by applying a cubic smoothing spline function to the data with a 66% variance cut-off (Cook and Holmes 1986), to generate 'Standard' and 'Residual' chronologies. Standard chronologies represent the robust bi-weight mean of the detrended radius series. Auto-correlation was removed from each raw ring-width series by auto-regressive (AR) modelling before computing the residual chronology. Stem chronologies were constructed using means of growth ring measurements taken in four directions (north, south, east and west) on each stem disk. Root chronologies were based on mean growth from the ten trees with separate chronologies for root sections at each of the four distances from the tree centre in four quadrants around the trees; north-east, south-east, south-west and north-west. There were therefore 16 separate root chronologies of each type; raw data, standard and residual. The south-west sector represented the windward side of the tree relative to the prevailing wind, and the north-east sector represented the leeward side.

Climate data

The closest meteorological station to the experiment site that had been in place for the life of the study trees was a UK Met Office station, 30 km to the north-east, at Eskdalemuir. This station has similar elevation (242 m) and aspect to the experiment site. Monthly mean air temperature, rainfall, monthly mean hourly wind speed and direction, and monthly mean of hourly maximum wind speed, were available from the Eskdalemuir station. To test the validity of using these data to represent wind climate on the Kershope experiment site, an anemometer was installed on a 10 m mast adjacent to the experiment site at Crookburn, Kershope in February 1996, and wind speed and direction were monitored for the next 12 months. Mean daily wind speed and direction were compared between Kershope and Eskdalemuir using linear regression. There was a highly significant positive linear regression between wind speeds at the two sites ($p < 0.001$) and between wind directions at the two sites ($p < 0.001$), indicating that data from Eskdalemuir could be used to represent the experiment site. The mean wind direction at Eskdalemuir was 250° (median 260°) and at Kershope it was 219° (median 235°).

During the life of the study trees, over 70% of the maximum hourly wind speeds at Eskdalemuir were from the south-west, with least wind (less than 3%) from the south-east. Monthly maximum and average hourly wind speeds over the same period were highest in December and January, falling to lowest in June (Figure 5-2). Monthly mean air temperature varied between 1.7°C in January, and 13.3°C in July. Monthly average precipitation over the life of the trees, was lowest in May (91 mm), and highest in January (169 mm).

Figure 5-2 Monthly mean wind speeds, wind maximum gusts, air temperature, and rainfall, based on 1947 to 1993 data from Eskdalemuir meteorological station. Error bars are standard errors above and below the means.



Statistical analysis

For this analysis, each chronology was correlated with mean and maximum wind speed, air temperature and rainfall, for each season of the 46 corresponding years to 1993. For the purpose of this analysis, seasons were defined as: 'Autumn' - previous September, October and November; 'Winter' – previous December, current January, current February; 'Spring' – current March, April and May; 'Summer' – current June, July and August. These correspond with the 'meteorological seasons' of the northern hemisphere defined by Battey (2000). Positive and negative correlations were classed as being significant when $p < 0.05$ or $p < 0.01$. Regression analysis was used to examine the relationships between chronologies and climatic variables where the correlations were significant at $p < 0.01$

Experiment 2

Site details

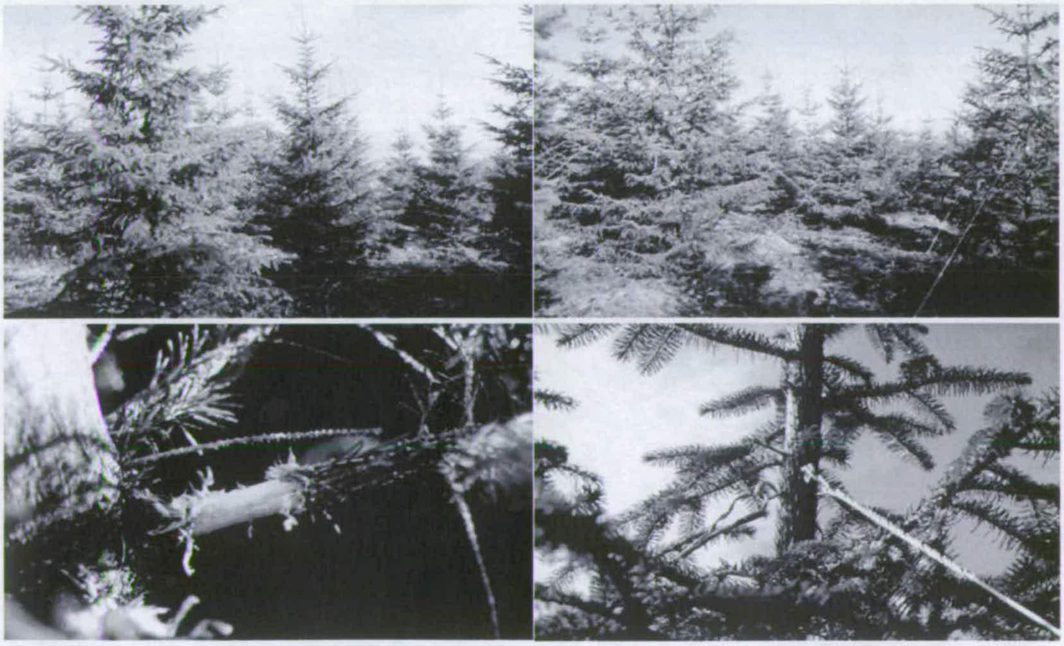
Experiment 2 was designed to investigate the effects of a sudden change in tree wind movement, and of a change in supply of assimilates from the shoot, on the development of the stem and of the structural roots. The experiment site was adjacent to the Experiment 1 site at Crookburn in Kershope Forest, Cumbria, UK (220 m altitude; OS grid reference NY494794) on peaty-gley (humic stagno-orthic gley) soil. Site details are as described for Experiment 1. Trees were Sitka spruce (QCI provenance), planted as 1+1 transplants in early 1986. They were flat-planted, i.e. without site cultivation, and the stand was not brashed or thinned before the experimental treatments were applied. The site had a stocking density of 2500 stems per hectare.

Experiment details

Treatments were applied at the end of February 1996 when the trees were ten-years old. Four treatments were applied to the trees; 'pruned and girdled', 'thinned', 'thinned and guyed', and unthinned 'control', with two plots per treatment. Six trees were selected at random for treatment within each plot (i.e. 12 trees per treatment). Trees had a mean height of 5.3 m and a mean DBH of 7.5 cm at the time of treatment. Treatment details were as follows:

1. 'Pruned and girdled' treatment trees. All branches on one side of the tree were girdled if they were larger than 10 mm diameter, or removed if they were smaller than 10 mm diameter. The treated side was either east or west-facing, and was chosen at random. Branches were girdled by removing all tissue down to the wood, in a 5 cm wide band (Figure 5-3).
2. 'Thinned' treatment trees. Trees were exposed to increased light and wind movement by removing all immediately neighbouring trees in the plot (Fig. 5-3).
3. 'Thinned and guyed' treatment trees. Trees were exposed in the same way as in the Thinned treatment, i.e. the plots were thinned by removal of immediate neighbours. They were then guyed by attaching steel wires (3 mm diameter) to three eye-screws at 0.5 x tree height (Figure 5-3) and secured to 0.75 m long ground anchors hammered 0.65 m into the ground. The guy wires were hand tightened to similar tension on each tree and were re-tightened as necessary in each year of the experiment.
4. Control trees. Trees were labelled and left untreated.

Figure 5-3. Photographs of the experimental site and treatments. Clockwise from top-left: 'Thinned' treatment, 'Thinned and Guyed' treatment, Cables attached to guyed tree; girdled branch in 'Pruned and Girdled' treatment.



Assessment and analysis

Tree heights were measured when the treatments were applied in February 1996 (i.e. before the start of the 1996 growing season), and during the experiment in February 1997 and 1998. Trees were harvested in early April 2000, four growing seasons after application of the treatments. Above-ground measurements were tree height (m), and growth ring analysis of stem radial growth on discs cut from the stem at four heights (0.1 m, 1.3 m, 3.0 m and 4.5 m). Below-ground measurements were root diameter, direction and depth of the ten largest structural roots on each tree at 0.25 m, 0.50 m and 0.75 m from the stump centre, and measurement of root growth rings on discs that were cut from these points.

Growth rings were measured on the stem and root disks using WinDendro software (Régent Instruments, Chicoutimi, Quebec, Canada), described by Guay *et al.* (1992). Growth rings were measured on each stem section on four radii corresponding with the north, south, east and west sides of the tree. Root sections were measured from the upper surface to the biological centre. Growth rings in the four directions were averaged for each stem section, and root growth was averaged for all disks on each tree for each distance from the stem centre. Relative growth responses were calculated as follows:

$$(5.1) \qquad \text{Relative growth response} = 100 \times \frac{\text{growth}_i - \text{growth}_0}{\text{growth}_0}$$

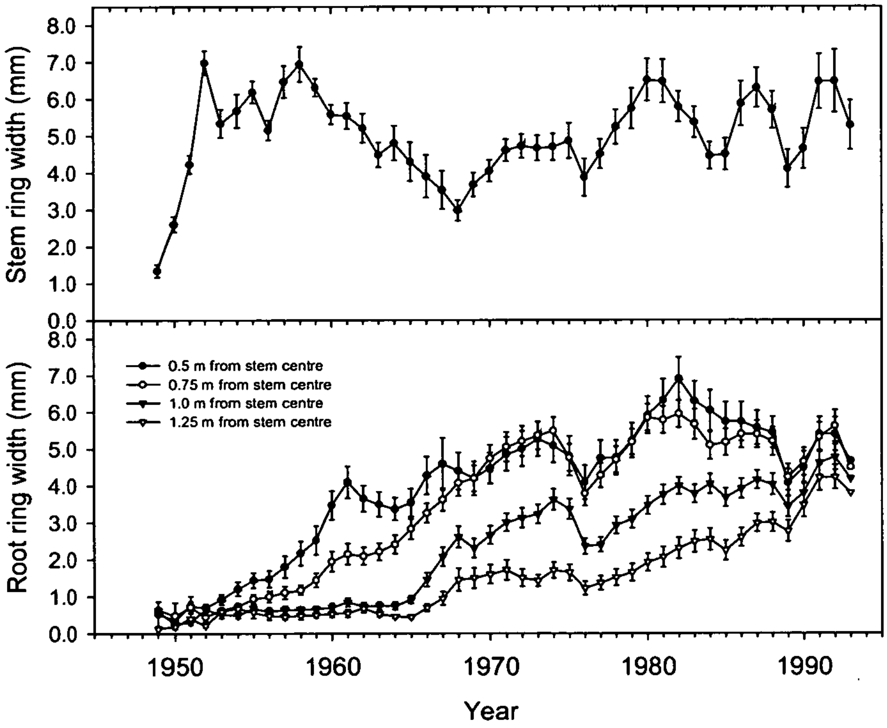
Where growth_0 is mean growth of the two years before treatment, and growth_i is growth during the year i after treatment. Root and stem growth after treatment were analysed as repeated measures series as described by Meredith (1991) and Ruel *et al.* (2003). The relative growth in each year and treatment was compared with growth before treatment using analysis of variance.

Results

Experiment 1

Stem radial growth increased rapidly for the first five years after planting, reaching a peak in 1952 (Figure 5-4). There was another peak in stem growth in 1958, followed by a steady decline in radial growth for ten years until 1968. An increase in growth after this date commenced between one and two years after the line thinning of the stand that was conducted in 1966 and 1967. Root radial growth showed peaks in 1961, 1967, 1974, 1982 and 1992. While only the last of these growth peaks corresponded with an above-ground peak, growth troughs occurred both above- and below-ground in 1976, 1984 and 1989 (Figure 5-4).

Figure 5-4. Mean stem and root ring widths with standard errors of the mean shown above and below the mean.



Growth ring chronologies from stem disks had few significant correlations with any seasonal climatic variables (Table 5-2). The only significant correlations were with the raw chronology, and there were none with either the standard or residual detrended chronologies. The correlation matrix shown in Table 5-3 relates each of the root growth ring chronologies (Figure 5-5) with mean climatic variables for each season in the corresponding years. There were a number of significant correlations, but most were with the raw data rather than the detrended standard or residual chronologies. There were however significant positive correlations ($p < 0.01$) with both winter temperature and autumn wind speed. The strongest significant correlations, and the only that were found with all three chronologies (raw, standard and residual), were between autumn wind speed and root radial growth in the leeward sector at 75 cm from the tree centre. At 1.25 m from the tree centre there was also a significant ($p < 0.05$) relationship between autumn wind speed and root radial growth (standard chronology). However, in contrast to the correlation with the 0.75 m chronology, this relationship was negative. Regression analysis showed a positive relationship between increasing root radial growth in this part of the system and previous autumn mean wind speed (Figure 5-6). The line of best fit was a second order polynomial ($R^2 = 0.5$), with the equation:

$$(5.2) \qquad y = -0.73\,x^2 + 7.62\,x - 12.32$$

where y = root radial growth (mm), and x = previous autumn mean wind speed ($m\ s^{-1}$). There was a steep increase in growth response to mean autumn wind speed up to around 4.5 $m\ s^{-1}$, but the relationship appeared to level off at higher mean wind speeds (Figure 5-6).

Figure 5-5. a). Mean seasonal wind speed, max gust, air temperature and precipitation at Eskdalemuir meteorological station between 1947 and 1993 (Data supplied by the Met Office); b). Standard chronologies from roots at 0.5, 0.75, 1.0 and 1.25 m from the tree centre, in the four quadrants.

