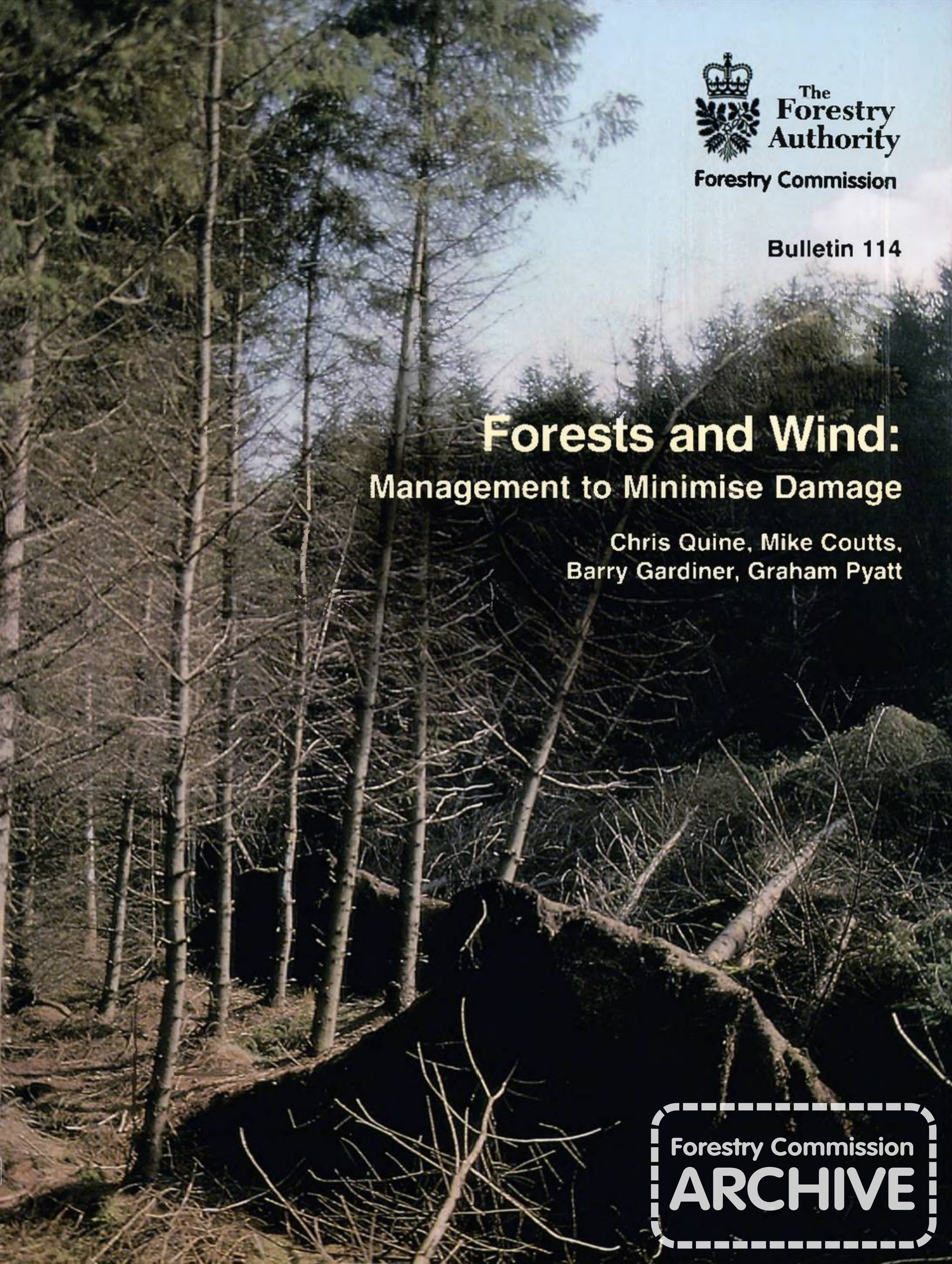

The Forestry Authority

Forestry Commission

Bulletin 114

Forests and Wind:

Management to Minimise Damage

Chris Quine, Mike Coutts,
Barry Gardiner, Graham Pyatt

FORESTRY COMMISSION BULLETIN 114

Forests and Wind: Management to Minimise Damage

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Front cover: Windthrow of 30-year-old Sitka spruce on a peaty gley soil in mid Wales. (C.P. QUINE)

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Summary

Wind damage is a serious threat to managed forests because it results in loss of timber yield, landscape quality and wildlife habitat. The most common form of wind damage in Britain is windthrow in which both stem and roots overturn. Prediction and prevention of wind damage have been important elements of forest management, and the windthrow hazard classification has been widely used to guide the selection of strategies. However, it is not possible to encompass all the knowledge of wind damage within a simple predictive system, or to detail advice for every set of circumstances that a forest manager may have to address. This Bulletin seeks to guide management by presenting a brief but comprehensive review of why and how storms damage trees, and the measures that can be adopted to mitigate such damage.

The principles of wind damage are elaborated in sections covering wind, soils, mechanics of wind damage, root anchorage, adaptive tree growth, and interactions and risk. These principles are then used to identify a series of silvicultural measures that a forester may adopt to reduce the extent of wind damage. The measures are listed by the main management stages of an upland coniferous forest but should be applicable to any type of woodland. The stages identified are establishment (site preparation, initial spacing and planting), tending (manipulation of spacing, edges and drain maintenance), and felling (coupe design and forest design plans). Main technical terms are defined in the Glossary and the Further reading section provides sources of additional information by specific topic.

Résumé

Les dommages causés par le vent constituent une menace sérieuse pour les forêts gérées du fait qu'ils entraînent une diminution du rendement en bois, de la qualité du paysage et de l'habitat des animaux sauvages. En Grande-Bretagne, la forme la plus courante de dommages causés par le vent est le déracinement avec renversement du tronc et des racines. Comme la prédiction et la prévention des dommages causés par le vent constituent d'importants éléments de la gestion forestière, la classification effectuée sur les risques de déracinement est très utilisée lors de la sélection des stratégies. Néanmoins un simple système de prédiction ne peut en aucun cas renfermer toutes les connaissances accumulées sur les dommages causés par le vent ou offrir des conseils détaillés qui soient adaptés à toutes les situations auxquelles le gestionnaire de la forêt peut avoir à faire face. Ce Bulletin vise à guider le gestion en présentant un bilan bref mais complet des raisons pour lesquelles les tempêtes endommagent les arbres et la façon dont cela arrive, en suggérant des mesures qui pourraient être adoptées pour atténuer de tels dommages.

Les principes de l'endommagement par le vent sont expliqués à l'aide de sections traitant du vent, des sols, du mécanisme de l'endommagement par le vent, de l'ancrage des racines, de la croissance adaptative des arbres, ainsi que des interactions et risques. On a utilisé ces principes pour identifier une série de mesures sylvicoles pouvant être adoptées par le forestier pour réduire l'importance des dommages causés par le vent. Ces mesures, bien qu'elles soient énumérées pour répondre aux principales étapes de gestion d'une forêt de conifères sur un site élevé, devraient pouvoir être appliquées à tout type de forêt. Les étapes identifiées sont l'établissement (préparation du site, espacement et plantation initiale), l'entretien (manipulation de l'espacement, lisières, entretien des fossés) et l'abattage (le plan de la coupe, les prévisions concernant le plan de la forêt). Un lexique donne la définition des principaux termes techniques et des sources d'informations complémentaires sont fournies par sujet particulier.

Wald und Wind: Forstwirtschaft zur Minimalisierung der Schäden

Zusammenfassung

Windschäden stellen eine große Bedrohung für Wirtschaftwald dar, da sie zum Verlust von Holzerträgen, Landschaftsqualität und Lebensräumen führen. Die häufigste Form von Windschaden in Britannien ist Windwurf bei dem sowohl Stamm als auch Wurzelwerk betroffen sind. Vorhersage und Vermeidung von Windschäden sind wichtige Elemente der Forstwirtschaft und die Windwurfgefahr Klassifizierung ist umfangreich verwendet worden, um die Wahl der Strategien zu erleichtern. Es ist jedoch nicht möglich all das vorhandene Wissen über Windschäden in einem einfachen Vorhersagesystem zu beinhalten, oder detailierten Rat für alle möglichen Umstände zu geben, die ein Forstwirt antreffen könnte. Dieses Bulletin versucht der Verwaltung behilflich zu sein, indem es einen kurzen aber umfangreichen Überblick gibt wie und warum Stürme Bäume beschädigen und welche Maßnahmen unternommen werden könmen um den Schaden zu verringern.

Die Prinzipien der Windschäden werden in Sektionen erläutert die Wind, Böden, Mechanik des Windschadens, Wurzelverankerung, angepasster Baumwuchs und Wechselwirkung und Risiko behandeln. Diese Prinzipien werden dann benutzt um eine Reihe von forstwirtschaftlichen Maßnahmen darzulegen, die der Forstwirt unternehmen kann um den Ausmaß des Schadens zu verringern. Die Maßnahmen werden unter den Hauptpflegephasen eines Hochland Nadelwaldes aufgeführt, sollten sich aber für jede Waldart verwenden lassen. Die Phasen die beschrieben werden sind Etablieurung (Standortvorbereitung, anfängliche Pflanzung und Abstände), Pflege (Änderung der Abstände, Ränder und Drainagepflege) und Fällung (Planung des zu fällenden Abteils, Waldaufbauformen). Die wichtigsten technischen Ausdrücke werden in einem Wörterverzeichnis erklärt und ein Quellenverzeichnis für weitere Information ist beeinhaltet.