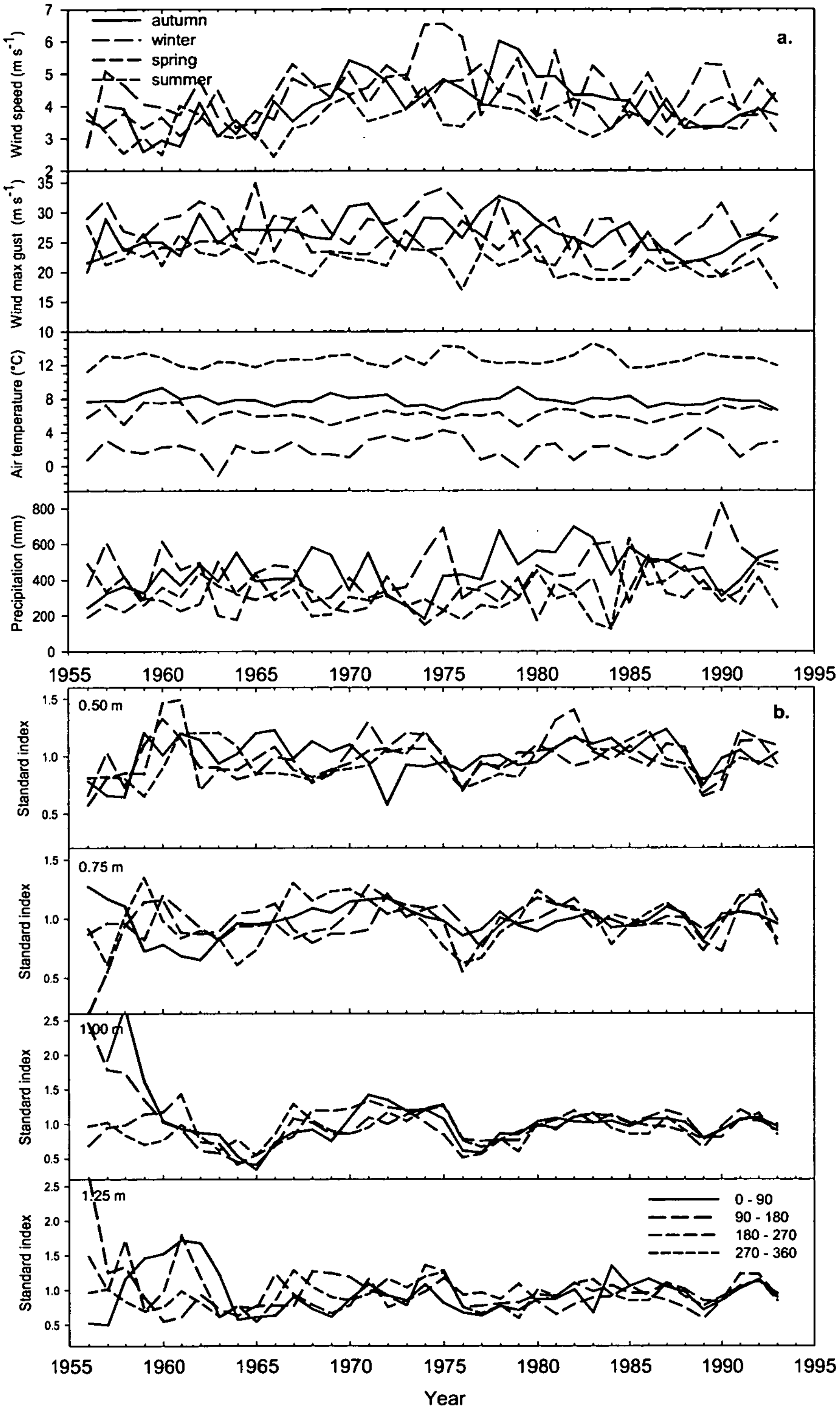


Table 5-2. Correlations between stem chronologies and climatic variables. Correlation coefficients are marked * where significant ($p < 0.05$).

stem chronologies	raw	standard	residual
Autumn mean wind	0.034	0.118	0.036
Autumn mean max gust	-0.088	-0.101	0.002
Autumn mean temp	-0.072	-0.053	0.132
Autumn rainfall	0.099	0	0.046
Winter mean wind	-0.17	-0.113	-0.075
Winter max gust	-0.281	-0.226	-0.21
Winter temp	-0.173	-0.187	-0.207
Winter rainfall	0.026	-0.148	0.003
Spring mean wind	-0.33*	-0.298	-0.287
Spring max gust	-0.309*	-0.271	-0.261
Spring mean temp	0.251	0.242	0.161
Spring rainfall	-0.067	-0.177	-0.145
Summer mean wind	-0.155	-0.064	-0.02
Summer max gust	0.017	0.183	0.173
Summer mean temp	-0.062	-0.103	-0.12
Summer rainfall	0.129	0.053	-0.027

Table 5-3. Correlations between root chronologies and climatic variables. Coefficients marked * indicate a significant positive correlation at $p < 0.05$, coefficients marked ** indicate a significant positive correlation at $p < 0.01$.

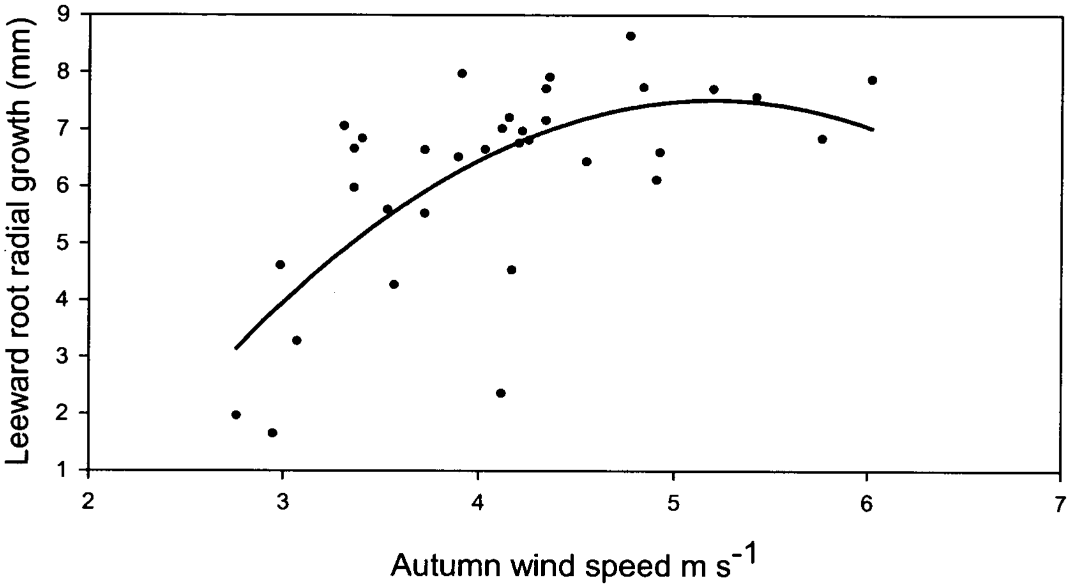
50 cm	0-90			90-180			180-270			270-360		
chronology	raw	standard	residual	raw	standard	residual	raw	standard	residual	raw	standard	residual
Autumn mean wind	0.28	-0.19	-0.27	0.39	0.12	0.09	0.23	-0.13	-0.24	0.28	-0.03	-0.03
Autumn mean max gust	0.26	0.02	0.03	0.20	0.28	0.16	0.11	0.02	-0.01	0.00	-0.01	0.02
Autumn mean temp	-0.03	-0.02	-0.10	-0.10	0.21	0.27	-0.16	0.11	0.04	-0.25	-0.17	-0.03
Autumn rainfall	0.57**	0.36*	0.21	0.57**	0.24	0.11	0.21	-0.06	0.00	0.43**	0.14	0.10
Winter mean wind	0.03	-0.30	-0.15	0.03	-0.08	-0.26	0.08	-0.12	-0.08	0.11	0.00	-0.07
Winter max gust	-0.29	-0.20	-0.08	-0.35*	-0.24	-0.33*	-0.24	-0.11	-0.06	-0.31	0.00	-0.13
Winter temp	-0.25	-0.35	-0.21	-0.05	-0.10	-0.34*	0.07	0.07	-0.05	0.03	-0.12	-0.14
Winter rainfall	0.03	0.04	0.11	0.04	0.03	-0.05	0.23	0.21	0.22	0.25	0.05	0.18
Spring mean wind	0.17	-0.15	-0.29	0.30	-0.02	0.00	0.25	-0.12	-0.02	0.16	-0.14	-0.11
Spring max gust	-0.01	-0.04	-0.12	-0.04	0.07	-0.06	-0.08	-0.04	0.01	-0.22	-0.06	-0.07
Spring mean temp	-0.23	-0.01	0.08	-0.03	0.39*	0.11	0.00	0.37*	0.26	-0.09	-0.03	0.16
Spring rainfall	0.14	0.00	-0.15	0.29	0.09	-0.04	0.05	-0.12	0.02	0.24	0.06	0.00
Summer mean wind	0.06	-0.07	-0.27	0.23	0.06	-0.11	0.24	0.03	-0.12	0.20	0.23	0.11
Summer max gust	-0.37*	-0.04	0.00	-0.44**	-0.03	0.07	-0.22	0.14	0.03	-0.45**	0.08	-0.05
Summer mean temp	0.20	-0.02	0.17	0.03	-0.04	-0.03	0.10	-0.06	0.07	0.08	-0.30	-0.27
Summer rainfall	-0.27	-0.14	-0.21	-0.15	-0.06	0.10	-0.17	-0.05	-0.08	-0.02	0.20	0.15

75 cm	0-90			90-180			180-270			270-360		
chronology	raw	standard	residual	raw	standard	residual	raw	standard	residual	raw	standard	residual
Autumn mean wind	0.58**	0.44**	0.48**	0.46**	0.03	0.03	0.54**	0.26	0.09	0.32	0.10	0.16
Autumn mean max gust	0.29	-0.01	-0.06	0.18	0.19	0.31	0.31	0.24	0.21	-0.01	-0.09	0.17
Autumn mean temp	-0.20	-0.19	-0.23	-0.27	0.01	0.11	-0.08	0.29	0.10	-0.16	0.22	0.21
Autumn rainfall	0.29	-0.10	0.07	0.45**	0.27	0.30	0.34*	0.03	-0.06	0.37*	0.10	0.01
Winter mean wind	0.36*	0.02	-0.20	0.20	0.13	0.27	0.20	-0.13	-0.10	0.13	-0.06	-0.04
Winter max gust	-0.13	-0.05	-0.11	-0.22	-0.17	-0.03	-0.19	-0.12	-0.04	-0.38*	-0.34*	-0.22
Winter temp	0.19	0.04	-0.09	0.13	0.13	0.17	0.08	-0.01	-0.02	0.07	-0.13	-0.20
Winter rainfall	0.04	0.02	0.01	0.20	0.03	0.18	0.14	0.17	0.26	0.18	-0.05	-0.01
Spring mean wind	0.55**	0.23	0.14	0.34	0.09	0.01	0.40*	-0.08	-0.10	0.34*	0.18	0.23
Spring max gust	-0.02	-0.18	-0.20	-0.02	0.22	0.10	-0.14	-0.23	-0.15	-0.21	-0.11	-0.05
Spring mean temp	-0.26	-0.18	-0.17	-0.07	0.19	0.20	-0.18	0.20	0.29	-0.19	-0.10	-0.11
Spring rainfall	0.15	-0.09	0.03	0.30	0.23	0.14	0.14	-0.23	-0.23	0.27	0.01	0.05
Summer mean wind	0.43**	0.13	0.11	0.21	-0.18	-0.23	0.37*	0.17	0.08	0.21	0.08	-0.04
Summer max gust	-0.40*	-0.06	-0.10	-0.49**	-0.21	-0.35*	-0.33	0.20	0.14	-0.46**	0.11	-0.03
Summer mean temp	0.17	-0.03	-0.22	0.14	0.19	0.26	0.03	-0.21	-0.15	0.12	0.00	0.10
Summer rainfall	-0.29	0.00	0.17	-0.16	-0.18	-0.23	-0.13	0.13	0.03	-0.07	0.05	0.12

100 cm	0-90			90-180			180-270			270-360		
chronology	raw	standard	residual	raw	standard	residual	raw	standard	residual	raw	standard	residual
Autumn mean wind	0.29	0.03	0.23	0.25	-0.01	0.07	0.31	0.06	0.06	0.20	0.16	0.19
Autumn mean max gust	-0.11	-0.09	0.09	-0.08	-0.35*	-0.20	-0.07	-0.05	0.06	-0.06	-0.10	-0.16
Autumn mean temp	-0.34*	0.03	-0.13	-0.36*	-0.13	-0.21	-0.14	0.26	0.21	-0.43**	-0.31	-0.34*
Autumn rainfall	0.22	-0.27	-0.14	0.37*	-0.33*	-0.07	0.32	0.00	-0.04	0.21	-0.04	-0.07
Winter mean wind	0.16	0.18	0.07	0.21	0.00	-0.18	0.08	0.07	-0.13	0.28	0.32	0.31
Winter max gust	-0.20	-0.02	-0.01	-0.23	0.02	-0.22	-0.29	-0.12	-0.05	-0.15	0.09	0.01
Winter temp	0.21	0.12	0.00	0.23	0.07	-0.17	0.10	0.02	-0.16	0.34*	0.42**	0.40*
Winter rainfall	0.36*	0.12	0.24	0.39	0.18	0.12	0.27	0.12	0.22	0.40	0.38*	0.38*
Spring mean wind	0.22	-0.20	-0.03	0.21	-0.22	0.12	0.21	-0.05	0.00	0.36	0.09	0.13
Spring max gust	-0.31	-0.19	-0.10	-0.27	-0.27	-0.09	-0.33	-0.28	-0.31	-0.09	-0.11	-0.14
Spring mean temp	-0.01	0.06	-0.19	-0.05	0.04	0.00	-0.03	0.23	0.29	-0.04	0.13	0.03
Spring rainfall	0.22	-0.22	-0.25	0.22	-0.30	-0.07	0.16	-0.18	-0.25	0.25	-0.13	-0.12
Summer mean wind	0.28	-0.20	-0.14	0.17	-0.03	0.02	0.28	0.20	-0.04	0.14	0.17	0.14
Summer max gust	-0.42**	0.14	-0.06	-0.54**	0.25	0.20	-0.42**	0.05	-0.05	-0.48**	-0.04	-0.06
Summer mean temp	0.03	0.12	-0.02	0.25	0.03	-0.06	0.10	0.07	0.06	0.21	0.18	0.20
Summer rainfall	0.01	0.10	0.19	-0.14	0.15	-0.04	-0.10	-0.17	-0.10	-0.17	-0.11	-0.08