Chapter 1
Introduction

Wind damage is a serious threat to managed forests because it results in loss of timber yield, landscape quality and wildlife habitat. The economic impact is particularly severe in semi-mature forests that are growing rapidly; each year of additional growth can bring substantial increases in total timber volume, average tree size and value. Damage reduces the yield of recoverable timber and increases the cost of harvesting the trees. Forest design requires varied age classes and habitats and retention of stands beyond economic maturity; it must take into account the potential for wind damage and the extent to which treatment of the stands could restrict the damage.

Records of wind damage to trees in Britain exist from as early as the 13th century. Storms in the late 19th century caused serious windthrow and resulted in glutted markets. However, the expansion of forest cover during the 20th century has taken place on uplands marginal for agriculture, where there was no historical record to indicate the likely extent of wind damage. As the earliest of the new forests began to mature, damage was caused by extreme storms, but it also became evident that some forests were vulnerable to normal winter gales.

Damage due to wind can take many forms, and be exacerbated by other conditions, for example wet snowfall or salt deposition (Plate 1). Leaves may be *abraded*, causing subsequent desiccation; young trees may *socket*, that is become loosened around the root collar by swaying, and in extreme cases *topple* due to inadequate rooting; leaders, branches and crowns may *break*; older trees may be *windthrown* when stem and root plate overturn (Plate 2), or may experience *windsnap* when the stem fails above ground level (Plate 11). In British conditions it is windthrow and windsnap that are most common and most serious; although windsnap is visually striking, and can be locally severe, it is usually less frequent than windthrow. In the remainder of this Bulletin wind damage is taken to be synonymous with windthrow unless stated otherwise.

Research on windthrow in Britain began in the early 1960s and from the start researchers sought both to prevent and predict the damage. Preventive treatments were tested on soils and trees, and a local ranking of sites was the first attempt at prediction. In 1977 a national predictive system, the windthrow hazard classification, was introduced. This classification was widely adopted throughout the forest industry, particularly to guide investment in new forests and to help forecast timber production from maturing forests. It also extended the basis for site selection and the choice of site preparation methods, thinning methods and rotation length. Improvements to the classification have recently been made and further developments are planned. The classification is summarised in the Appendix.

It is not possible, however, to encompass all the knowledge of wind damage within a simple predictive system, or to discuss all the preventive strategies that a forester may have available. This Bulletin seeks to guide management by presenting a brief but comprehensive review of our understanding of why and how storms damage trees, together with suggestions for a series of measures to reduce the extent of the damage. Other management pressures will determine which of the suggested measures are appropriate to a particular forest. The measures are organised around the main management stages of an upland coniferous forest, but should be applicable to any type of woodland. Selected terms are explained in the Glossary.

Chapter 2

Principles of wind damage

Wind

Britain has a severe wind climate compared to most of the world, including the rest of Europe (see Figure 2.1). Strong winds typically result from the passage of Atlantic depressions and only very rarely originate from thunderstorms, tornadoes or squalls. Approximately 150 depressions affect Britain per year, forming in the Atlantic (on the polar front) and crossing from west to east. Circulation of air around a depression is anti-clockwise and the strongest winds are commonly found to the west and south of the centre of the low pressure. The track of each depression is determined by the position of origin and the pattern of the general pressure field. Most depressions track to the north and west of Britain and their cumulative influence is responsible for the tendency to stronger winds in northern Britain. Winds are generally strongest in winter months, but there is substantial variability in the timing and magnitude of storms from year to year.

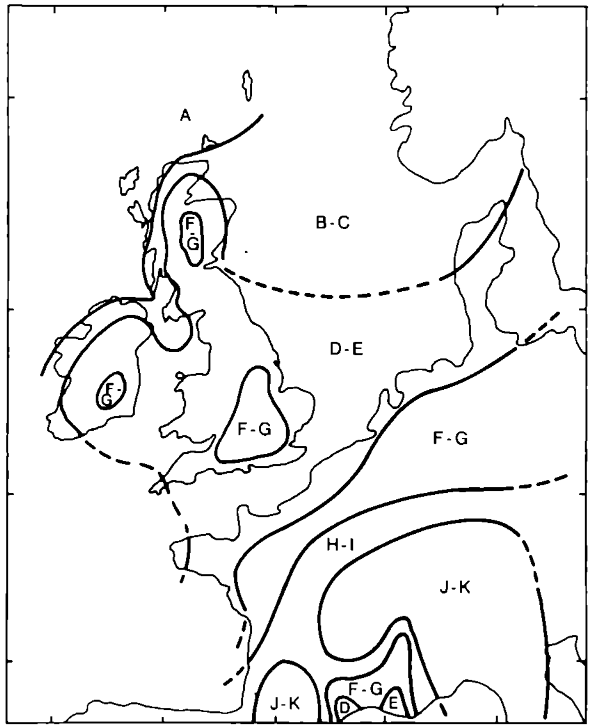


Figure 2.1 Wind zonation of Europe in the manner of the zonation of Britain included in the windthrow hazard classification. This is on scale of A (most windy) to K (least windy).

Among the notable storms which have affected Britain's forests are those that occurred on 31 January 1953, 15 January 1968, 2 January 1976, 16 October 1987 and 25 January 1990. These resulted in up to 30% destruction of the forest stock in the affected areas (Table 2.1, Plate 3). Windthrow due to less extreme storms (Plate 4) accounts for approximately 15% of the annual production of Britain's forests but the stochastic nature of storm occurrence means that the degree of wind damage can vary significantly from year to year. A succession of quiet winters can be followed by a sequence of winters with very damaging storms (Figure 2.2). The occurrence of a particularly severe storm in one year does not modify the chance of the same intensity of storm occurring in the following year.

Close to the earth's surface the wind is turbulent because of the drag caused by the ground over which the air is moving; the rougher the surface the more turbulent is the air. Forests form a particularly rough surface and the wind over them is much more turbu-

Table 2.1 Summary of data for catastrophic storms affecting Britain since 1945

Date of storm	Area affected by 36 m s^{-1} gusts (km^2)	Max. gust recorded (m s^{-1})	Mean of max. gusts recorded within 36 m s^{-1} zone (m s^{-1})	Volume of windthrown timber (m^3 x 10^6)	Growing stock windthrown (%)
31 January 1953	370	50	43	1.80	10–25
15 January 1968	510	52	43	1.64	15–30[b]
2 January 1976	890	47	39	0.96	<5
16 October 1987	220	51	41	3.91[a]	13–24
25 January 1990	690	48	39	1.26[a]	1–3

[a] Known to include non-woodland trees.
[b] Percentage of crops aged 31 years and over.

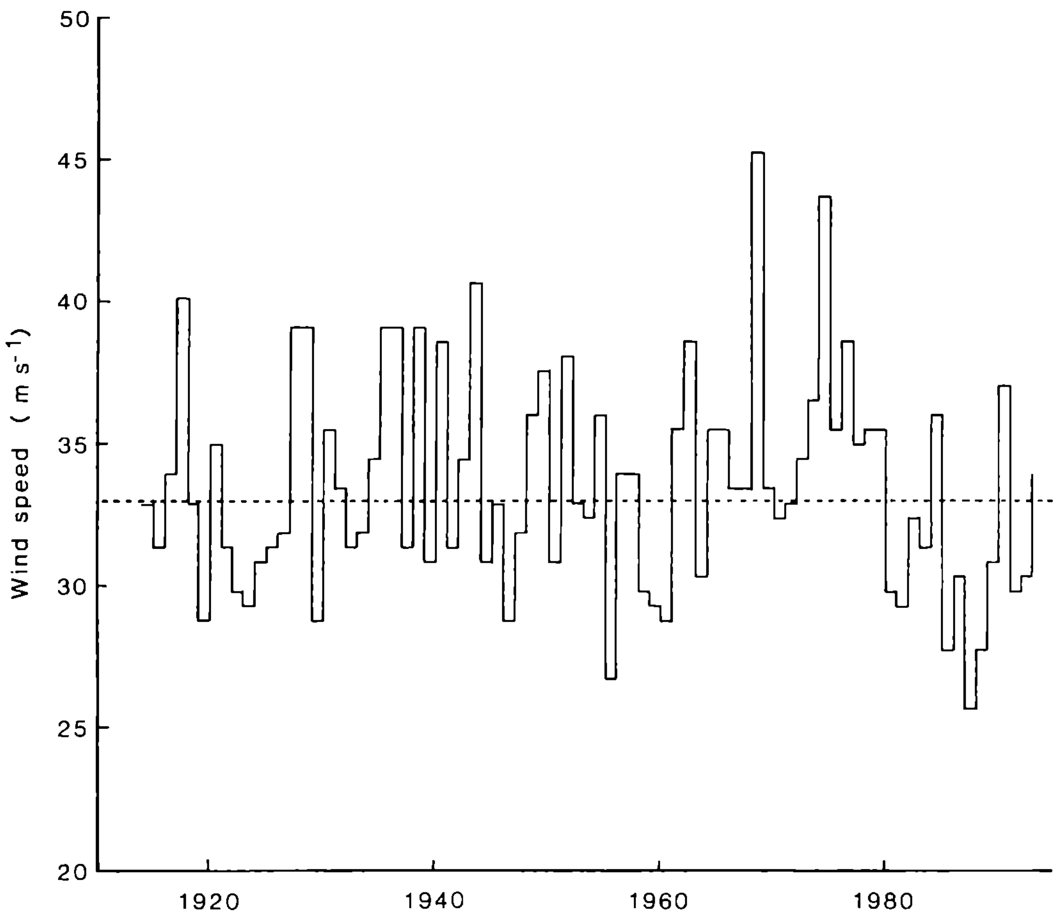


Figure 2.2 Annual maximum gust (m s^{-1}) at Eskdalemuir Meteorological Office Station from 1914 to 1993, demonstrating the variation in wind speed that can occur from year to year. The dotted line shows the period mean for these annual maxima. Eskdalemuir Observatory is an inland site in the southern uplands of Scotland at an elevation of 259 m, and therefore broadly representative of many upland forests.

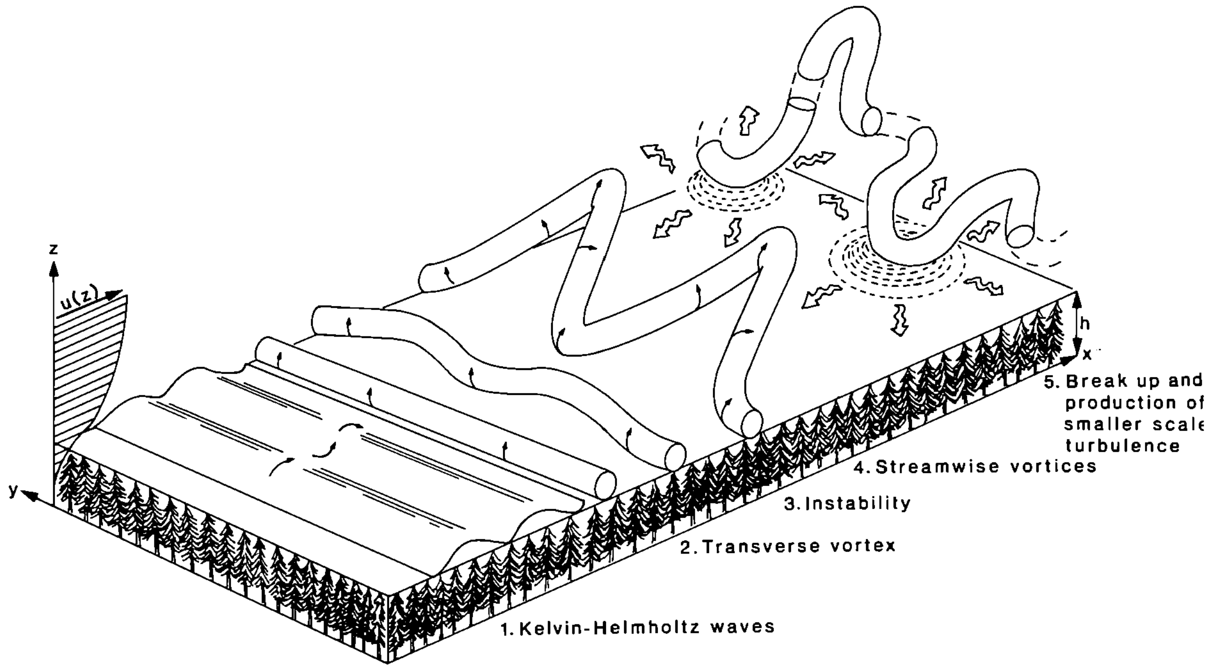


Figure 2.3 Idealised diagram of the formation of coherent gusts over a forest. (After Finnigan and Brunet, 1994.)

1. The rapid change of wind speed (u) at the top of the canopy ($z = h$) is unstable and leads to the emergence of Kelvin-Helmholtz waves.
2. The waves become transformed into across wind vortices.
3. These vortices are unstable and begin to distort.
4. The distortion produces coherent gusts aligned in the direction of the wind. The gusts propagate across the forest and if strong enough lead to wind damage.
5. Eventually the gusts become distorted and break up.

lent than over farmland. The turbulence is organised into coherent gusts that move for large distances over the forest (Figure 2.3). Similar wind features can be seen moving like waves across cornfields on a windy day. Each gust consists of a rapid increase in wind speed together with downward movement of air into the canopy. These gusts are the main cause of damage in forests, with the strongest gusts exerting a force on the trees up to ten times larger than that due to the mean wind.

Changes in the nature of vegetation or sudden changes in its height induce additional turbulence and acceleration of the wind. Upward deflection of the wind by forest edges formed by rides, roads and other open ground tends to increase damage at a distance equivalent to a few tree heights inside the forest where the air returns towards the ground. The wind force on trees close to a forest edge is also substantially greater than that on trees inside the forest, so that trees suddenly exposed by the formation of a new edge will become more vulnerable.

Topography determines where the strongest winds within a region are found, for example on ridge tops and west-facing slopes. Wind speed also increases with elevation and proximity to the sea. In complex terrain the topography can alter the wind speed and direction significantly with wind accelerating over hilltops and being funnelled through valleys. Trees on the windward lower slopes of a hill will tend to reduce the wind strength at the hilltop (Figure 2.4). This may allow tree planting towards the top of a hill which would not

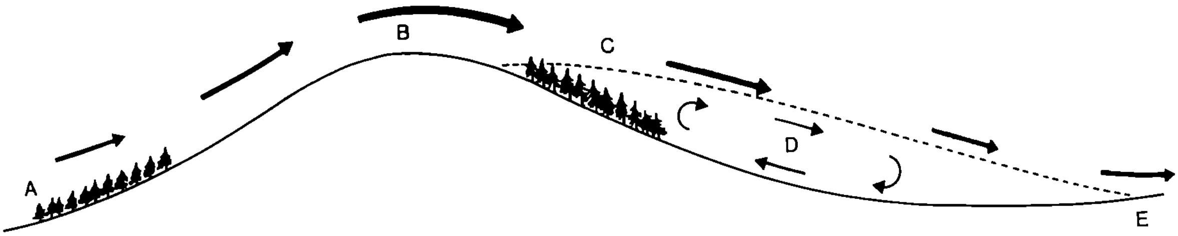


Figure 2.4 Features of the airflow over forested hills. A: presence of forest on lower slopes reduces wind speed at top; B: speed-up of the wind at summit; C: separation of flow in lee of hill encouraged by presence of trees; D: slack air in lee of hill; E: reattachment of flow downstream of hill.

have been possible on an otherwise bare hillside. Trees also induce the flow to separate from leeward slopes so that large areas of relatively calm air may be found behind a forested hill. However, under certain conditions (the presence of a strong temperature inversion close to a hilltop) air can be forced down the lee slope, like water flowing over a weir, creating extremely strong downslope winds in an area which under normal circumstances one might expect to be reasonably sheltered. The 'helm wind' in the Eden Valley, Cumbria and the 'Bora wind' along the Adriatic coast of Yugoslavia are good examples.

Soils

As the medium in which the tree is anchored, soil is of vital importance in tree stability. It has long been evident that different soil types provide a variety of limitations to rooting and give rise to different amounts of windthrow. In the absence of limiting factors, root systems of mature trees would exceed 1 m in depth, but in Britain probably the majority of our soils fall short of this ideal. The most favourable soils are the freely draining brown earths (Plates 5 and 6), but in the uplands even these soils are often shallow. Wet and poorly aerated soils such as surface-water gleys and peaty gleys typically restrict root systems to less than 50 cm depth (Plates 7 and 8).

In order to maximise tree stability the soil should have the strength to resist the shear stresses and the tensile forces exerted by the roots within it when the tree is being rocked by the wind. The greater the mass of soil adhering to the root system of a tree the more wind firm it is. This mass depends on its volume and bulk density. The volume of soil can be simply measured by the depth and spread of the central core of roots, because the soil within this core is bound by the root system into a coherent root/soil 'plate' or 'ball'. Mineral soils have bulk densities (including their organic matter and water) between about 1.0 and 2.0 mg m^{-3}, whereas peat soils have a density close to 1.0 mg m^{-3} over a wide range of water contents. Soil strength is increased by soil bulk density, but at the expense of the ease of penetration by roots. An increase in soil water content also increases soil bulk density but rapidly reduces soil strength and the ability of the soil to pass oxygen to the respiring roots. The ideal soil material has a bulk density between 1.0 and 1.7 mg m^{-3}, a volumetric water content of about 30% and a volumetric air content of about 20%. One of the usual aims of cultivation is to loosen and mix the soil so as to create these conditions.