125 cm	0-90			90-180			180-270			270-360		
chronology	raw	standard	residual	raw	standard	residual	raw	standard	residual	raw	standard	residual
Autumn mean wind	-0.04	-0.36*	-0.16	-0.02	0.31	0.28	0.04	-0.02	-0.05	0.25	0.07	0.10
Autumn mean max gust	-0.22	-0.10	0.02	-0.28	-0.23	0.07	-0.12	-0.08	-0.05	0.00	-0.18	-0.18
Autumn mean temp	-0.30	0.22	0.14	-0.33*	-0.17	-0.12	-0.31	0.00	0.01	-0.08	0.17	0.01
Autumn rainfall	0.29	-0.05	-0.14	0.33*	-0.25	0.07	0.22	-0.23	-0.27	0.22	-0.06	-0.05
Winter mean wind	-0.06	-0.08	-0.06	0.03	-0.07	0.14	0.03	-0.18	-0.20	0.15	0.05	0.12
Winter max gust	-0.29	-0.01	-0.02	-0.26	0.06	0.00	-0.17	-0.01	0.02	-0.24	-0.06	-0.09
Winter temp	0.07	-0.09	-0.04	0.17	-0.11	0.05	0.12	-0.04	-0.05	0.04	-0.01	0.02
Winter rainfall	0.41*	0.12	0.34	0.43**	0.05	0.06	0.43**	0.14	0.09	0.26	0.25	0.13
Spring mean wind	0.00	-0.31	-0.24	0.02	-0.12	-0.12	0.18	-0.16	-0.14	0.37*	0.09	0.24
Spring max gust	-0.29	-0.05	-0.09	-0.33*	-0.29	-0.34*	-0.11	0.13	0.18	-0.21	-0.14	-0.04
Spring mean temp	0.07	0.23	0.17	0.06	-0.25	-0.34*	0.07	-0.03	-0.02	-0.20	-0.07	-0.23
Spring rainfall	0.30	-0.07	-0.32	0.34*	-0.34*	-0.32	0.31	-0.27	-0.30	0.05	-0.26	-0.19
Summer mean wind	0.04	-0.04	-0.14	0.03	0.23	0.28	0.06	-0.02	-0.01	0.26	-0.07	0.04
Summer max gust	-0.46**	0.16	0.12	-0.53	0.25	0.01	-0.37*	0.31	0.37*	-0.38*	-0.08	-0.08
Summer mean temp	0.00	-0.15	0.09	0.14	-0.13	0.00	0.13	-0.20	-0.21	0.28	0.14	0.09
Summer rainfall	0.12	0.14	-0.07	0.04	0.18	0.00	-0.01	0.18	0.18	-0.16	0.03	0.02

Figure 5-6. Regression of the raw windward root growth index (0.75 m) against mean autumn wind speed.



Experiment 2

Climate

Annual rainfall during the life of trees in Experiment 2 was between 1500 and 2000 mm and annual mean air temperature was between 6° and 8°C, both at Eskdalemuir. Annual mean wind speed at Crookburn, Kershope was between 6 and 8 m s^{-1} (see Figure 5-7). Wind direction at Crookburn, Kershope between 2 February 1996 and 3 April 2000 was from the south-west (mean 225°, median 234°, standard error of the mean 0.8°). A frequency distribution and wind rose are shown in Figure 5-8.

Figure 5-7. Total yearly rainfall and mean air temperature at Eskdalemuir and mean wind speed at Crookburn, Kershope, for the duration of Experiment 2. Eskdalemuir data supplied by the Met Office.

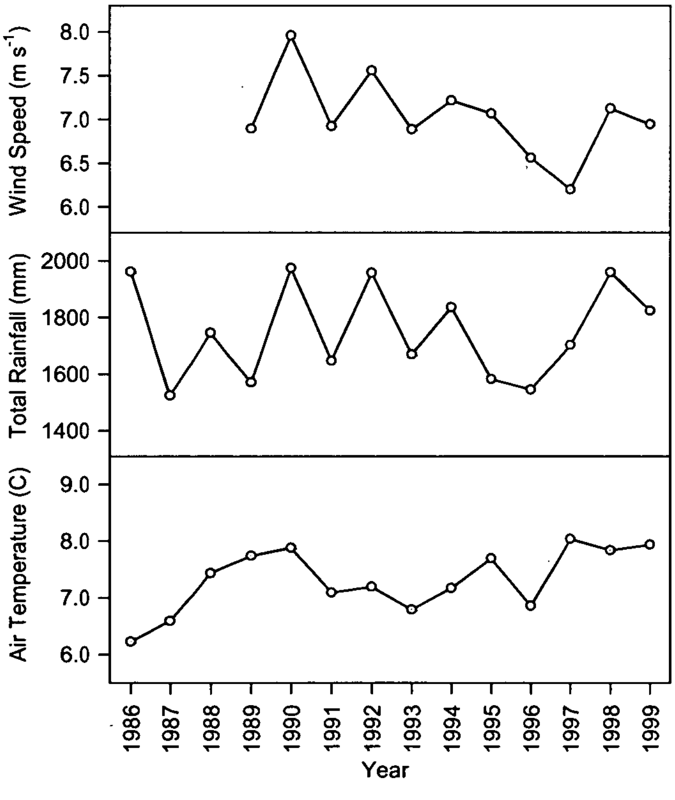
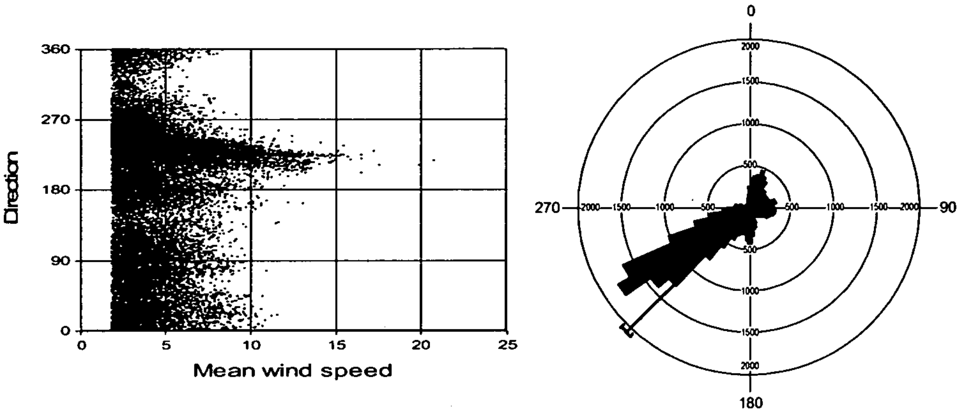


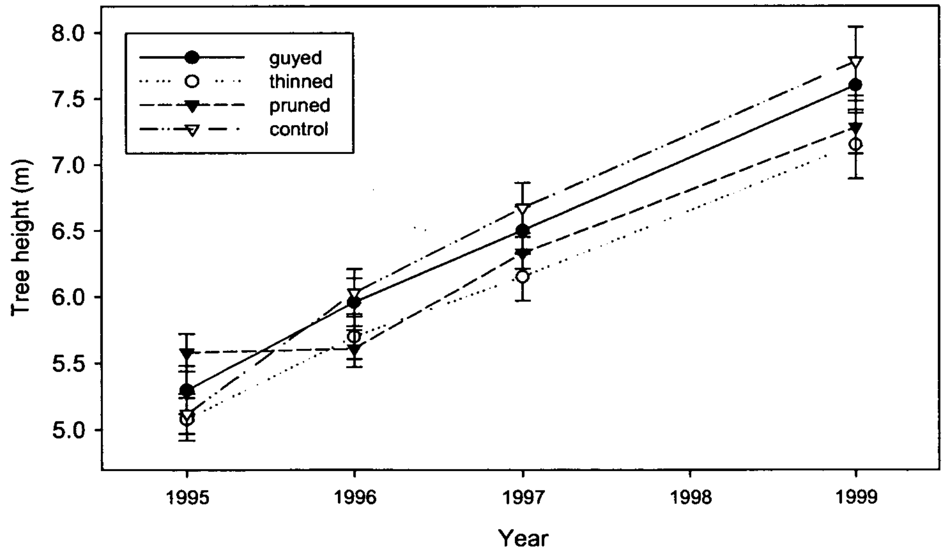
Figure 5-8. Wind frequency distribution and wind rose for Crookburn, Kershope between February 1996 and April 2000. The line indicates the mean wind direction (with standard error bars).



Tree height

In the first year after treatment, 'pruned and girdled' trees showed no height increment while the 'control' trees showed the fastest increment (Figure 5-9). By the end of the experiment, 'control' trees were the tallest and 'thinned' trees were the smallest, but differences were not statistically significant.

Figure 5-9. Mean tree height (and standard error above and below the mean) at the end of 1995, 1996, 1997 and 1999 growing seasons.



Stem and root radial growth

Trees on this site showed a rapid increase in radial growth at the stem base (Figure 5-10) for the first four years of growth, peaking in 1993. This was followed by a slow decline that was broken, in the untreated control trees, by a smaller peak four years later in 1997 (Figure 5-10). The first radial growth peak was progressively later at increasing heights on the stem; 1995 at 1.3 m, 1997 at 3.0 m and 1999 at 4.5 m. Roots in the 'control' treatment showed a peak of radial growth simultaneously at all distances from the stem (0.25, 0.50 and 0.75 m) in 1997.

In the year following treatment (1996), there was a decrease of stem radial growth at 0.1 m and 1.3 m in all treatments, but this decrease was most pronounced in the 'pruned and girdled' treatment. This coincided with a marked decrease in root growth at 0.25 m. The above- and below-ground growth reduction in 1996 corresponded with a relatively large decrease in mean air temperature and rainfall (Figure 5-7). After the large initial decrease in growth in the pruned and girdled treatment, growth levelled out to be similar to that of the control (Figure 5-10). Below-ground, there was a positive growth response (85%) in the 'thinned' treatment in the first growing season after thinning (1996), but this was small compared to responses in the second growing season (see Figures 5-10 and 5-12). Trees in the 'thinned', and 'thinned and guyed' treatments, showed large increases in stem relative growth at 0.1 and 1.3 m (Figure 5-11), and in root relative growth at all distances in the second growing season after treatment (Figure 5-12). These increases were greatest at 0.1 m in the stem (93% and 42% for 'thinned' and 'thinned and guyed' treatments respectively), and at 0.5 m in the roots (397% and 149% respectively), and decreased with increasing height on the stem and distance along the roots. 'Thinned' treatment trees showed a considerably greater growth response after treatment than 'thinned and guyed' treatment trees, both above- and below-ground. The difference was significant in the lower stem at 0.1 and 1.3 m, and in the roots at 0.25 m and 0.5 m from the stem (all $p < 0.05$). After the second year, relative growth decreased slightly in the lower stem (Figure 5-11), and continued to increase slightly below-ground (Figure 5-12), in all treatments except for the control.

Figure 5-10. Mean (and standard error above and below the mean) radial growth in the stem (0.1 m, 1.3 m, 3.0 m and 4.5 m) and in the structural roots (0.25 m, 0.50 m and 0.75 m from the tree centre) in each of the four treatments between the 1990 and 1999 growing seasons. The dashed vertical lines mark the last growing season before treatment.