The spread of roots is not normally limited by the nature of the soil, but soil conditions are paramount in determining rooting depth. The main causes of restricted rooting depth are inadequate oxygen supply and hard soil layers, but roots can also be deflected by stones and boulders. Oxygen moves from the air above mainly by diffusion along continuous air-filled passages. The size ('diameter') of an individual passage has little direct effect on diffusion but has an indirect effect because smaller pores are more likely to be filled with water. Water virtually stops diffusion, and waterlogged soil is usually oxygen deficient unless the water is moving rapidly. Soils with high bulk density or with fine (clayey) texture have small pores that tend to conduct water and air poorly. Soils with poor permeability because of fine texture or high bulk density frequently have a high water-table (for example, less than 40 cm deep on average in the winter), but even in light textured, fairly porous soils the water-table may be supported by an underlying impervious stratum such as the bedrock. Such soils may occur on flat land or on slopes. The effect of slope gradient, especially if the slope is convex, is to increase the speed of movement of water through the soil and to encourage downslope instead of vertical flow. This effect becomes so strong with increasing gradient that on slopes over about 15° it is usual to find even unfavourable fine-textured materials supporting well-aerated soils. However, in the wettest climates of our western uplands there may be persistent waterlogging of soils even on steep slopes.

Apart from bedrock the two main examples of hard soil layers are a thin ironpan and indurated material. A thin ironpan (normally 1-5 mm thick) has overlying wet and poorly aerated layers, often including peat (Plate 9). These layers usually present a greater problem for roots than the ironpan itself which is seldom so hard or continuous as to prevent penetration at some point. The subsoil beneath the pan is often better oxygenated and provides good rooting conditions. In some soils a particularly strongly developed ironpan lies directly on a thick, dense and hard layer of indurated material. Indurated material, whether including an ironpan or not, is impenetrable to roots except along a few fissures (Plate 10). Most ironpans are penetrable by tree roots once the overlying layers have been dried out and aerated by tree growth.

The drying effect of a forest canopy reduces the average soil water content and improves soil aeration. This is sufficient in most ironpan soils to cure the surface wetness and create a well-aerated soil. In well-decomposed, deep blanket peats the drying causes wide and deep cracks to form and the water-table falls dramatically. In fine loamy and clayey gleys,

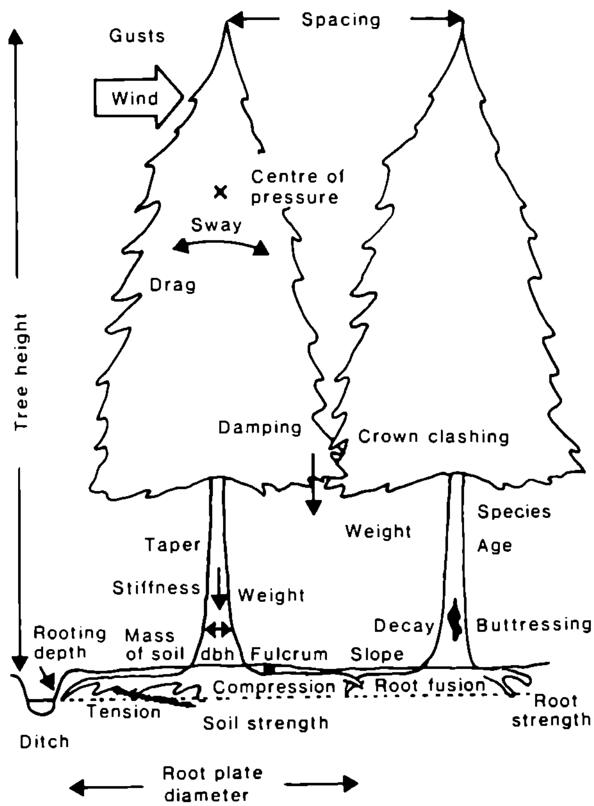


Figure 2.5 Mechanical factors influencing the stability of a single tree.

including peaty gleys, soil improvements are more difficult to obtain, whether by tree growth or through artificial drainage. These are the soils that give most of our windthrow problems, and it looks as though it will require more than one rotation of trees to achieve substantial improvements in rooting depth.

Mechanics of wind damage

Windthrow occurs when the overturning moment caused by the wind exceeds various resistive forces in the root anchorage (Figure 2.5). The overturning moment itself has two components. Firstly there is the lateral force (drag) applied to the tree crown by the wind. Assuming the wind acts at a centre of pressure in the crown, the force at that point multiplied by the height above the ground gives

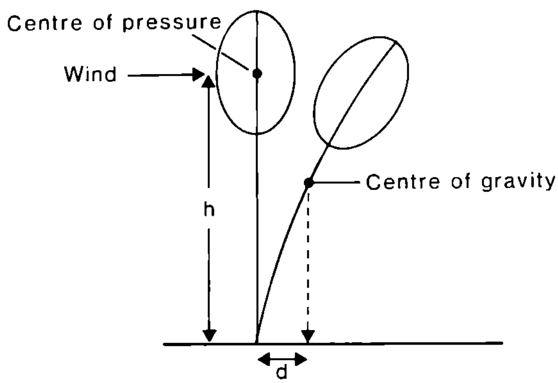


Figure 2.6 The overturning moments acting on a single tree. The wind acts at a centre of pressure in the crown at a height (h) above the ground. The applied turning moment at the stem base is a product of drag x height. Once the tree has been bent, the weight at the centre of gravity, acting over the lever arm (d), provides an additional turning moment at the stem base.

the applied turning moment (Figure 2.6). The second turning moment develops as the tree is bent by the wind. It is caused by the displaced weight of the stem and crown. The distance in a horizontal direction between the position of the fulcrum (or hinge) and the centre of gravity of the bent tree, multiplied by the weight, gives this second overturning moment. It can be considerable: by the time a 20 metre tall spruce tree has been forced over by the wind to the point at which it uproots, the turning moment caused by the weight is up to 30% of the total uprooting turning moment. Wet snow can add a considerable additional mass to the canopy, up to twice the weight of the canopy itself. In species to which snow readily attaches, such as lodgepole pine, snow loading is probably the major cause of damage.

There are two main resistive forces. The principal one is root anchorage, a topic discussed in more detail later in this chapter. A further resistance to windthrow is provided by contact between tree crowns. The increased vulnerability of crops immediately after thinning can partly be attributed to the reduced support given by adjacent crowns.

Understanding the dynamic behaviour of trees is fundamental to assessing their response to the wind. Gusts sweeping across the forest cause trees to sway and this oscillation will be a function of the tree's height, canopy mass, dbh and taper. These characteristics vary from tree to tree even in a plantation forest so that individual trees will tend to move in and out of phase with their neighbours. At times, therefore, trees may strongly restrict each other's motion through crown contact while at other times they may have lit-

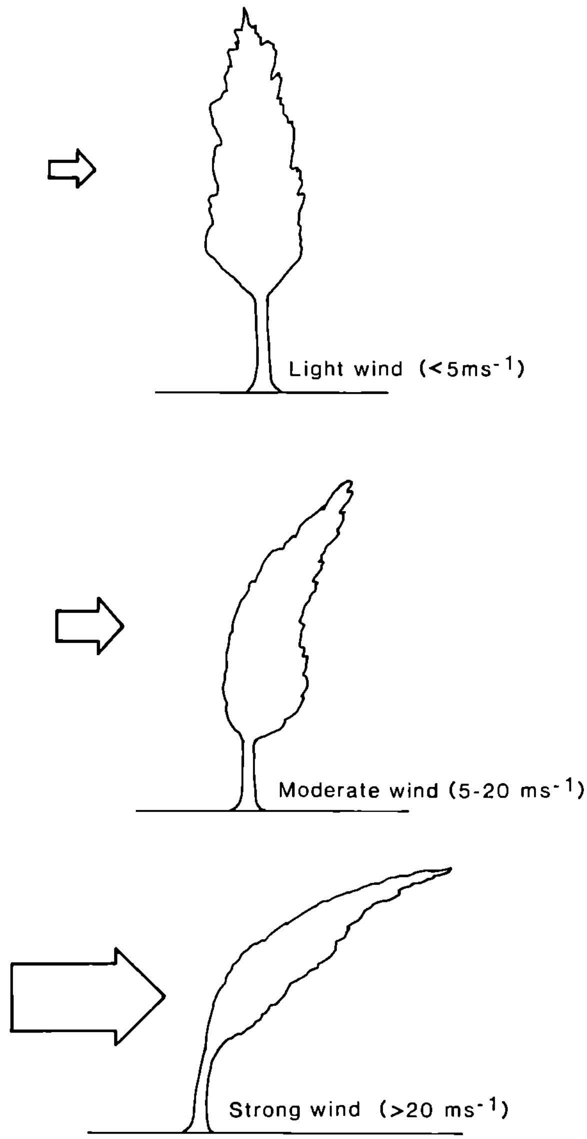


Figure 2.7 Progressive streamlining of trees as wind speed increases.

Plate 1 *Wind, exacerbated by salt spray, has limited the height growth of trees in this woodland in North Uist and created a streamlined canopy.* (A. L. MACKIE)

Plate 2 *Windthrow: the root systems have failed due to shallowness (soil wetness causing poor aeration) and lack of root spread (plough furrows). (36716).*

Plate 3 *Widespread damage to Glenbranter Forest in Argyll during a single storm in January 1968. (CS17527).*

Plate 4 *Windthrown pockets in an unthinned spruce forest in Galloway. Such pockets may form and spread during a number of storms.* (C. P. QUINE)

Plate 5 *An example of a brown earth soil where rooting depth is not limited by poor aeration.*
(D. G. PYATT)

Plate 6 *A root system of Norway spruce found on the brown earth soil shown in Plate 5. Note rooting depth in comparison with Plate 8 (use spade as scale).*
(D. G. PYATT)

Plate 7 *An example of a surface-water gley soil where rooting depth is limited by poor aeration.*
(D. G. PYATT)

Plate 8 *A root system of Norway spruce found on the surface-water gley soil shown in Plate 7. Note rooting depth in comparison with Plate 6 (use spade as scale).* (D. G. PYATT)

Plate 10 *An example of a podzol overlying an indurated layer (the pinkish-brown layer in the lower half of the profile). The induration is impenetrable to roots and normal cultivation does little to improve rooting depth.*
(D. G. PYATT)

Plate 9 *An example of a peaty ironpan soil. Rooting depth may be limited by the poor aeration of the horizons above the ironpan and by the pan itself. Soil horizons below the ironpan are better aerated and available for root development, particularly when the pan is broken by cultivation.* (D. G. PYATT)

Plate 11 *Windsnap: the stem has failed while the roots have remained securely anchored.*
(C. P. QUINE)

Plate 12 *Buttressing of the stem of a Sitka spruce in response to wind exposure.*

Plate 13 *Windthrow following removal of two rows with additional thinning between the racks. The wind was able to penetrate the gaps before the canopy reformed.* (C. P. QUINE)

Plate 14 *Roots of Sitka spruce crossing shallow furrows in a deep peat that is drying as a result of tree growth.* (D. RAY)

Plate 15 *Wind damage at the edge of a clearfelled area due to lack of adaptation to such exposure.* (C. P. QUINE)

Plate 16 *An example of a severance cut made to develop a wind firm edge where no ride or other adapted edge had previously existed.* (S. J. LEE) tle influence. Each tree has a preferred or fundamental frequency of oscillation and it has been suggested that resonance with turbulence at the tree's natural frequency is responsible for tree failure. This may occur at very high wind speeds, but in general trees respond to the individual strong gusts, oscillating about their rest position for a few seconds after the passage of the gust until damping reduces their motion.

A tree can be regarded as a mechanical oscillator with a certain mass, stiffness and damping. The wind acts as the driving force and the characteristics of the tree determine its resulting displacement and the uprooting turning moment. The crucial factors in determining the tree's behaviour are its mass, the stem stiffness, the effective canopy drag area, the height of the centre of pressure and the degree of damping. Damping results from heat produced in the stem during bending, the drag of branches through the air and contact between tree crowns. Tree displacement and the turning moment at the base of the tree increase with tree mass, effective drag area and height of the centre of pressure, but are reduced by increased stiffness and damping.

Tests of trees in a wind-tunnel have shown that, in general, spruces have a higher drag factor than pines and firs because the branches of spruce trees are stiffer. Whereas the drag force on unyielding structures, such as buildings, is related to the square of the wind speed, tree crowns accommodate themselves to the wind (Figure 2.7) and so the drag force shows a more linear relationship. There is so much mutual sheltering between branches that almost 70% of the crown needs to be removed before there is a significant effect on the drag force of an individual tree. The drag of individual deciduous trees is reduced by almost a factor of 10 when the trees are leafless.

Opening up the forest canopy by thinning, respacing or by creating a ride or road will tend to increase the effective drag area. In widely spaced crops this is not only because the wind can affect a greater depth of crown but also because there is a larger crown. When deciduous trees are leafless, wind speeds within the canopy are increased, partly counteracting the benefits of their reduced drag. In general, the more even and closely packed the canopy the better it is in aerodynamic terms because the area on which the wind can act is reduced.

The height of the centre of pressure and hence the overturning moment increase as the tree matures. It follows that wind loading on dominants is likely to be greater than on other trees, but there is no evidence that they are any more vulnerable overall. Presumably their thicker stems and larger root systems compensate for their large crowns and high wind loading. Any silvicultural treatments that keep the stand structure as even as possible are likely to be beneficial, for example fertilising poor areas to reduce checked growth or using clonal material.

Thinning reduces crown contact and the consequent reduction in damping is likely to be detrimental for a period. Widely spaced trees are heavier and stiffer and the increased stiffness will compensate for the heavier crown. However, widely spaced trees have reduced damping because they have less contact with their neighbours. Overall, as the spacing between trees increases so the overturning moment experienced will increase. However, where root growth is not restricted the root systems will develop to withstand this increased load. The evidence suggests that spacing does not have a large influence on the likelihood of overturning although as spacing is increased the vulnerability of individual trees will be less compromised by nearby trees blowing down.

Widely spaced trees are much less likely to be broken because their thicker stems are substantially stronger (strength is proportional to diameter cubed). Calculations of the stresses in tree stems caused by wind loading suggest that the stem is most likely to break in the lower third because of the shape of the stem (Plate 11). However, this is not always true with pine trees which have a habit of breaking in the crown at the point of weakness caused by a whorl of branches.

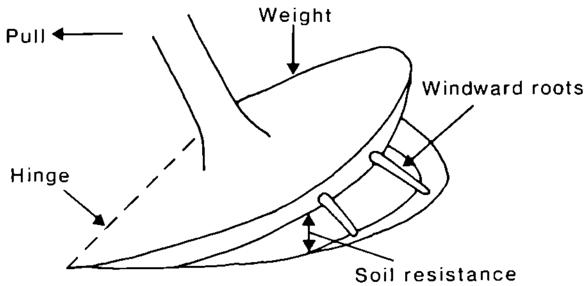


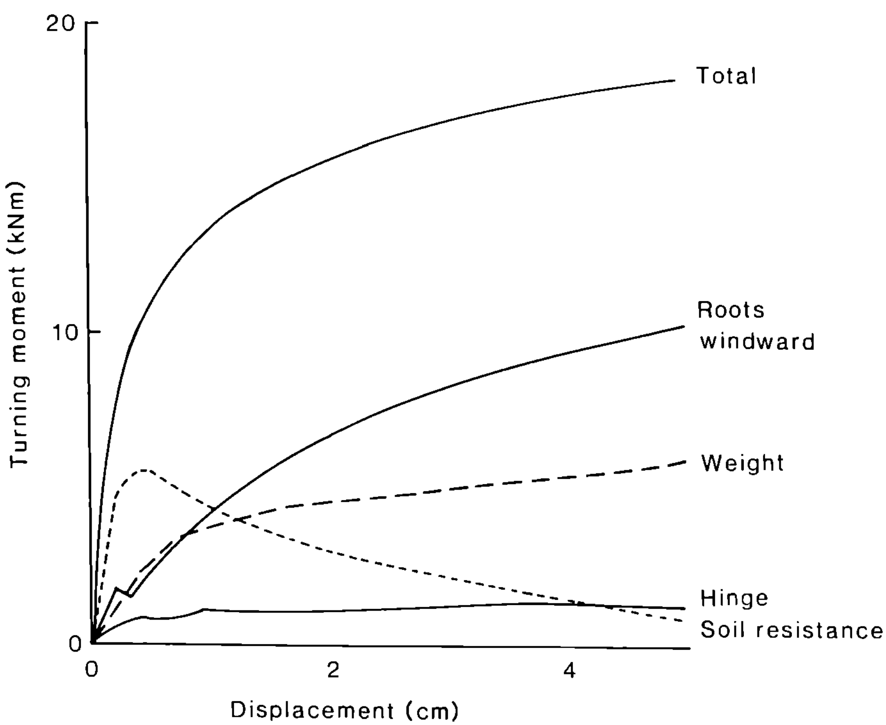
Figure 2.8 The four components of the anchorage of a shallowly rooted tree which resist the horizontal force acting on the stem: the weight of the root/soil plate; resistance of the soil to (mainly) tensile failure; resistance of the roots placed under tension on the windward side of the tree; resistance to bending at the hinge.

Root anchorage

The strength of the anchorage depends on the mechanical properties of the roots and soil, and on the size and architecture of the root system. Four components of anchorage have been identified for shallowly rooted trees (Figure 2.8). Firstly, when the tree stem is displaced by the wind the weight of roots and adhering soil helps to hold down the root/soil plate and thus resists the overturning forces. Secondly, the soil underneath and around the edges of the plate has to be broken during uprooting and this contributes a further resistance. A third component is produced by the tensile strength of roots on the windward perimeter of the plate. The fourth is the resistance to bending of the roots and soil in the hinge region on the lee side of the tree.