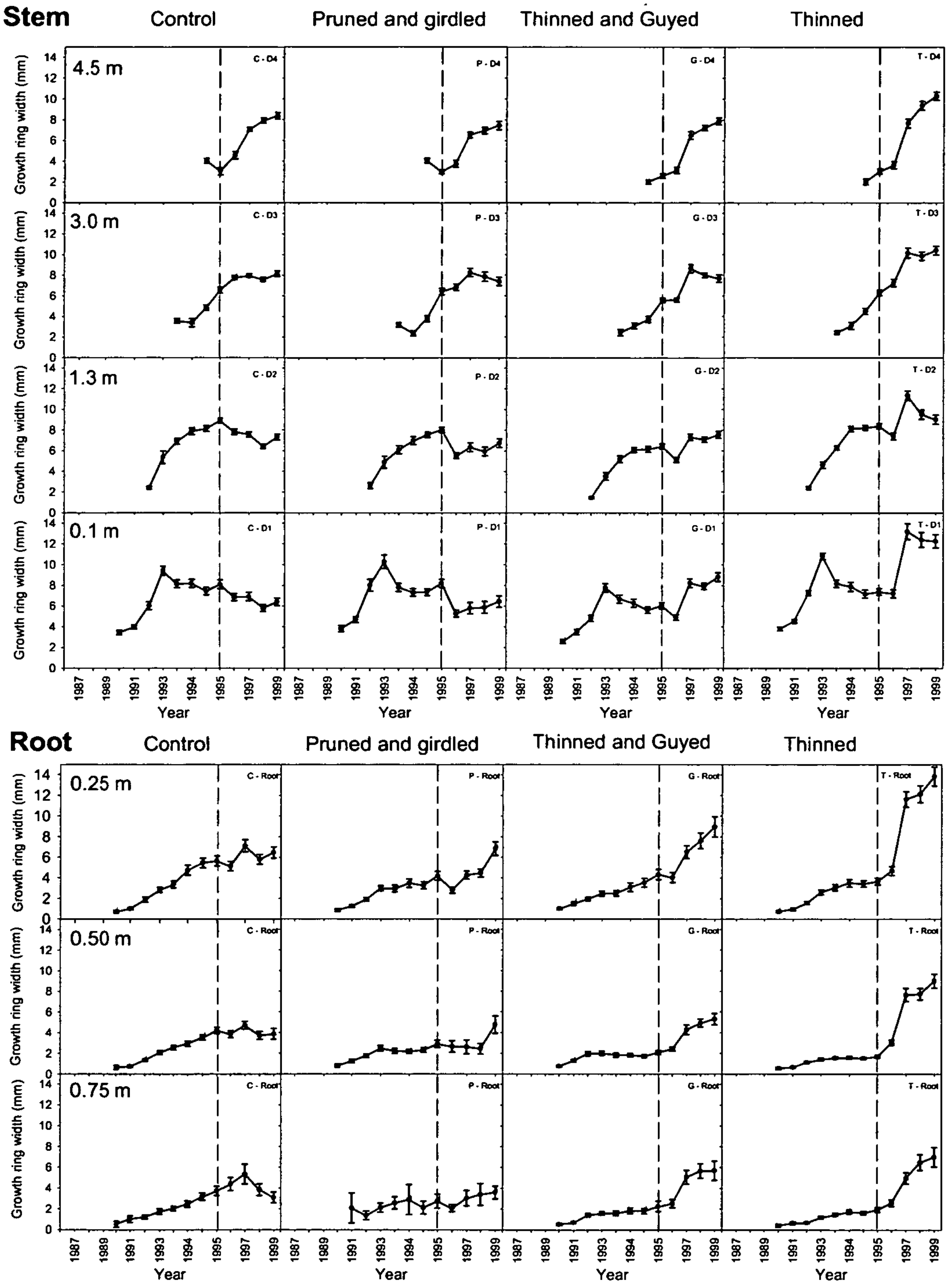


Figure 5-11. The relative growth response to treatments, in stems at 0.1 m, 1.3 m, 3.0 m and 4.5 m. Vertical bars are the least significant differences between means ($p < 0.05$) for comparisons between treatments within a year and between years within a treatment. Note that the scale on the vertical axis is different on each graph.

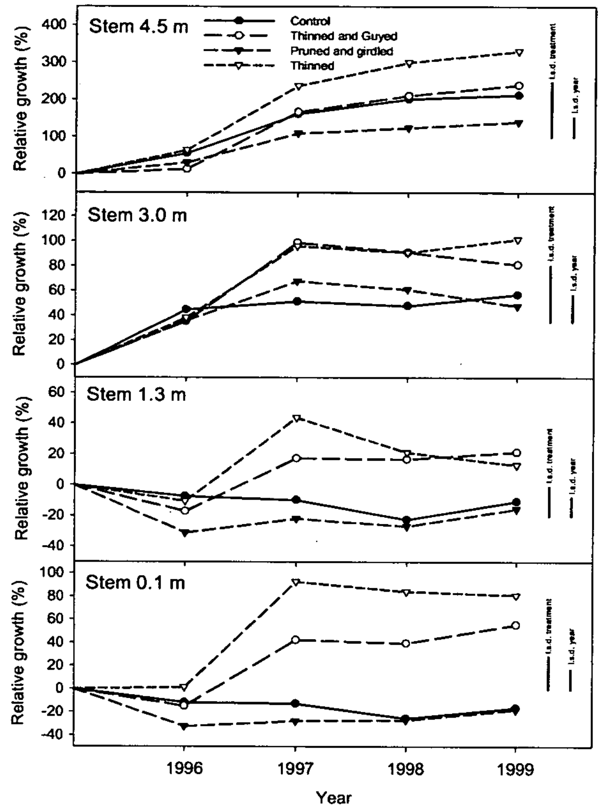
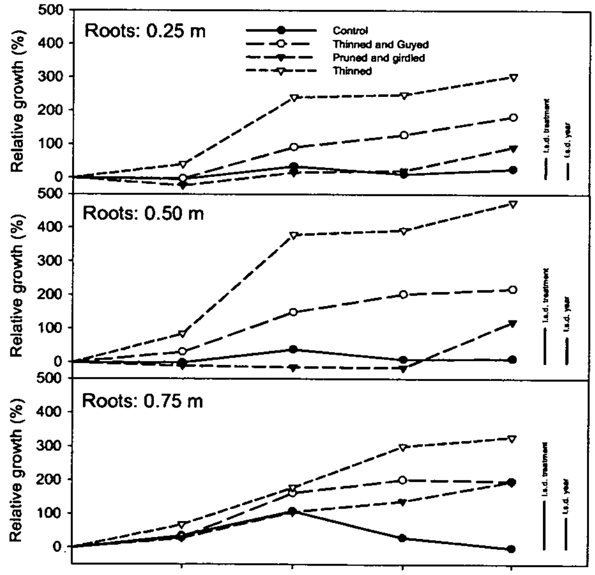


Figure 5-12. The relative growth response to treatments in structural roots at 0.25 m, 0.5 m and 0.75 m from the tree centre. Vertical bars are the least significant differences between means ($p < 0.05$) as in Figure 5-11.



Discussion

Although, in Experiment 1, there were no significant correlations between wind speed and the detrended stem chronologies, there were several positive correlations with root chronologies. The analysis indicated that there was an overall increase in allocation of assimilates to the structural roots on the lee side of the tree in response to wind. The allocation of assimilates to structural roots on the lee-side at 0.75 m was positively correlated with wind speed, and appeared to be at the expense of growth in roots with less of a structural role further from the tree (where correlations were negative). Increased thickening of structural roots on the lee side of trees relative to the prevailing wind direction has been observed previously (Nicoll *et al.* 1995; Nicoll and Ray 1996). In wind tunnel and mechanical flexing studies, Stokes *et al.* (1995a; 1997a) also found more growth of windward and leeward (flexed) roots, compared to perpendicular (twisted) roots. The correlation between wind action and root radial growth at 0.75 m from the stem in Experiment 1, and the larger growth response in roots at 0.5 m from the stem than at 0.25m or 0.75 m, appear to correspond with the part of the root systems that would be expected to bend most as trees sway in the wind. Close to the stem, in the 'zone of rapid taper' (Coutts 1987), buttresses are commonly large enough to minimise bending (Ennos 1993). Rizzo and Harrington (1988) found the greatest movement of surface roots to be between 40 and 80 cm from the stems of 10 – 19 cm DBH red spruce (*Picea rubens* Sarg.) and balsam fir (*Abies balsamea* (L.) Mill.). Stokes and Mattheck (1996) described structural root compression strength in >40 year old Norway spruce (*Picea abies* (L.) Karst.) (ca. 35 cm DBH) as increasing with distance from the tree to a maximum at around 0.75 m, where bending was expected to be greatest. Ray and Nicoll (1998) recorded the bending during uprooting of the root plates that were the source of root material for Experiment 1, and found maximum bending to be approximately 0.8 m from the tree on both the compression and tension sides.

The amount of secondary thickening at any part of the root system may be proportional to the amount of bending stress experienced at that point. This is compatible with, but not the same as, the 'uniform stress hypothesis', in which stress is kept constant over the stem and root surface as the tree undergoes secondary thickening. More research is required to find the shape of the dose response curve for conifer roots in response to mechanical stress, but the relationship found in this study between mean wind speed and root radial growth, indicates that there may be a threshold above which increasing wind action no longer increases growth rate.

The time of year at which the roots experience mechanical stress appears to be important. The most significant correlations between mean wind speed and root growth-ring chronologies were from wind movement during the autumn before the 'current' growing season. As Sitka spruce roots are expected to show only minimal growth in upland Britain between September and November (Coutts and Nicoll 1990a), these correlations may indicate the presence of a stored signal or resource. The growth promoter most commonly associated with plant responses to mechanical stress is ethylene, but as this is unlikely to persist long enough to be the signal involved here, a precursor or other growth promoter could be responsible. Alternatively, as Sitka spruce shows positive net photosynthesis throughout the autumn and winter while the temperature remains above -5°C (Ludlow and Jarvis 1971; Neilson *et al.* 1972), a possible mechanism is the storage of assimilates during this period in ray parenchyma adjacent to the dormant cambium particularly in regions of the structural roots that experience the most stress. The stored assimilates would enhance radial growth in these regions when the cambium becomes active in the spring (Wargo 1979; Zimmerman 1964). Although this hypothesis remains to be tested, it is backed up by the observation that during spring and summer while most assimilates are being used directly in shoot extension growth and stem radial growth, there appeared to be little influence of wind speed on root development. Valinger *et al.* (1994; 1995) and Lundqvist and Valinger (1996) demonstrated similar responses above-ground in Scots pine. They found that tree stems had increased diameter growth after being subjected to mechanical loading in the dormant season, compared to unflexed controls. There would certainly be benefits to trees responding to wind movement during dormancy – the highest wind speeds are usually experienced in the autumn and winter, and the loads on the tree at this time of year can sometimes be further increased by snow and ice accumulation in the crown. Trees would therefore adapt their above- and below-ground morphology to resist to the largest loads that they experience.

It is important to remember that the effect of increased wind speeds on a tree is not purely to increase mechanical stress on its component parts. Wind decreases humidity around the leaves, and the plant can respond to this by increasing leaf diffusive resistance, which in turn decreases photosynthetic rate and growth (Grace *et al.* 1975). However, on the exposed upland site described here, thinned trees that were allowed to move more in the wind increased their growth faster that those that were restrained by guy wires. Therefore, any effect of increased wind movement around needles on swaying trees appeared to be more than offset by increased growth in response to improved light availability and in response to increased mechanical stress in the stem and roots.

Growth reductions above- and below-ground in Experiment 1 in 1989 and 1993, followed between one and two years later by a marked growth increase, did not appear to correspond with any measured climatic variable. It is possible that these reductions resulted from partial defoliation by *Elatobium abietinum* (Walker), the green spruce aphid, that is a common forest insect in the British Isles. This insect can defoliate spruce trees by more than 50% of their older needles, resulting in a reduction in annual increment for between one and several seasons (Straw *et al.*). In the present study, growth reductions were in the order of 30%, with a growth recovery within 4-5 years. This is comparable to the symptoms of *Elatobium* attack reported in the literature, for example Seaby and Mowat (1993) reported an initial 40% growth reduction with observable inhibited growth for 4 years in response to a severe *Elatobium* attack. These growth reductions were observed both above- and below-ground, and were similar to the pattern of growth reduction observed in Experiment 2, following what was effectively a 50% defoliation in the 'pruned and girdled' treatment. In Experiment 2, reduction of radial growth above-ground was also close to 30% in the first year, and growth was maintained as being less than the control trees for the following two years. These responses were also comparable to the stem and root ring-width decreases described by Krause and Morin (1999) following defoliation of black spruce (*Picea mariana* (Mill.) BSP) by spruce budworm (*Choristoneura fumiferana* (Clem.)) in Quebec, Canada.

The observations in Experiment 1 of a response in root radial growth to previous autumn wind stress correspond well with results from Experiment 2 where there was little response in the growth season directly following treatment but a strong response in the next year. Other authors have found similar delays in response to thinning treatments, but the duration of the reported delay varies. Urban *et al.* (1994) used dendrochronological techniques to examine the response of 120-year-old white spruce (*Picea glauca* (Moench) Voss) to increased light and wind stress following road clearing. These trees showed an immediate 'release' in structural root radial growth and a release of above-ground growth (at 1.3 m) that was delayed by between 3 and 9 years. Trees appeared to have allocated assimilates below-ground at the expense of that above-ground. Ruel *et al.* (2003) found a similar immediate response in structural roots of balsam fir to stand thinning at ages 17 and 22 years old, and a significant increase in stem growth (at 1.4 m) only after 2 years. The below-ground response in the Ruel *et al.* (2003) study was in the growing season following the year of treatment, and as the thinning treatment would have been in the summer (Achim, A. *personal communication*), the response is comparable to the present Experiment 2 where the largest response followed the first autumn and winter after treatment. These results are also similar to those of Kneeshaw *et al.* (2002) who found a root radial growth response in the year following stand thinning, a one-year delay before a stem response, and 2-3 year growth reductions in branch radial growth and leader height growth.

Fayle (1976) removed soil from around structural roots of eight, ca. 3.4 m tall, Scots pine (*Pinus sylvestris* L.) trees to allow increased wind movement, and then guyed four of them to prevent movement. In the first year after treatment there was no effect on exposed free-standing trees (compared to guyed trees) on stem radial growth below guy height, but there was a large increase in the second year. Below-ground there was a large response in both the first and second year after treatment. The decrease in response with height would lead to increased stem taper. It is however, important to remember that following stand thinning, trees are exposed to an increase in both light and wind movement. The light effect was removed in a previous experiment where tree seedlings were mechanically flexed or kept relatively motionless as they grew in a glasshouse (Stokes *et al.* 1997b). Shoot extension growth was found to be reduced by the flexing treatment, while basal stem diameter and root mass were increased.