The resistance offered by the roots and soil depends on their physical properties. Roots are three to five orders of magnitude stronger than soil under tension. However, in the zone where the root/soil plate breaks away from surrounding soil, the area of soil broken is three orders of magnitude greater than the cross sectional area of the roots, therefore soil strength is important. Roots stretch under tension by 10-20% of their length before failure whereas soils stretch by less than 2%. As a result, force applied to the root system breaks the soil before it breaks the roots. This

Figure 2.9 The relative contributions of the four components of anchorage for shallowly rooted Sitka spruce on a peaty gley soil. By the time total uprooting force is at a maximum the roots which are pulled under tension on the windward side are the largest component, followed by the weight of the root/soil plate, while the hinge and soil make smaller contributions. At an earlier stage, under a small displacement of the root/soil plate, the resistance of the soil to failure is the largest component.



explains the importance of the soil during the earliest stages of uprooting (Figure 2.9). Once the soil has failed the tree becomes free to rock and the anchorage may become progressively weakened by root loosening. Two or more gales can therefore have a cumulative effect. Decay can greatly reduce the strength of the woody roots and can be an important factor contributing to windthrow, especially in old trees.

Because of the importance of the roots on the windward side of the tree in anchorage, anything which restricts their development, such as a deep plough furrow or drain close to the tree, or which reduces their hold on the soil, for example wet conditions, will reduce the total strength of the anchorage. Similar problems can occur on the lee side. Bending at the hinge is a small resistance but the distance of the hinge from the base of the stem influences the uprooting turning moment. Obstacles such as plough furrows, which can cause main roots to branch close to the tree and thereby reduce thickening further out, will diminish the distance to the fulcrum and render the tree less stable. Asymmetric root systems, which have few or only small roots on the lee side, will also fail close to the tree. Where soil conditions prevent deep rooting radial symmetry becomes important; a shallowly rooted tree should possess some 5-6 evenly spaced main lateral roots.

The mass of the root/soil plate can exceed that of the above-ground parts of the tree. In shallowly rooted (30-40 cm) Sitka spruce on a peaty gley soil the mass of the plate was 850-2900 kg, and in lodgepole pine rooting to 1 m depth on deep peat the mass of the root system and attached peat was 3000-4000 kg. The weight component of the anchorage varies not only with the quantity and properties of the adhering soil but also with the shape of the root/soil plate. All components increase with root system size, thus the root system should ideally be as wide as possible and at least 1 m deep.

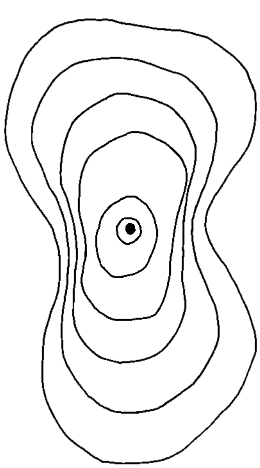


Figure 2.10 Cross-section through a woody lateral root of Sitka spruce with growth rings shown at five-year intervals. The root was approximately circular in the early years, but then growth became allocated to the top and bottom parts at the expense of the sides.

Adaptive tree growth

Trees growing in exposed places tend to be shorter and more tapered than trees in sheltered positions (Plate 12). These adaptations are largely the result of the mechanical effects of movement in the wind. Growth regulators such as ethylene are produced by mechanical stress in the trees' tissues, and tend to make the main stem and branches shorter and sometimes thicker.

Below ground, effects of wind action on the growth of the root system are evident in many species. In cross-sections a woody root of Sitka spruce, for example, will often show that the root was more or less circular during the first few years of its life but became increasingly eccentric in shape, with time; growth having been allocated to the top and bottom of the root at the expense of growth at the sides. In this way the root becomes shaped rather like an 'I' beam, and the one illustrated (Figure 2.10) would be about three times more resistant to bending in the vertical direction than a root that had the same cross-sectional area but was circular in section. This shows a remarkable economy in the use of materials to achieve the greatest strength. It also illustrates how trees modify their growth to increase their stability when they grow in exposed locations. However, exposure to wind is often associated with increased exposure to light, and the effects of these two factors are often difficult to distinguish. For example, trees growing at forest edges are particularly wind firm, and although this results partly

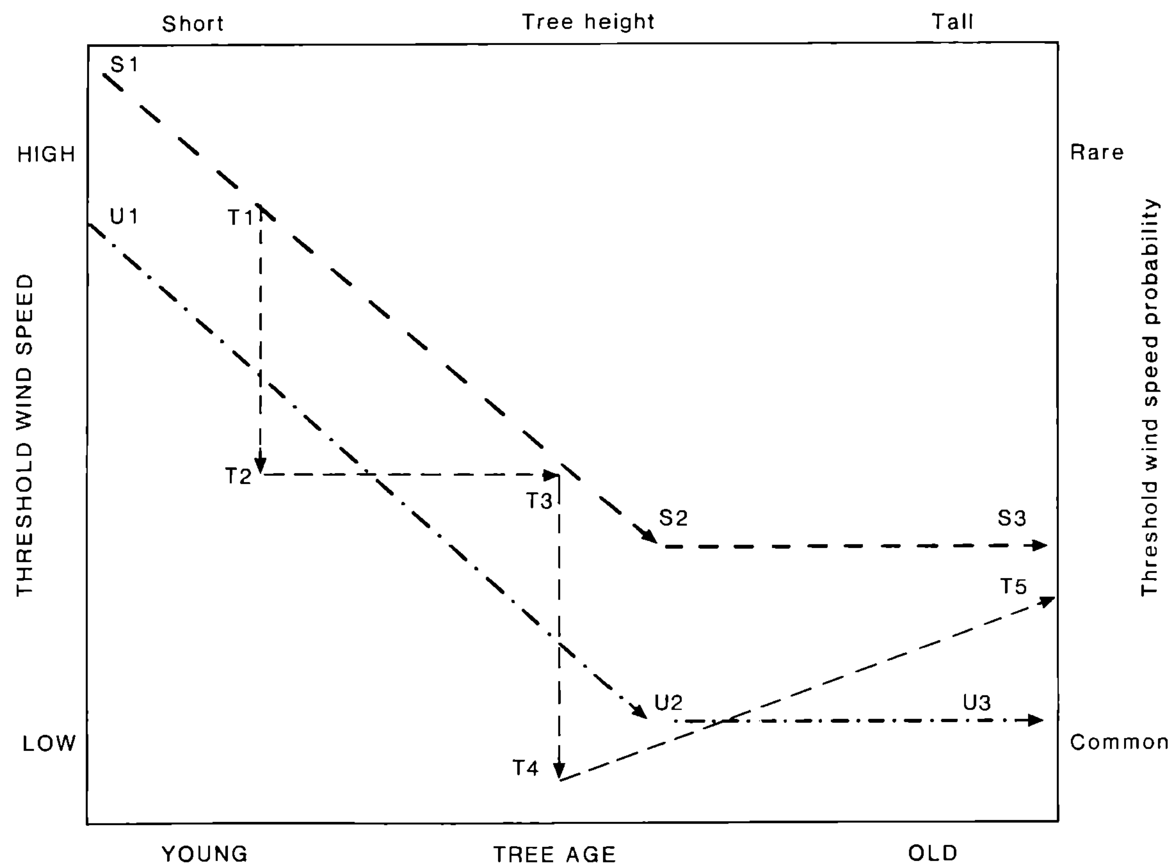


Figure 2.11 The change in tree vulnerability with time expressed as three components – persistent, progressive and episodic. S1-U1 represents the difference in persistent vulnerability between a stable and unstable soil. S1-S2 and U1-U2 represent the change in progressive vulnerability due to the growth of the tree, and S2-S3 and U2-U3 a period when progressive change levels off. T1-T2 represents an episodic change in vulnerability induced by thinning, and T2-T3 the recovery period after thinning; T3-T5 represents a further thinning.

from adaptive growth to wind exposure, increased light interception by large, exposed crowns also plays a part, as more assimilates are available for root growth than in trees with smaller crowns, growing under competition within the stand. The root systems of widely spaced trees benefit in the same way and are wider than those of trees at closer spacings. However, when spacing is increased by thinning, it takes time both for the tree crown to expand to make use of the additional light available, and for adaptive growth to take place in the root system. There is therefore a period of increased vulnerability, when not only has the canopy been broken, allowing more wind into the stand, but in addition the trees have not had time to adapt to the new conditions (Plate 13).

Interactions and risk

The preceding sections have highlighted the individual factors that contribute to the stability of a tree and the nature of the forces that the wind exerts on a tree. These factors all vary with space and time because of growth of the tree and variability in climate, and their interaction makes windthrow both difficult to predict and to interpret. The existing predictive system (the windthrow hazard classifica-

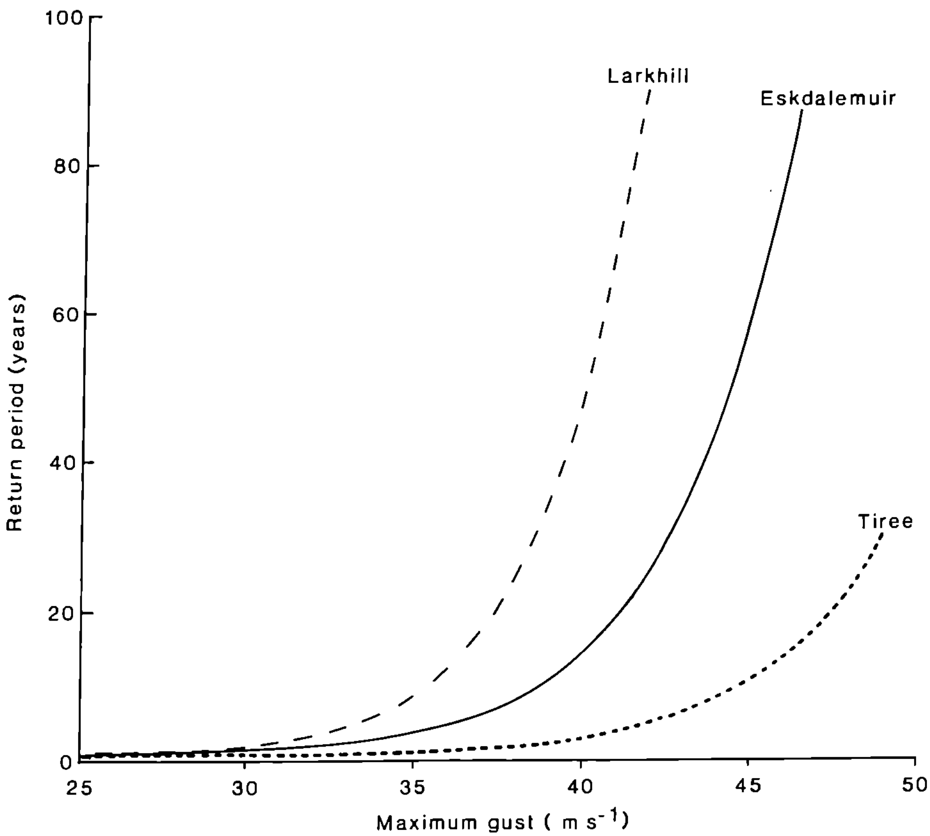


Figure 2.12 Relationship between wind speed (maximum gust) and recurrence (expressed as return period, that is, the average interval in years between exceedances) for three Meteorological Office sites - Eskdalemuir (south Scotland midslope site), Tiree (Western Isles coastal site) and Larkhill (central England lowland site).

tion) is summarised in the Appendix, and the following discussion takes a broader view of the risk of windthrow.

It can be helpful to consider how the siting, growth and management of a tree contribute to its 'vulnerability'. The vulnerability of a particular tree on a particular site can be expressed as the threshold wind speed required to blow it over (Figure 2.11). The site contribution (the soil and its modification by site preparation) may change little over the life of a tree, and is therefore a *persistent* component of vulnerability. As the tree grows the form it adopts (height, diameter, crown form, root system) also contributes to vulnerability and this can be regarded as a *progressive* component. Finally, there are events that contribute to the vulnerability for a limited period (for example, removal of neighbours in thinning, loading of crown by wet snow or soil saturation) and form an *episodic* component. Therefore vulnerability can vary in a complex way over time and can vary between trees, depending upon particular combinations of persistent, progressive and episodic components.

The risk of windthrow at any time is the probability of the threshold wind speed being exceeded. This will depend upon the site location, and local factors such as elevation, topography and presence of upwind stands. However, windthrow of almost any tree is possible given a sufficient (albeit very rare) wind speed or a severe episodic increase in vulnerability. Observations of windthrow in simple terrain indicate that damage is likely when wind speeds exceed 30 m s^{-1} (60 knots, 69 mph) and that speeds over 40 m s^{-1} can cause widespread damage. The recurrence of these winds varies markedly across the country as a whole, and also within a region depending upon topography. Return periods are often quoted to illustrate the rarity of certain wind speeds, for example a 50-year return period, and represent the average interval until the wind speed is likely to be equalled or exceeded. For example the return period for a 35 m s^{-1} wind is 20 years in central England, 5 years in a midslope position in south Scotland and 1 year at sea level in the Western Isles. The return period for a 40 m s^{-1} wind is 100 years in central England, 20 years in a midslope position in south Scotland and 5 years at sea level in the Western Isles (Figure 2.12). It is clear that wind damage would vary from region to region even more than it does if it were not for the compensating effect of the adaptive growth of trees.

Risk will be high for trees with threshold wind speeds that are likely to be exceeded in normal winter storms. In extreme storms the threshold wind speeds of trees on a wide range of sites may be exceeded and therefore observed windthrow may be the result of innumerable combinations of vulnerability and wind speed. The amount of windthrow and its pattern within a forest or stand will depend upon the interaction between the spatial arrangement of vulnerable trees and distribution of severe gusts. Prediction of damage will be most successful for trees at greatest risk (vulnerable trees on high wind speed sites). Preventive strategies aim to reduce the vulnerability of trees and thus make damage less likely; the non-linear relationship between wind speed and recurrence (Figure 2.12) means that small improvements in tree stability can make the risk of damage very much less.

Chapter 3

Silvicultural measures to minimise damage

Establishment phase

Site preparation

Site preparation for establishment may prejudice future stability by restricting root spread. This is particularly a problem where spaced furrow ploughing is used on mineral gley and peaty gley soils. Moling can be as effective as spaced furrow ploughing in draining such soils and should allow better spread of roots. Roots are more likely to cross the furrows on deep peats which dry out beneath the trees, especially if the furrows are shallow (Plate 14).

A strongly developed ironpan should be ruptured by tining if there is a friable and therefore rootable subsoil beneath. Where indurated material occurs, the hard layer is at least 30 cm thick and it is rarely possible to disrupt it sufficiently to permit rooting beneath the layer. In well-drained soils including ironpan soils, it is possible to increase rooting depth by breaking up the upper part of the indurated material, but this is unlikely to be economic. Indurated material beneath gley soils would need drainage as well as cultivation to improve aeration and thence rooting depth.

Drainage aims to increase the speed of movement of the water beneath the water-table and to provide frequent channels to carry away the excess. The average depth to the water-table is thereby increased and the water content of the uppermost unsaturated layer is reduced. This not only improves aeration but also increases soil strength. The first aim of drainage is to prevent water lying in cultivation channels or natural hollows. Additional drains may be worth while in more permeable soils to keep the water-table below the depth of the cultivation channels. See also Pyatt (1990), Research Information Note (RIN) 196.

Recommendations for site preparation

- Choose mounding, patch scarifying or complete cultivation in preference to spaced furrow ploughing or disc trenching on sites where cultivation is necessary for establishment and where rooting depth is restricted.
- On mineral gleys or peaty gleys use moling, either alone or in combination with the above.
- Where spaced furrow ploughing is used on gleys or deep peats, plough as shallowly as possible.
- Before planting ex-arable farmland disrupt any cultivation pan.
- On soils where lowering of the water-table beyond the level achieved by cultivation alone is possible, drain at an appropriate spacing.
- Do not rely on tile or pipe drainage systems beneath former farmland to last for a forest rotation. Additional open drains should be provided, linked to the existing system wherever possible.

Initial spacing and planting

The effect of spacing on tree stability is a much disputed topic, but within the range of 1500-3000 planted trees ha^{-1} there are no clear effects of initial spacing on future stand stability other than through the need for thinning. The main structural roots are determined during the first few years of the tree's life, therefore the type of root system planted, method of planting and conditions at the planting site may have a lasting influence on the form of the root system.

There are no clear differences between species in their stability on a given soil type. Deeper rooting of lodgepole pine than Sitka spruce on some deep peats has been noted but this may not be translated into greater stability because of differences in root spread or other factors. There are no 'shallow-rooting species', all species root deeply on suitable soils. Species that do not readily produce adventitious roots (including pines, Douglas fir and larches) should be planted with their root system well distributed.

Recommendations for spacing and planting

- On sites of high windthrow hazard where thinning would be an unacceptable risk the planting of self-thinning mixtures is an alternative. An example would be to plant an intimate mixture of Scots pine and Sitka spruce to produce a final crop mainly of the spruce.
- Where there is a risk of early instability (toppling) avoid applying fertilisers as this may increase the shoot/root ratio.
- Locate long-term stable edges on deeply rootable soils, avoiding areas of high wind exposure (see also Edges).
- Do not plant within 1 m of an open drain, mole channel or pipe.

Tending phase

Manipulation of spacing

Thinning causes a sudden increase in stand vulnerability, with the duration of the subsequent recovery period depending on yield class and age. The increase in vulnerability depends on the type, weight and timing of the thinning. Respacing or early thinning incur the lowest risks and late, mechanical thinnings the most. The smaller the gaps created in the canopy the better, so that, for example, 1 row in 4 line thinning is preferable to 2 rows in 8. When a stand has recovered full canopy after thinning it is at least as stable as an equivalent unthinned stand. Respacing has little influence on stability so long as lateral root spread is not restricted.

Recommendations for thinning

- Avoid delayed, heavy and uneven thinnings that create large gaps into which the wind can penetrate.
- Minimise damage to roots and soil by appropriate choice of machine and the use of brash mats.
- Thin the most vulnerable stands in spring to allow quickest recovery.
- Leave unthinned margins on the upwind side of the most vulnerable stands.