The considerably greater growth response below-ground than above-ground, indicates that there was an alteration in the allocation of assimilates between above- and below-ground components in response to increased mechanical stress. This may also explain the relatively slow shoot extension growth in the thinned trees that experienced increased movement. However, despite this alteration of allocation, growth was greater in the 'thinned' than in the 'thinned and guyed' treatment both above- and below-ground. Trees in these two treatments may be expected to have similar amounts of assimilate available for cambial growth, so if the greater growth response in the moving trees is not purely a reallocation to parts of the tree that experience the greatest stress, a possible explanation would be that the density of wood in the new growth rings is reduced in the moving tree. Koga *et al.* (2002) examined the effects of stand thinning on 14-year-old Balsam fir stem radial growth and wood density. They examined stem disks from 0.2 m, 0.7 m, 1.3 m, 5 m, 7 m and 9 m, and found an immediate growth response that was greatest in the lower stem, and decreased, in relative terms, with increasing height. The increased stem radial growth corresponded with an increase in earlywood rather than latewood. As earlywood has lower density than latewood, the resulting smaller latewood percentage gave lower ring densities for these trees. Again, the thinning treatment was applied in July and the response was observed in the next year, so the response followed the first autumn and winter of increased exposure. The analysis by Koga *et al.* (2002) may therefore indicate a mechanism for the larger overall growth response of thinned, compared to thinned and guyed trees, in Experiment 2, but this should be tested in future experiments.

Experiment 2 was not maintained for long enough to enable an examination of any longer-term growth trends. After three years of treatment, stem relative radial growth had started to reduce, but at the end of the experiment, four years after treatment, root relative radial growth was still increasing. It is therefore impossible to predict from these data when root radial growth would start to slow. Peltola *et al.* (2002) reported that the fastest diameter growth of Scots pine (*Pinus sylvestris* L.) was observed close to the stem base, between seven and nine years after thinning. Similarly, Koga *et al.* (2002) found that balsam fir (*Abies balsamea* (L.) Mill.) showed a positive increase in stem base radial growth that lasted for seven years after stand thinning. Kneeshaw *et al.* (2002) found that stem and root radial increment peaked four years after stand thinning of Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) and lodgepole pine (*Pinus contorta* Dougl.). Unfortunately, none of these studies included a comparison of trees in a thinned treatment with trees in a similarly thinned, but non-moving, control treatment. Therefore, to be able to adequately model whole tree responses to changes in wind action, controlled experiments should be established, and maintained for longer time periods. Ideally, the 'thinned' and 'thinned and guyed' treatments that were applied to trees in Experiment 2 should be repeated in a new experiment that would run for 10 years or more.

6. General Discussion

Models of tree anchorage and stability

The results of four decades of windthrow and tree stability research in Britain have been incorporated into a variety of models and decision support systems. Following the earliest intensive period of investigation, Fraser and Gardiner (1967) described linear relationships between critical turning moment and stem mass for Sitka spruce, on a range of forest soils. This, for the first time, allowed the anchorage of trees to be predicted, based on site conditions. These relationships have been extended in Chapter 2 of this thesis, incorporating further tree-pulling experiments, into a system that describes anchorage of twelve of the most commonly planted conifer species, in all soil groupings and soil rooting depths encountered in British forests. The new system provides an objective means to compare the anchorage provided by the root systems of trees of different species, between soil groups. However, the models described by Fraser and Gardiner (1967), and those in the new system described in Chapter 2, can not be used on their own to compare vulnerability to windthrow as they ignore the effects of variation in above-ground characteristics, such as between species in crown sail area and height growth.

In the 1970s and 1980s, a system was developed based on observations of windthrow, that allowed a simple prediction of the onset of windthrow. This is the Windthrow Hazard Classification ('WHC') (Booth 1977; Miller 1985) that can be used to estimate the 'critical' and 'terminal' heights of stands of trees on a particular site, based on windiness, exposure, elevation and soil. These are the heights at which damage would be expected to start, and at which the extent of damage would require clearance, respectively (Quine and Gardiner 1998). This system uses mostly wind climate and above-ground characteristics, and it avoids the use of any below-ground characteristics except soil type and drainage, which it interprets simply as rooting depth. Sites are scored based on wind zone (from a windiness map of Great Britain), elevation, Topex (degree of topographic exposure) and soil. Notably WHC takes no account of the variation of anchorage found by Fraser and Gardiner (1967), or that could be found by analysing the tree-pulling data from other species and site types that had been generated in a continuation of Fraser and Gardiner's tree pulling experiments in the late 1960s and 70s. Therefore the grouping of soils for estimation of root development in WHC ignored the differences in physical properties between these soils and took no account of the resulting large differences in anchorage between different soils of the same depth described in Chapter 2. Although the WHC system was a beneficial tool for the British forest industry in that it reduced losses to windthrow, over time it was found to be deficient in a number of ways. In particular WHC was pessimistic in its predictions, and its use resulted in premature harvesting of crops, i.e. before their optimum age of economic return and before they would now be expected to be damaged by wind. In addition, as it was prescriptive in its approach, it included no opportunity for the user to decide an appropriate level of risk for a particular forest stand (Quine and Gardiner 1998).

The WHC system was replaced in the 1990s with a more sophisticated decision support system, 'ForestGALES', that calculates the risk of windthrow to a stand (Quine and Gardiner 1998). Development of this model represented a substantial leap in understanding of windthrow. For the first time, the various strands of the windthrow process; the anchorage provided by the root system, the above-ground lever and sail area, and the wind climate and exposure of the stand, were incorporated into a single system. This provided a tool for the management of forest windthrow risk for the British Isles, that forest managers can use to compare developing risks to stands that have contrasting site, soil and environmental conditions. As the results are output as a return-time for a wind speed that is expected to damage the crop, the user is given the information needed to manage for the optimum combination of minimised windthrow and maximised economic return, without being forced to harvest at a fixed tree height. However, despite the advantages of ForestGALES compared to WHC, there remain some limitations to the underlying model that require attention.

Firstly, the regressions of critical turning moment against stem mass that are the basis for the anchorage module within ForestGALES were based on a simplistic analysis of the Forestry Commission tree-pulling data set, using soil groups that contained soils with very different physical properties, and made no distinction between trees that were deep and shallowly rooted. In addition, the analysis made no attempt to take into account the limited sample size for many of the minority species contained in the tree-pulling database, and used regression equations regardless of their significance. The analysis presented in Chapter 2 uses a more robust approach, making a logical separation between soil types and rooting depths, and compares minority species with Sitka spruce, which is still the dominant species in the data-set. This allows regressions for a particular conifer species to be used where there are adequate tree-pulling data, and where they are significantly different to Sitka spruce. But, where this is not the case, they can be replaced with the equivalent Sitka spruce regression equation until better data become available. The new soil grouping, rooting depth prediction, and corresponding critical turning moment against stem mass regressions in Chapter 2, should be implemented in a future version of ForestGALES.

Secondly, although ForestGALES takes topography into account in the calculation of wind climate, there was no attempt in its construction to allow for any topographic effects on root anchorage. All data in the tree-pulling data-set were derived from tree pulling experiments conducted on either horizontal or shallowly sloping sites, and so it was necessary in building the model to make the assumption that terrain had no effect on tree anchorage. However, as some aerial photographs of windthrow have shown relatively greater damage within steep-sided valleys, it was important that the hypothesis was tested that this damage resulted from funnelling of wind, as opposed to an inherently poorer anchorage due to altered root architecture on slopes. In the experiment described in Chapter 3, anchorage of Sitka spruce was found to be the same on a steep slope as on the horizontal, therefore supporting the assumption in ForestGALES. However, there were directional differences in anchorage that imply that trees may be less stable when exposed to a downslope wind than an upslope wind (Chapter 3). This finding conformed with the observed root asymmetry of the same trees described in Chapter 4, where the largest sector without structural roots was downslope. Existing models of tree anchorage (Blackwell *et al.* 1990, Coutts *et* *al.* 1999) would predict that such an asymmetry would result in a considerably reduced critical turning moment for downslope overturning. The anchorage effects of the asymmetry of root mass around these trees, with a greater concentration perpendicular to the slope, towards the west, remain to be quantified, as comparison of anchorage between the two across-slope directions was not part of the treatment structure. This should be investigated in further experiments, either by tree-pulling, or by modelling the changes in anchorage resulting from changes in root system asymmetry. As it stands, therefore, there is no evidence to suggest that ForestGALES will require any modification to allow for the topography of a stand. However, if directional differences in anchorage are confirmed by repetition of this experiment on other sites, there may be benefits of producing a version of ForestGALES in which risks are associated with, and can be varied according to, wind direction.

Thirdly, although ForestGALES allows the user to input thinning treatments that have been, or will be, applied to the stand, these are used only to adjust the wind loading and above-ground growth characteristics, and not to adjust the anchorage of trees. The results of Chapter 5 indicate that trees are continually responding to changes in their wind environment. As trees grow, their sail area, above-ground lever arm length, and hence wind motion, increases. As mean wind speed varies from year to year, so does tree motion. And when a stand is thinned, there is a sudden increase in wind motion at the same time as a large increase in above-ground growth. Without mechanisms to respond to changes in mechanical stress, tree survival would be limited in windy locations. The results presented in Chapter 5 represent a starting point in understanding the scale of above- and below-ground responses to changes in wind motion and light regime. They show increasing allocation to roots on the lee-side of a tree in response to increasing autumn wind speed, but only up to a point. Above a certain mean autumn wind speed, the response appears to remain constant. In addition, contrary to some previous studies, the results show rapid responses, both above- and below-ground, to changes in wind movement as a result of stand thinning. However, in the first year after thinning, above-ground growth was slightly reduced while there was a small increase in below-ground growth. In the second year after thinning there was a fast increase in radial growth both above- and below-ground but with a very much larger below-ground than above-ground response. These results indicate that trees alter their allocation of available assimilates to shoots and roots in response to changes in wind motion, and thereby re-stabilise themselves following stand thinning. This, in turn, implies that the anchorage of trees will be modified rapidly following stand thinning or respacing, a hypothesis that should be tested in future experiments, to facilitate the development of a dynamic model of tree anchorage.

Forest soil conservation

Research into tree anchorage has largely been stimulated by the practical problems and economic costs that result from trees being uprooted by the wind. A related area of practical importance is the stabilisation of soil on slopes by tree roots. Research on this topic has focussed on the nature of the root-soil bond (for example, Waldron and Dakessian 1981; Waldron and Dakessian 1982). However, the effects of trees on soil stability are more complex than this. Trees provide considerable protection to slopes by sheltering the slope surface from the direct effects of wind and rain, by extracting soil water through transpiration, and by holding soil on both fine and course roots (Keim and Skaugset 2003). The combined benefits provided by trees on vulnerable slopes can easily be demonstrated in many parts of the world where deforestation has led to massive soil loss (Sidle *et al.* 1985). To maintain these benefits in upland plantation forests that are actively managed, consideration should be given to soil conservation at all stages during planning, managing and harvesting. The ForestGALES decision support system is used by managers to minimise windthrow risk whilst optimising economic returns from timber. To do this, the manager must decide what level of risk he or she can accept and must always be prepared to accept some loss through windthrow. However, on steep slopes, the risk is not only the loss of timber and increased harvesting costs following windthrow, but also the risk of substantial soil loss from the site. The investigation presented in Chapter 3 predicts that for dense forest stands on steep slopes, where windthrow overturns root plates downslope, the potential downslope displacement of soil is in the order of 1800 m^3 ha^{-1} from the displaced soil-root plates alone, even before additional soil is displaced by erosion processes. This rate of soil loss is more than 1000 times the rate expected from standard forestry operations. As soil loss must be considered as an almost permanent degradation of the site, with considerably greater long-term consequences in terms of forest sustainability than windthrow, soil conservation should become the primary consideration on such sites. The results presented in Chapter 2 show that species choice, soil type, and rooting depth all influence anchorage. Therefore, these criteria may be used in conjunction with ForestGALES to decide how forest stands should be designed, established and managed on steep slopes. Species with relatively good predicted anchorage may be chosen for such sites, and the suitability of silvicultural treatments to be applied to them should be assessed based on the risks of windthrow and resulting soil loss. For example, particular care should be taken in applying thinning treatments or in respacing for conversion to continuous cover forestry (CCF) on vulnerable slopes. While CCF would, on the whole, be expected to be beneficial for soil conservation once established, the conversion process itself creates an immediate increase in windthrow risk. Therefore there is a strong argument for converting to CCF in a more sensitive manner on steep slopes, either by respacing when the trees are young enough not to show an increased windthrow risk, or by planting at an appropriate spacing to encourage natural regeneration and the development of an uneven-aged stand structure.

Models of tree root architecture

One research area that stands out from the work presented here, as requiring a substantial modelling effort, is the development of tree root architecture. There is clearly a requirement for methods to predict the development of root architecture in relation to establishment method, site type and forest management, to improve predictions of tree stability, below-ground carbon storage, and soil stability.

An improved understanding of root development is particularly important in understanding tree stability because the root system provides anchorage and structural support. Where rooting depth is limited by soil conditions, the radial symmetry of the structural root system becomes critical for anchorage (Coutts

1983b). Field observations have shown that root systems are often markedly asymmetric; for example, they develop less in the direction of plough furrows (Coutts *et al.* 1990) or nearby tree stumps (Prest *et al.* 1991; Quine *et al.* 1991). Even where there is no physical obstruction and the site is relatively even, root systems often have uneven development (Nicoll *et al.* 1995; Nicoll and Ray 1996). The analysis in Chapter 4 indicates that root asymmetry may result from both wind action on the tree and from the effects of steep terrain, and this appears to correspond with the directional instability of trees reported in Chapter 3. It must be remembered, however that not only the structural root part of the system, but also the fine roots, are necessary for tree anchorage. Fine roots hold the soil together within the soil-root plate and play a large part in defining the dimensions of the plate. They consolidate the soil within the plate, increasing the mass of the plate, and they act under tension to resist breakage of the soil at the edge of, and beneath, the plate. In a similar way, fine roots hold soil on slopes and enhance soil cohesion, thereby resisting landslips and soil erosion. In performing these functions, fine roots depend on the whole root system being held together by a structure of coarse roots, and it will therefore be necessary in future studies to consider ways to relate coarse root architecture to fine root mass. In addition to contributing to models that predict tree and slope stability, understanding the distributions of tree root sizes, and the ways that these distributions change with depth and vary between species and soil types, will be necessary in improving predictions of the accumulation of soil carbon (Kramer *et al.* 2004).

Modelling would be expected to improve our understanding of the many factors involved in root system development, and expose important areas where little is known. It should ultimately be possible to link a root development model to other mechanical models, for example the root anchorage model described by Blackwell *et al.* (1990), or to finite element models of root anchorage (Dupuy 2003; Fourcaud *et al.* 2003). It is therefore important that we start to collate the information on root system architecture and growth that will be required for modelling tree root system development. The internal and environmental factors that control the development, with respect to symmetry and rigidity, of shallow structural root systems are now fairly well understood, at least for Sitka spruce (Coutts *et al.* 1999). Much of the relevant research has been carried out on this species because of problems of windthrow in upland Britain and Ireland, but information on other species is increasingly available. For example, recent developments in the technology available for 3-D digitising of root architecture (see Chapter 4), and in the methods for coding root topology (Danjon *et al.* 1999b), have stimulated research into tree root architecture on a range of species (for example, Danjon *et al.* 1999a; Danjon *et al.* 2005; Di Iorio *et al.* 2005; Drexhage *et al.* 1999; Drexhage and Gruber 1998; Mickovski and Ennos 2002).

There would clearly be benefits to building a process based model that will predict tree root architecture parameters, based on inputs including site properties, soil type, cultivation, management regime, species, and climate. Such a model could be designed to provide outputs that would benefit a range of research areas including: tree establishment, afforestation of reclamation sites, conversion of stands to CCF, tree pathology, forest C sequestration, tree improvement, tree stability and slope stability.

A simple conceptual model has been developed that develops a woody root system, using physiological principles, as a set of roots that are variable in number and distribution around the stem, with mass and rigidity varying between and along them (Coutts *et al.* 1999). Using this as a basis, and with the addition of root branching, the root system may be modelled as a zone of competition for assimilates, where allocation to individual roots depends upon their position and local variations in conditions. Important factors to include will be the effects of changing soil conditions, such as the supply of mineral nutrients and water, on the growth of primary and woody roots, the effects of terrain on primary root growth and on secondary thickening, and the effect of mechanical stress on growth of the cambium. As root system development is also substantially influenced by site cultivation, drainage, spacing, thinning and slope, the model should use these silvicultural influences and constraints to modify the development of the system.

However, root system symmetry with respect to tree stability, should not only be considered in terms of the allocation of biomass between roots and their distribution round the tree. Allocation within each individual root also varies, producing shapes of significance to mechanical stability (Nicoll and Ray 1996). In a root development model, root size and shape should be defined so that stiffness can be calculated (see the 2nd moment of area calculation in Chapter 1) for the determination of the hinge position in a tree anchorage model, such as Blackwell *et al.* (1990).

One benefit from attempting to model a complicated system is to highlight areas where research is most needed. Even before commencing the construction of a root development model, there are some areas that obviously lack adequate data. In particular it will be important to define the relationships between the fine and coarse root architecture of trees, and to obtain quantitative data on the effects of climatic changes on structural root radial growth and development of cross-sectional shape.

Conclusion

Overall, our understanding of tree responses to wind is now at a stage where useful models can be developed that integrate the various parts of the processes involved. It is evident that above- and below ground processes and responses should be considered together. Each component of a tree is dependent on each of the others and an examination of the development of any component in isolation will miss a large part of the story. In a similar way, it is important that the processes involved in the windthrow of trees, including soil properties, development of root architecture and anchorage, stem properties, canopy structure, wind profiles, and climate, are considered together. By improving our understanding of the interactions between tree components, and by integrating the models that exist of the various processes involved in windthrow, we will be able to make reliable predictions of windthrow risk to a range of forest structures, and of how the risk will change in a changing climate.

Overall findings

1. Differences in anchorage between the range of coniferous tree species commonly grown in the British Isles, and their interactions with soil group and rooting depth, have been quantified for the first time. When implemented in decision support systems for forest stand management in relation to wind risk, the regressions of critical turning moment developed here will allow reliable predictions to be made of the return times to the critical wind speed required for windthrow. Revised risk assessments based on the new regression equations will result in modifications of forest harvesting schedules and timber production forecasts.

2. Anchorage of Sitka spruce was found to be similar between a steep slope and a neighbouring horizontal site with the same soil. However trees overturned significantly more easily downslope than upslope. The results indicate that the estimation of wind risk on complex terrain will be substantially improved by incorporating wind direction in relation to terrain into decision support systems

3. Root architecture was found to be influenced by terrain. The centres of root mass of trees on a steep slope were concentrated across slope toward the prevailing wind, while on the horizontal there was more root mass on the lee side of trees relative to the prevailing wind. The largest sector without roots on root systems on slopes was directed downhill. The architecture data from this study should be incorporated into models of soil holding by tree roots, to assist in the development of appropriate forest management techniques for soil conservation.

4. Measurements of soil displacement by trees overturned on steep slopes indicates that the risk of soil erosion on complex terrain following windthrow is considerably greater than from forest operations. The results indicate that steep forested slopes must be managed particularly sensitively, with the aim of minimising the risk of windthrow and therefore soil loss.

5. Analysis of tree development in a ‘thinning’ and ‘guying’ experiment showed that the largest proportion of assimilates were allocated to radial growth at the stem base, and in the structural roots, in response to increased mechanical stress following stand thinning. Allocation to the parts of the tree where stress is greatest, at the expense of height growth and thickening higher up the stem, will improve tree stability following stand thinning. Findings from this study should be used in the development of models to predict changes in wind risk to trees following the respacing of forest stands.

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8. Appendix

Published paper related to the thesis

Nicoll, B.C., A. Achim, S. Mochan and B.A. Gardiner 2005. Does sloping terrain influence tree stability? - A field investigation. Canadian Journal of Forest Research. 35: 2360-2367.

Does steep terrain influence tree stability? A field investigation

Bruce C. Nicoll, Alexis Achim, Shaun Mochan, and Barry A. Gardiner

Abstract: The anchorage of 40-year-old Sitka spruce (*Picea sitchensis* (Bong.) Carr.) trees grown in a plantation on a steep (ca. 30°) slope was compared with that of trees grown on an adjacent horizontal area. There was similar gleyed mineral soil on the sloping and horizontal areas. Trees were mechanically overturned using a winch, and anchorage was quantified by measuring load, stem angle, and tree dimensions. Trees on the slope were overturned upslope, downslope, or across-slope. Critical turning moments were calculated around the tree base and the actual hinge point. Critical wind speeds required to uproot or snap trees in this stand were modelled to compare the vulnerability of trees to upslope and downslope winds. No overall difference in anchorage was found between trees grown on the horizontal and sloping parts of the site. However, for trees on the slope, those pulled upslope showed significantly more resistance to overturning for a given stem mass than those pulled downslope. Critical turning moments calculated at the hinge point were smaller than those calculated at the stem base, but differences were small and had no effect on the comparison between treatments. Critical wind speeds for uprooting were estimated to be 28 $m\cdot s^{-1}$ for an upslope wind and 24 $m\cdot s^{-1}$ for a downslope wind on this site. The implications of these results are discussed in relation to windthrow-risk modelling and forest soil conservation.

Résumé : L'ancrage de tiges d'épinette de Sitka (*Picea sitchensis* (Bong.) Carr.) dans une plantation âgée de 40 ans établie sur pente abrupte (30°) a été comparé à celui d'arbres croissant sur une surface horizontale adjacente. Dans les deux cas, le sol était semblable, soit un sol minéral gleyifié. Les arbres ont été déracinés mécaniquement à l'aide d'un treuil et l'ancrage a été quantifié en mesurant la charge, l'angle de la tige et les dimensions de l'arbre. Les arbres situés en pente ont été déracinés vers le haut de la pente, vers le bas et perpendiculairement à la pente. Les moments de flexion critiques ont été calculés par rapport à la base de l'arbre ainsi que par rapport à la charnière de déracinement. Les vitesses de vent critiques nécessaires au déracinement ou au bris de la tige ont été modélisées pour comparer la vulnérabilité des arbres à des vents soufflant vers le haut ou vers le bas de la pente. Globalement, aucune différence d'ancrage n'a été constatée entre les arbres du site qu'ils croissent sur une surface horizontale ou en pente. Toutefois, dans le cas des arbres situés en pente, ceux qui ont été treuillés vers le haut de la pente étaient significativement plus résistants au déracinement que ceux qui ont été treuillés vers le bas pour une même masse de tige. Les moments de flexion critiques calculés à la charnière étaient inférieurs à ceux calculés à la base de la tige, mais les différences étaient faibles et n'avaient pas d'effet sur la comparaison entre les traitements. Sur le site étudié, les vitesses de vent critiques pour le déracinement ont été estimées à 28 $m\cdot s^{-1}$ pour un vent soufflant vers le haut de la pente et à 24 $m\cdot s^{-1}$ pour un vent soufflant vers le bas de la pente. Les répercussions de ces résultats sur la modélisation du risque de chablis et la conservation des sols forestiers sont discutées.

[Traduit par la Rédaction]

Introduction

Problems of managing forest stands in areas vulnerable to wind damage have necessitated the development of predictive models of windthrow, such as ForestGALES (Gardiner et al. 2004; Quine and Gardiner 1998), HWIND (Peltola et al. 1997), and WINDA (Blennow and Sallnäs 2004). Although in the development of these models local wind climate has been adjusted to allow for topography (Peltola et al. 1999; Suárez et al. 1999), the assumption is made that there is no difference in anchorage between trees growing on horizontal and sloping sites. However, aerial photographs of wind damage to forest plantations taken after storms have shown more damage to trees on slopes and valley sides in some areas compared with trees grown on more horizontal sites (C.P. Quine, personal communication, 1999). It is not clear if these observations result from localized variation in wind exposure, funnelling of wind in valleys (Savill 1983), mechanical differences in anchorage resulting from variation in root architecture, or a combination of these effects. A number of studies of tree anchorage have attempted to relate critical turning moments to measurable tree characteristics. All have shown good linear relationships between critical turning moment and stem mass, stem volume, or stem diam-

Received 24 January 2005. Accepted 7 July 2005. Published on the NRC Research Press Web site at http://cjfr.nrc.ca on 28 October 2005.

B.C. Nicoll,[1] A. Achim, S. Mochan, and B.A. Gardiner. Forest Research, Northern Research Station, Roslin, Midlothian, EH25 9SY, Scotland, UK.

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[1] Corresponding author (e-mail: bruce.nicoll@forestry.gsi.gov.uk).

Can. J. For. Res. 35: 2360–2367 (2005) doi: 10.1139/X05-157

eter for trees on particular soil types (for example, see Fraser and Gardiner 1967; Fredericksen et al. 1993; Moore 2000). These simple relationships can be used within windthrow models to predict tree vulnerability based on measured or predicted tree dimensions for particular defined soil and site conditions. In improving the accuracy of forest windthrow models, it is important that we test whether the anchorage of trees on slopes is different from that of trees on horizontal sites.

Understanding the stability of trees on slopes is also important for the development of models to predict soil loss and slope stability. Trees have a positive effect on soil stability on vulnerable slopes (O'Loughlin 1974; Swanston 1974) by reducing soil losses through erosion and shallow landslides. The network of coarse and fine tree roots close below the surface binds soil together, while sinker roots anchor the surface layers to the deeper, more stable soil mass (Zhou et al. 1997). However, windthrow of trees has a negative effect on soil stability and may be the most important factor in downslope movement of soil on many forested slopes (Schaetzl 1986). Soil from upturned root–soil plates on steep slopes is frequently deposited downslope of the original tree position as windthrown trees are harvested or the roots decompose (Beatty and Stone 1986). Recently disturbed, unconsolidated soil that is unprotected by vegetation can easily be eroded by surface water flow (Schaetzl et al. 1990), and water penetrating deeper soil horizons from craters formed under overturned root–soil plates may trigger shallow slides on unstable slopes (Swanston 1974). Increasing pressure on the forest industry to conserve soil and minimize sediment input to streams and water courses has led to calls for better assessments of the risk of soil loss from forested sites (Montgomery and Dietrich 1994).

Understanding the mechanics of tree anchorage on slopes will therefore improve the accuracy of predicting both economic loss and soil loss that can result from windthrow events. An important development in our understanding of tree stability on sloping terrain will be to describe anchorage in relation to the direction in which the wind blows during a storm, that is, upslope, downslope, or across-slope. Two hypotheses were tested in a field investigation: (1) trees on slopes are less stable than trees on horizontal terrain and (2) the stability of trees on slopes will vary with the direction of overturning. Trees on a steep (ca. 30°) slope were mechanically overturned either upslope, downslope, or across-slope and their resistance to overturning was compared with that of trees grown on a horizontal part of the site with similar soil. Critical wind speeds required to overturn these trees were calculated using the GALES method (Gardiner et al. 2000) modified for forest stands on slopes. Wind stability was compared among directions and a sensitivity analysis was performed to examine the relative influence of changes in parameters influenced by slope. In addition, measurement of uprooted root–soil plate dimensions allowed us to quantify the soil that could become available for erosion following windthrow of trees on sloping terrain.