Edges

Long-established edges of stands are more wind firm than edges newly created by felling (Plate 15). Although wind loading on edge trees is greater than on trees within the stand, growth of the stem and root system more than compensates for this. The forest edge deflects the wind and increases turbulence for a distance equal to several tree heights downwind; this can exacerbate damage. Increasing the permeability of the stand edge or smoothing its profile can reduce these effects. High pruning has proved effective in reducing damage close to forest edges. The tending phase is an opportunity to form more wind firm edges in preparation for the felling phase (Plate 16). See also Quine and Gardiner (1992), RIN 220.

Recommendations for maintaining stand edges

- Use severance cuts to expose new edge trees during a period of negligible to low risk.
- Make the width of the cut equal to the height of the trees when the risk will be moderate.

- Do not create concave sections to the edges that accentuate the topographic funnelling of the wind.
- Consider increasing the spacing of trees near the edge or high pruning the edge trees to increase stand permeability.
- Consider planting slower growing conifers or broadleaves outside the stand edge to smooth the profile.
- Minimise the length of new edge required.

Drain maintenance

It is only on deep peats that drains may need extensive restoration of depth. They may become obstructed by the growth of mosses or sedges, or lose depth because of ground subsidence due to drying of the peat beneath the trees. On well-decomposed peats where extensive cracking is expected it will only be necessary to deepen alternate drains. Generally, drains should not be considered for deepening until they are less than 50 cm deep. Major roots on the edges or bottom of drains, however shallow, should never be damaged.

Recommendations for drain maintenance

- On deep peats, deepen drains less than 50 cm to 90 cm before canopy closure if possible.
- On mineral gleys and peaty gleys limit drain maintenance to the clearance of gross blockages.

Felling phase

Coupe design

Felling increases wind loading on the newly exposed edge trees. For coupes with a diameter greater than five tree heights this is equivalent to complete exposure. Although coupes smaller than this experience less wind loading, the greater amount of edge for a given area felled leads to more damage overall. Shapes of coupe with a larger edge-to-area ratio are also likely to suffer more damage.

Recommendations for coupes

- Fell coupes to natural or established edges, for example rides, roads, water courses, young stands and areas of checked growth, or to more wind firm stands on deeply-rooted soils.
- Where unadapted edges are used consider topping the newly exposed edge trees to smooth the profile and aid short-term retention.
- A single large coupe of simple shape is preferable to many small coupes of the same total area or a coupe with a complex shape and extended edge.
- Do not create edges that will funnel the prevailing wind into a corner.
- Within a coupe start felling at the down-wind edge.

Forest design plans

When planning a felling coupe consideration should be given to the effect on adjacent stands. The most vulnerable stands should be felled first and care should be taken to avoid exposing other vulnerable stands to the prevailing wind by removing stands immediately upwind. When planning stand retentions avoid exposed sites, wet soils and stands that are immediately downwind of planned fellings. Sites at exceptional risk should be considered for future use as open space or non-commercial woodland. There may be a desire to replace the clearfell silvicultural system with more sophisticated systems that give more diversity of structure or continuity of forest cover. Unfortunately there is as yet insufficient evidence to prove that such systems suffer less wind damage over a full rotation. See also Quine and Gardiner (1992), RIN 220.

Recommendations for felling

- Fell the most vulnerable stands first.
- Where a series of planned coupes will be vulnerable, start at the downwind end.

Recommendations for stand retention

- Avoid south-west facing slopes, hilltops and ridge crests in smooth, rolling terrain.

- Avoid spurs and convex slopes on the sides of major valleys, where the wind is constricted and accelerated.
- Avoid hillocks in valley bottoms in complex terrain.
- Avoid selecting retentions that all have the same aspect.
- Avoid soils where rooting depth is limited by a high water-table, induration, strong ironpan or shallowness to bedrock.
- Avoid sites with deep, spaced furrow ploughing, particularly where parallel to the contour or at right angles to the prevailing wind.

The preceding sections have been based upon interpretation of the best available evidence on the complex phenomenon of wind damage. Selected sources where readers may pursue individual topics in greater detail are given in the Further reading section.

Glossary

Anchorage The complex of mechanisms by which the root system and soil resist the wind forces on the stem and crown.

Centre of pressure The average position in the crown of the tree where the total force of the wind can be said to act.

Coherent gusts Organised rotational motions in the air (= vortices).

Damping The processes by which oscillations are reduced in size and tend to stop. Damping processes include canopy clashing, canopy drag through the air and frictional movement of stem fibres.

Drag area The surface area of the tree (canopy and stem) presented to the wind. Drag area can be reduced as wind speed increases due to streamlining of the tree.

Drag force The force on the tree caused by the pressure exerted by the wind on the crown (= wind loading).

Frequency of oscillation The number of sway cycles of the tree per second.

Fulcrum The position on the lee side of the tree where the root system pivots when the tree is bent by the wind (= hinge).

Gust A rapid increase in wind speed over a short period of time (seconds rather than minutes).

Hinge *See* Fulcrum.

Leeward The side of the tree facing away from the wind.

Lever The distance between the point of action of a force and the fulcrum.

Moment Force multiplied by distance (= torque).

Overturning moment The force on the tree multiplied by the distance from where the force acts (the centre of pressure) to the fulcrum, plus the additional moment due to the weight of the overhanging crown.

Risk (for a tree) The probability in a particular year of the threshold wind speed being exceeded. *See* Vulnerability.

Root architecture The appearance and structure of the root system, particularly the number and arrangement in three dimensions of the thickest roots.

Temperature inversion A zone or layer in the atmosphere where the temperature increases with height. In windy conditions the air beneath the inversion may be confined and thus accelerated over mountains.

Turbulence The random variations in wind speed and direction.

Vortices *See* Coherent gusts.

Vulnerability (of a tree) The threshold wind speed required to blow over a particular tree on a particular site.

Wind loading *See* Drag force.

Windward The side of the tree facing towards the wind.

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Appendix

The use of the windthrow hazard classification to predict windthrow

Assessment of windthrow hazard class

A simple predictive system, the windthrow hazard classification, is used to assess the threat of windthrow and to guide management decisions (Miller, 1985; Quine and White, 1993). The classification combines four factors that together predict the windiness of a site (namely wind zone, elevation, topographic exposure and aspect) with one that predicts the anchorage of the trees (soil type and phase). Together these define the hazard class of the site, and this is linked to a stand top height at which windthrow is expected to commence (critical height), and a stand top height at which windthrow is expected to reach such a level that the stand justifies being clearfelled (terminal height). These heights are influenced by thinning practice.

The windiness scores for a site are obtained by reference to maps (wind zone, elevation, aspect) and site measurements (topex); or topex can be obtained from maps or can be derived from digital terrain models (Quine and Wright, 1993). Soil type is identified on site or obtained from a soil map; accurate identification is important as this factor can produce rapid changes over short distances.

Hazard class is usually mapped at a scale of 1:10 000, and further maps can usefully be derived, for example maps of critical and terminal height, or (when combined with accurate growing stock information) maps of years to critical and terminal height. The latter can provide a very valuable indication of flexibility in forest design possible on the site.

Interpretation and analysis

Low windthrow hazard classes indicate that the risk of windthrow is low and that damage will occur infrequently, except when the trees are becoming moribund; low hazard class does not mean that damage will never occur but that it is unlikely. High hazard classes indicate that there is a substantial risk of windthrow, and damage is likely to be more frequent, particularly if management makes the stands more vulnerable. High hazard classes are commonly found on exposed upland sites where soil types provide poor rooting.

Critical and terminal heights provide general estimates on the timing of damage; actual damage may depart from that predicted because of wind climate variability, the simplicity of the classification failing adequately to represent the site risk, or because of incorrect application of the classification. Terminal heights equating to 40% damage may be inappropriate for sensitive sites, and lower damage levels (and therefore lower heights) may be required to guide the felling decision. Field visits to validate the chosen felling heights are important and can be used to identify stable and unstable stands.

Presence of windthrow can guide the order of felling as further windthrow is likely in damaged stands (except where the original damage occurred in particularly extreme conditions). Aerial photographs allow damage to be easily assessed.

The threat of windthrow, as assessed by the windthrow hazard classification, has three major implications for the management of a forest. Firstly, it provides a timescale within which the overall management of the forest will be constrained and controls the timing of certain operations, for example the creation of new edges and the planning of felling ages and retentions. Secondly, it constrains the type of operation that is feasible, for example decisions on thinning and the choice of silvicultural system. Finally, it necessitates flexibility within forest plans – particularly those that have a long life – to allow forest managers to respond to wind damage – or lack of it.

Future improvements

The windthrow hazard classification is a simple model seeking to represent very complex phenomena, as this Bulletin makes clear. At present, the model does not include representation of the effect of cultivation, and may underestimate the role of soil. The model is also deterministic, that is to say it gives no idea of the range of possible outcomes, for example the spread of heights at which the 40% terminal damage level is reached. A new classification is now being developed that will address these inadequacies, and provide estimates of the probability of damage for combinations of tree, site and location.

References

See Further reading : Silviculture, page 22.

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