Materials and methods

Site details

Thirty-six Sitka spruce (*Picea sitchensis* (Bong.) Carr.) trees were mechanically overturned in Leanachan Forest near Fort William, west Scotland (56°51.95′N, 4°58.40′W). The site was an almost uniform north-facing slope, 300 m wide and 25 m deep, with an inclination of between 26° and 33° and with horizontal areas at top and bottom. Trees were planted on the site in 1962 as 2-year-old "1+1" transplants. At the time of the investigation (November 2001), mean tree height was 22.3 m and mean diameter at breast height (DBH) was 23.4 cm. Trees were spaced, on average, 2.66 m apart, representing 1415 stems·ha^{-1} in plan view, which equated to 2.86 m between trees and 1225 stems·ha^{-1} parallel to the slope. Weather before and during the field investigation was wet, with periods of light to moderate rainfall. The soil on both the sloping and the horizontal areas was a mineral soil, classed as a surface-water gley (Kennedy 2002), with some induration in places. Typically, the soil profile consisted of a thin leaf litter over a gleyed humic loamy A horizon (15–25 cm thick) over a well-drained loamy B horizon (40–100 cm thick) that extended down to an induration or to rock. The soil had a predominantly silty loam texture. Wind, monitored on open moorland 1 km from the experiment site between 1988 and 1999, had a prevailing direction of 255° from north.

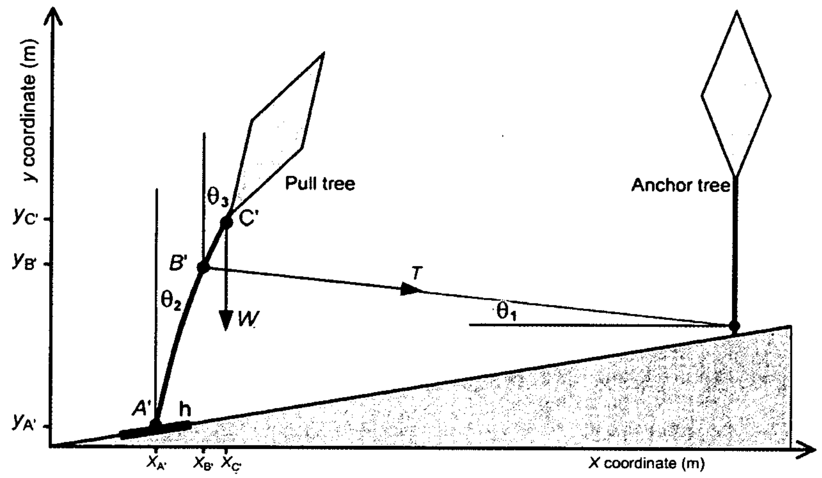
Treatments

We selected a total of nine trees for each of four pulling treatments: pulled across-slope, pulled downslope, pulled upslope, and pulled on the horizontal part of the site. In the across-slope treatment, four trees were pulled east and five were pulled west. In the horizontal treatment, trees were overturned in random directions. To obtain a consistent range of tree sizes in all pulling treatments, we selected three dominant, three codominant, and three subdominant trees for each treatment. For the purpose of sample selection, dominant trees were defined as being close to the upper quartile of DBHs of trees measured in tariff plots, subdominant trees had DBHs close to the lower quartile, and codominant trees had DBHs close to the median. Trees were selected randomly within these constraints from across the site.

Measurements and instrumentation

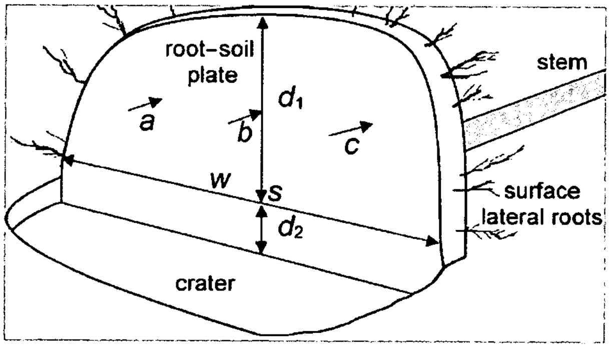
The site slope angle was measured around each selected tree, and digital biaxial clinometers (Applied Geomechanics, Santa Cruz, California, USA) were fixed to the stem 1.3 m above the base and at half tree height. Neighbouring trees were felled where necessary to avoid crown interference during tree-pulling. A chainsaw-powered winch (Habegger, Thun, Switzerland) was attached to an anchor tree using a 2 m long polyester round-sling (safe working load 5 t). Each anchor tree was selected to be more than one tree length in the selected direction from the pull tree. A load-cell (maximum load 3 t) was positioned on an 8.2 mm diameter steel cable between the winch and the pull tree. Both clinometers and the load-cell were connected to a data logger. To protect the operator when the tree was pulled downslope, the winch was offset by up to 90° by attaching a pulley block to another tree in the pull direction. The pulling cable was fixed to the pull tree with a polyester round-sling placed on the tree at approximately half tree height. The distance between the anchor tree and the pull, or offset, tree was recorded. The angle of the cable was measured from the winch attachment point (or pulley on the offset tree) to the attachment point on the pull tree (Fig. 1).

Fig. 1. Tree-pulling on a slope, showing an example of a tree being overturned upslope (not to scale), and the method for calculating the critical turning moment using a coordinate system. A, B, and C are the stem base, cable-attachment point, and centre of mass on the pull tree, respectively; T is the applied force; θ_1 is the angle of the pull cable, θ_2 is the stem-base angle, and θ_3 is the stem angle at half tree height.



After a zero reading was taken from the load-cell and both clinometers, the strain was taken up and the tree was pulled over using the winch. The tree stem angles, measured from the clinometers, were recorded by the data logger when the maximum load was reached. Once the tree was on the ground, crown spread was measured and instrument- and cable-attachment points were marked on the stem, as was the position of the lowest live-branch whorl. Live and dead branches were removed and weighed in bundles by hanging them from a weighing balance suspended under a 3 m high steel tripod. The height of the winch-cable attachment point, height of attachment of both clinometers, position of the lowest live-branch whorl, and height of the tree were then measured on the debranched stem. Stem diameters were measured at 1-m intervals up the stem from the base using measuring callipers with 1-mm resolution. A 1 m long central section of the stem was removed for green density (i.e., fresh mass per unit green volume) determination. The dimensions of the root–soil plate were then measured as shown in Fig. 2, that is, 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 soil depth at 3 points in a line across the plate at 0.5 × d_1. The edge of the plate was defined as being where soil was no longer held by the roots (see Fig. 2). The volume of the root–soil plate was estimated from these measurements, using the mean plate depth and assuming a half-ellipse shape for the area above the stem centre, and a rectangular shape below the stem centre.

Fig. 2. Measurement of the root–soil plate: plate 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.



Calculation of the critical turning moment

The relative positions (x, y coordinates in the vertical plane) of the base of the anchor tree, the hinge, the attachment point, and the centre of gravity of the pull tree were all determined for the moment in time when the maximum load was reached (Fig. 1). From these, the length of the complete lever arm (stem plus part of the root–soil plate) and an accurate measurement of the angle of the pull-cable at maximum load (θ_1) were calculated. The stem and root–soil plate were considered to be rigid for the purpose of this calculation. Critical turning moments were calculated at the stem base and the hinge point (h), excluding trees that snapped as they overturned. The inclination of the stem was taken to be the mean of angles at the tree base (θ_2) and at half tree height (θ_3) when the maximum load was reached. The average hinge distance was used for three trees for which the hinge distance could not be measured on site. Critical turning moments were calculated as follows:

$$[1] \quad M_{\text{applied}} = T_x(y_{B'} - y_{A'}) + T_y(x_{B'} - x_{A'})$$

$$[2] \quad M_{\text{total}} = M_{\text{applied}} + W(x_{C'} - x_{A'})$$

where $x_{A'}$,$y_{A'}$ represents the coordinates (m) of the stem base or hinge position, $x_{B'}$,$y_{B'}$ the cable-attachment point, and $x_{C'}$,$y_{C'}$ the centre of gravity of the tree at the time when maximum force was reached (see Fig. 1). M_{applied} (N·m) is the critical turning moment applied by the winch. T_x (N) and T_y (N) are the horizontal and vertical components of the applied force, respectively, calculated from the wire pull angle at the time when the maximum applied load was reached (Fig. 1). M_{total} (N·m) is the total critical turning moment of both the force applied by the winch cable and the force resulting from the overhanging weight of the leaning tree. W (N) is the total weight of the tree. The centre of gravity of each tree was calculated from the mass data from the tree sections, with the crown mass added at half crown depth.

Calculation of critical wind speed

Critical wind speeds at which average trees in a stand would uproot (U_{uproot}) or snap (U_{snap}) were calculated using the GALES method (Gardiner et al. 2000) for the treatments that showed significant differences in anchorage. This analysis was based on mean site conditions, that is, 22.3 m tall Sitka spruce with DBH 23.4 cm at a spacing of 2.86 m on a slope of 30°. These calculations assumed that only anchorage parameters varied between treatments. The equations given by Gardiner et al. (2000) for trees on flat ground were modified for slopes, and an idealized slope was assumed, where the wind flowed parallel to the ground and was not influenced by topographic obstacles. The maximum bending moment applied to the base of the average stem in a stand by an hourly averaged top wind speed in the canopy (u_h, m·s^{-1}) was calculated using the following equation:

$$[3] \qquad M_{max} = d\rho G\left[\frac{Du_h k}{\ln\left(\dfrac{h-d}{z_0}\right)}\right]^2$$

where d (m) is the zero plane displacement height, ρ (1.226 g·m^{-3}) is air density, G (dimensionless) is a wind-gust factor (the ratio of maximum to mean bending moment), D (m) is the average spacing between trees, k is Von Karman's constant (= 0.41), h (m) is canopy height, and z_0 (m) is aerodynamic roughness (Gardiner et al. 2000).

The constants k and ρ are not influenced by slope conditions. D is usually obtained from assessments of the number of trees per hectare, either from field surveys or aerial photography and assumes the ground to be horizontal. We therefore adjusted the calculation of D to make it representative of spacing across the real surface area of our sloping site. G may be expected to vary between horizontal and sloping terrain, and between parts of a slope, but as this variation has not been quantified, G was calculated as described by Gardiner et al. (1997) for horizontal terrain, assuming an airflow that is parallel to slope. The values of z_0 and d were derived from h and a frontal area index (λ, dimensionless) with simple analytical expressions developed by Raupach (1994). Rather than being the mean height of the trees, h_{slope} was the distance, perpendicular to the slope, between the top of the canopy and the ground; λ was calculated by dividing the crown area of the average tree, assuming a diamond-shaped crown profile (Gardiner et al. 2000), by the area of the surface the tree occupied on the ground.

A sensitivity analysis was performed to examine the percent changes in U_{uproot} and U_{snap} predicted using the GALES method that result from variations in parameters that may be affected by slope, that is, slope inclination, G, crown area, stand density, and stem deflection at maximum turning moment. Each parameter was increased and reduced by 20% as in Gardiner et al. (2000). Changes in crown area (±20%) were calculated using a proportional change in width and depth. Changes in stem deflection were increases or decreases in the tree's deflection from vertical at the time when maximum load was reached.

Statistical analysis

Means of above- and below-ground tree components were compared using one-way analysis of variance with "across-slope", "downslope", "upslope" and "horizontal" as the treatment structure. Critical turning moments were compared between treatments (excluding snapped trees) using linear regression analysis with stem mass as the covariate. Regression lines were compared as a-priori contrasts between trees pulled upslope, downslope, and across-slope, and between trees grown on the slope and on the horizontal.

Results

Most trees in all treatments were uprooted, exposing a well-defined root–soil plate, but the stems of three trees pulled across-slope and two from each of the other treatments snapped as they were winched over. Aboveground characteristics were similar among trees subjected to the different pull treatments (Table 1). The root–soil plate depth of trees pulled downslope was greater than the depth of those in the other treatments ($p = 0.02$). The estimated volume of the root–soil plate (Table 1) was greatest for trees pulled downslope and smallest for trees pulled upslope ($p = 0.04$). The overall mean root–soil plate volume was 1.44 m^3.

The effect of the treatments on the relationship between critical turning moment, calculated at the stem base, and stem weight is shown in Fig. 3 and Table 2. The intercept terms of the regressions were not significantly different from zero and were removed to correspond to the convention in previous tree-anchorage studies (for example, see Peltola et al. 2000; Achim et al. 2005).

For a given stem weight, no significant difference in the critical turning moment was found between trees on horizontal ground and those on slopes, that is, the average of across-slope, downslope, and upslope ($p = 0.98$). However, significantly smaller moments (Fig. 3, Table 2) were required to uproot trees downslope than upslope ($p < 0.05$). The critical turning moments calculated at the hinge point of the root–soil plates were slightly smaller than those calculated at the base of the stem for all treatments, but the ranking remained the same, with the upslope treatment having the largest moments and the downslope treatment having the smallest moments. The hinge : stem base ratio of critical turning moments for the average tree was 0.91, 0.96, 0.90, and 0.97 for the across-slope, downslope, horizontal, and upslope treatments, respectively.

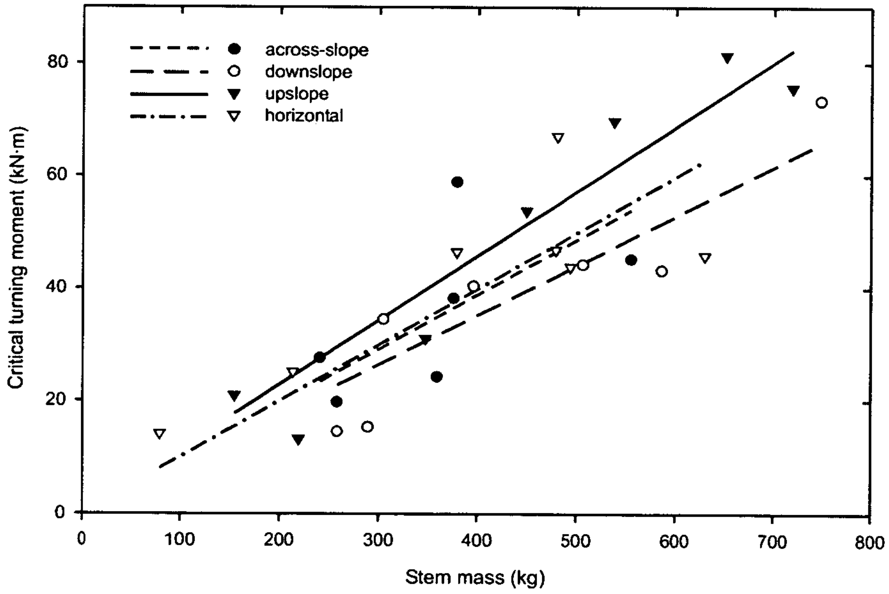
As the only significant difference between critical turning moments was between trees pulled up- and downslope, critical wind speeds for overturning were calculated separately for trees pulled in these directions and for all treatments combined (Fig. 4). Although there was predicted to be little difference in the wind speed required to snap trees upslope

Table 1. Tree characteristics and mean critical turning moments calculated at the stem base for different pull treatments.

	Across-slope		Downslope		Upslope		Horizontal		
Characteristic	Mean	SE	Mean	SE	Mean	SE	Mean	SE	*p*
Above ground									
Tree height (m)	22.69	0.50	22.89	0.47	22.95	0.84	20.82	1.02	0.16
DBH (cm)	23.0	1.5	22.9	1.6	22.4	1.3	23.4	1.5	0.96
Crown diameter (m)	3.08	0.29	3.07	0.14	3.01	0.28	3.29	0.21	0.85
Crown depth (m)	11.98	0.75	12.86	0.70	12.22	0.81	11.24	0.71	0.50
Stem volume (m^3)	0.45	0.07	0.46	0.07	0.46	0.07	0.42	0.06	0.97
Total stem mass (kg)	422.9	63.7	405.6	60.7	421.5	64.7	368.2	57.0	0.91
Live crown mass (kg)	66.7	13.7	69.5	14.4	68.3	13.7	69.9	15.4	1.00
Dead crown mass (kg)	15.1	1.9	19.2	3.9	21.0	4.0	25.5	4.4	0.27
Shoot mass total (kg)	504.6	77.1	494.3	75.8	510.8	79.3	463.6	73.6	0.97
Stem wood density ($kg \cdot m^{-3}$)	945.2	24.9	880.0	28.0	907.3	25.0	849.3	36.1	0.13
Below ground									
Max. root depth (m)	0.94	0.10	1.24	0.14	0.92	0.07	0.89	0.07	0.06
Depth of root–soil plate (m)	0.66	0.11	0.78	0.11	0.43	0.04	0.48	0.04	0.02
Area of root–soil plate (m^2)	2.40	0.47	2.52	0.22	1.90	0.37	3.05	0.49	0.25
Volume of root–soil plate (m^3)	1.42	0.21	2.01	0.36	0.82	0.18	1.51	0.28	0.04
Distance of hinge from stem centre (m)	0.57	0.06	0.48	0.04	0.59	0.07	0.70	0.08	0.17
Critical turning moment									
Applied critical turning moment at stem base (kN·m)	38.818	7.452	28.992	5.444	38.640	6.567	34.249	4.632	0.64
Total critical turning moment at stem base (kN·m)	46.987	8.763	36.501	6.390	47.933	8.427	40.152	5.065	0.64

Note: Values are given as the mean and standard error (SE). *F* test *p* values from ANOVA are given for the comparison between means. The sample size is $n = 9$ per treatment for aboveground characteristics; sample sizes for the other characteristics are given in Table 2.

Fig. 3. Linear regressions of critical turning moment at the stem base against stem mass. Data exclude trees that snapped during overturning, and all regression lines are fitted through zero.



(26.5 $m \cdot s^{-1}$) and downslope (26.8 $m \cdot s^{-1}$), a considerably greater wind speed would be required to uproot trees upslope (27.7 $m \cdot s^{-1}$) than downslope (23.6 $m \cdot s^{-1}$). For all treatments combined, U_{uproot} was predicted to be 25.1 $m \cdot s^{-1}$ and U_{snap} to be 25.5 $m \cdot s^{-1}$.

The sensitivity analysis (Table 3) predicted a relatively small (<3%) increase or decrease in U_{uproot} and U_{snap} from ±20% changes in crown area and stem deflection. Changes of ±20% in the slope angle were predicted to cause a <7% increase or decrease in critical wind speed. The method was

Table 2. Number of trees uprooted (excluding snapped trees), coefficient of the linear regression of critical turning moment against stem mass, and R^2 for each treatment.

Pull treatment	No. of trees uprooted	Coefficient	R^2
Across-slope	6	89.4	0.24
Downslope	7	83.7	0.84
Upslope	7	110.4	0.91
Horizontal	7	88.6	0.39

most sensitive to changes in G and stand density, and ±20% changes in these parameters were predicted to alter critical wind speed by up to 11%.

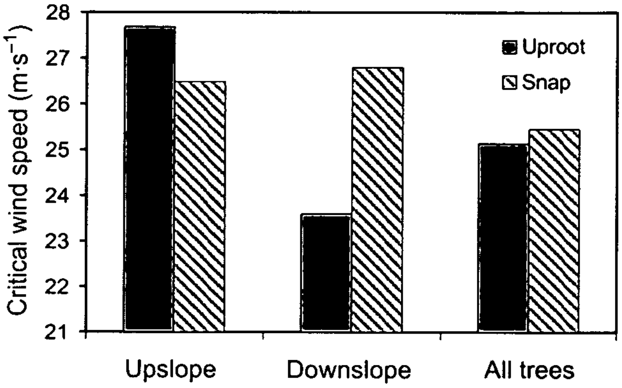
Discussion

There was no overall difference in the critical turning moments of trees on horizontal and steeply sloping terrain. Based on these findings, therefore, we have evidence to reject our first hypothesis and confirm the implicit assumptions in predictive models of windthrow (Quine and Gardiner 1998; Peltola et al. 1999; Blennow and Sallnäs 2004) that regressions of critical turning moment against stem mass remain unaltered by the terrain on which the stand is located, provided that soil type is constant.

Trees in this study were significantly more vulnerable to uprooting downslope than upslope, and the difference in critical turning moment was of the order of 25%. This supports our second hypothesis, that the stability of trees on slopes will vary with the direction of overturning. Increased anchorage of trees when a force is applied in an upslope compared with a downslope direction provides trees with better resistance to the stronger winds that tend to occur on the windward face of a hill. Mean wind speeds on sites on hilly terrain will tend to be lower in a downslope than in an upslope direction, owing to the shelter effect on the lee side of hills. Airflow tracks the slope closely on the windward side of a hill as the wind travels upslope, but the flow commonly separates from the slope on the lee side. As a result, wind speeds are reduced in the "wake" region and wind direction can sometimes be reversed if a "separation bubble" forms below the separated flow on the lee side (Finnigan and Brunet 1995).

Root–soil plate volume and depth were less for trees overturned upslope than for those overturned downslope, directly reducing two of the components of tree anchorage defined by Coutts (1986): root–soil plate mass and soil strength. The increase in resistive turning moment of upslope trees must therefore result from increases in either, or both, of the remaining two components identified by Coutts (1986), that is, the pull-out resistance of roots and the resistance to bending of structural roots at the "hinge". Therefore, the observed difference between upslope and downslope anchorage could result from increased root growth on the downhill side of the tree, providing better combined pull-out resistance of roots on the windward side of the tree. Alternatively it may result from relatively greater structural root development on the upslope side, with a corresponding increase in rigidity that would move the hinge point farther from the tree and, hence, increase the resistive turning moment (Stokes et al. 1997; Coutts et al. 1999; Achim et al. 2003). As structural root mass has been found to be greater on the lee side of wind-exposed trees (Nicoll and Ray 1996), we might expect to find more root mass on the upslope side of exposed trees on slopes. Therefore, adaptations of the root system in response to wind could explain the increase we found in resistance to upslope overturning. The architecture of the excavated root systems from this site was measured and will be described in a subsequent paper. It is worth remembering that this study examined the stability of trees on only one site that was north-facing and may therefore have been relatively sheltered. Future studies should examine trees grown on sloping sites that have more exposed aspects.

Fig. 4. Critical wind speeds required to uproot and snap average trees on the site calculated using the modified GALES method and compared between those pulled upslope and downslope and all treatments combined.



The small decrease in critical turning moment calculated at the hinge point compared with the stem base results from differences in the length and angle of the lever arm induced by repositioning of the rotation point. Ideally, tree anchorage should be calculated at the position of the hinge rather than at the stem base, because this most accurately represents the moment resulting from soil and root resistance. However, when determining critical wind speed it is important that turning moments are compared at a standard point, and turning moments calculated at the tree base (as in Fig. 1) are most useful for comparison in risk-assessment tools such as ForestGALES.

In this study, U_{snap} was the same for trees pulled up- and downslope, but U_{uproot} was greater upslope than downslope. This indicates that in storms where critical wind speeds are reached, more trees on this site may be snapped than uprooted in an upslope wind, while more may be uprooted than snapped in a downslope wind. However, an improved understanding of tree breakage and further modelling of the mechanics of tree stability on slopes are required to confirm these findings.

Our sensitivity analysis used the GALES method (Gardiner et al. 2000) to reveal the relative importance of each input parameter that is affected by slope. The smallest effect on critical wind speed was caused by changes in stem deflection at the time of maximum load. This indicates that there was little effect of rotating the stand on the sloping site

Table 3. Sensitivity of the prediction of critical wind speed for uprooting (U_{uproot}) and snapping trees (U_{snap}) to ±20% changes in factors that may be affected by slope, using the modified GALES method and based on mean characteristics for the site.

		U_{uproot}		U_{snap}	
Variable	% change	Upslope	Downslope	Upslope	Downslope
Slope	+20	6.0	5.9	6.4	6.4
	−20	−4.4	−4.3	−4.7	−4.6
Gust factor (G)	+20	−8.1	−8.1	−8.2	−8.2
	−20	11.0	11.0	11.0	11.0
Crown area	+20	2.5	2.5	2.4	2.4
	−20	−2.9	−3.0	−2.8	−2.8
Stand density	+20	10.6	10.6	10.5	10.5
	−20	−11.4	−11.4	−11.3	−11.3
Stem deflection	+20	1.8	1.8	1.9	1.9
	−20	−2.0	−2.0	−1.9	−1.9

to be horizontal for the purpose of calculating critical wind speed. Equally, our simple estimation of crown area, using a diamond shape, appeared to be adequate, as a 20% change in crown area resulted in a change of only <3% in critical wind speed. Of the remaining parameters, slope and stand density were relatively important in the calculation, but should be measurable with a high level of precision. The other remaining parameter, G, the gust factor, made the most important contribution to the calculation, with a change of up to 11% in critical wind speed resulting from a 20% change in G. As our calculation assumed G to be the same on a slope as on horizontal terrain, the sensitivity analysis indicates that measurement or modelling of G in complex terrain should have high priority in future tree-stability research.

The findings of this study also have implications for soil conservation and for the prediction of soil loss from forest sites during and following storm events. In some forest areas, the greatest loss of soil from forest sites is reported to result from root–soil plate overturning during windthrow (Schaetzl 1986; Schaetzl et al. 1990). On our experimental site, average root–soil plate volume was calculated to be 1.44 m^3. The average calculated root volume of trees on this site was 0.11 m^3 (B.C. Nicoll, S. Berthier, A. Achim, K. Gouskou, F. Danjon, and L.P.H. van Beek, unpublished data), that is, 7.6% of the total root–soil plate volume, leaving 1.33 m^3 soil per root–soil plate. Therefore, the potential volume of soil displaced on this sloping site with 1415 $\mathrm{stems{\cdot}ha^{-1}}$ if all trees were uprooted is in the order of 1882 $\mathrm{m^3{\cdot}ha^{-1}}$. This is the maximum volume of soil that could be displaced downslope from root–soil plates if all trees were uprooted during a storm, and if none of the soil was to fall back into the craters. However, the volume of soil lost from the site may be expected to be greater if the initial disturbance was to lead to further erosion or slope instability, as described by Swanston (1974).

Displacement of soil as root–soil plate overturn will have some benefits for subsequent regeneration and growth of stands, in that the inversion of plates and mixing of soil (Schaetzl 1986) can provide nutritional benefits to trees planted or grown from seed on the site (Clinton and Baker 2000; Ruel and Pineau 2002). Overturning of root–soil plates can also contribute to accumulation of carbon in mineral-soil horizons (Kramer et al. 2004). However, soil conservation is a vital part of sustainable forestry practice (Carling et al. 2001), and the loss of large quantities of soil from forest stands on sloping terrain, with related damage to the ecology of water courses (Nisbet 2001; Stott and Mount 2004), should be avoided where possible (Forestry Commission 1993). The potential for increased soil erosion associated with extensive windthrow indicates that less risk of overturning should be tolerated on steeply sloping terrain, and this in turn has implications for the structure of forests that should be maintained in such areas.

Acknowledgements

We thank the following for their considerable contributions to the fieldwork, often in particularly unpleasant weather conditions: Juergen Boehl, Alasdair Blain, David Clark, James Duff, and Colin Gordon. Thanks are extended to Andrew Kennedy for classifying the soil on the site and Andrew Peace for statistical analysis of the tree-anchorage data, and to Duncan Ray, who provided helpful comments on the manuscript. Thanks are also extended to staff at the Forest Enterprise Lochaber district office at Torlundy for their cooperation with the work in Leanachan Forest. This investigation was funded by the UK Forestry Commission and the European Commission as part of the "Ecoslopes" project "Eco-engineering and conservation of slopes for long-term protection against landslides, erosion and storms" (QLK5-2001-00289).

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