Windthrow Hazard in Conifer Plantations

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INTRODUCTION

This paper describes the development and applications of the Forestry Commission's windthrow hazard classification system, and outlines current research aimed at improving the prediction of windthrow in spruce plantations.

Serious economic implications arise from the scale of plantation windthrow in Britain: in an average year, it is estimated that up to 5000 hectares of spruce plantations are affected by windthrow, either as fresh initiation of damage, or as progressive spread of earlier damage. Although it is difficult to quantify to economic penalties of this damage precisely, a current annual loss of up to £3 million is estimated. If it were possible to grow Sitka spruce plantations on the 25% of our forests which lie on the most vulnerable sites, for an extra 1 metre in height before wind damage develops, this could give sustained additional timber revenue of over £1 million per annum. As the extensive areas of forest planted on the more exposed wet upland sites since 1970 develop to a vulnerable stage, the scale of economic loss will rise rapidly.

In Britain we recognise 2 categories of wind damage: firstly, catastrophic damage resulting from the infrequent storm events which appear to affect some part of the country about once in every 15 to 20 years. The great storm of 1968 across west and central Scotland is the most obvious example (Holtham, 1971). A similar storm also affected a narrow belt across central Wales, the Midlands and East Anglia in 1976. Very severe localised damage, including a substantial proportion of stem snap, arose in these cases, affecting both windfirm and relatively unstable stands, but catastrophic damage is associated with relatively long recurrence periods of around 15 years in Britain. Of greater importance is the problem of *endemic windthrow* which arises in most upland forests every year, as a result of normal winter gales. Endemic windthrow comprises either individual stem blowdown, or groups of blown trees, and spreads progressively over several years. Damage is normally confined to sites which are recognised as inherently unstable, due to soil type or topography, and usually affects stands above a particular height. Uprooting of spruces on wet or compacted soils is the predominant effect. On a national scale, endemic damage is certainly associated with economic penalties which are substantially greater than the loss arising from localised catastrophic damage. Since endemic windthrow appears to be related to particularly vulnerable sites, and because damage recurs on an annual, or regular basis, greater efforts have been applied to the problems of predicting where and when this type of damage will arise, and investigations into methods preventing or delaying onset of endemic windthrow has been given higher research priority.

WINDTHROW HAZARD CLASSIFICASTION

Before describing the system of windthrow hazard classification in detail, it is important to outline the underlying concepts of critical and terminal heights in windthrow prediction and management of windthrow susceptible sites. 'Critical height' is defined as the stand top height when initial endemic windthrow arises, and is indicated when 3% of the stems become windthrown. 'Terminal height' is the residual stand top height when terminal damage levels have developed, and between 40% to 60% of the stems are windthrown. This is normally the stage when clearfelling of the residual stand is required to recover the tree growth potential of the site. In economic terms, a stand becomes terminally damaged when the increase in value of the residual stand is exceeded by the interest occurring on the investment.

The Forestry Commission's windthrow hazard classification (WHC) (BOOTH, 1977; Miller, 1985) developed from the need to produce a general or national system of windthrow prediction, to identify the nature, location and extent of windthrow problems which would arise in the future. By the 1970s, it had become clear that endemic windthrow would dominate much of our harvesting and marketing activity, through its effects on rotation length, felling ages, tree sizes and thinning activity.

During the mid 1970s, an extensive programme of windthrow surveys was undertaken, involving both aerial photographic interpretation and ground truth surveys in several key forest areas, where endemic windthrow was becoming a serious problem. By assembling detailed crop and site data for compartments where new damage had arisen, it was possible to carry out statistical analysis to determine the site factors most closely associated with the observed damage patterns. Eventually, 4 primary site related components detailed below were isolated as the main interacting factors which could explain most of the variations in windthrow in stands of different top heights.

1. *Windzone.* The more northerly and western parts of Britain experience higher windspeeds and a greater frequency of gale events than the south east.Coastal areas are also windier than inland areas. The windzone map shown in Fig 1 is a very approximate zonation of Britain, and was assembled by analysing the regional variation in flag tatter rates over a range of site elevations, and combining these with published Met. Office mean windspeed maps (Hardman et al,1973). These regional changes in wind conditions will clearly affect the windthrow vulnerability of forests in any particular part of the country.

An attempt has been made to produce an equivalent windzone map for Ireland in Fig 2. This map is based on some exposure flag data from Northern Ireland, which was extrapolated across the whole of Ireland using published maps of physiography and regional variation in mean annual windspeed.It is important to appreciate that these Irish windzones are very much a first approximation and much more exposure flag data is needed to give an accurate wind zonation.

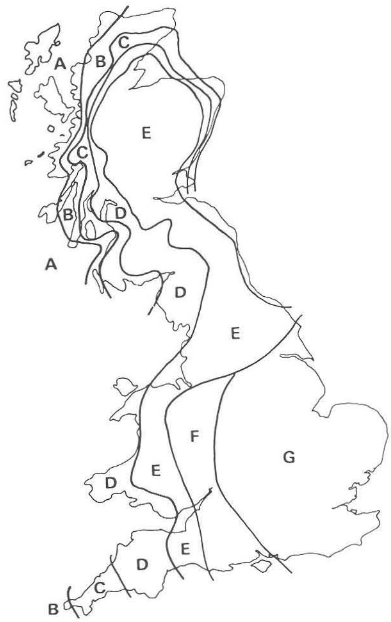

Fig 1 Wind Zonation of Britain.

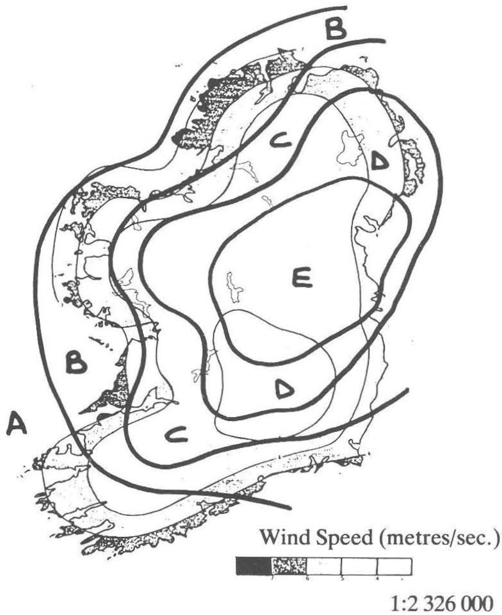

Fig 2 Preliminary Wind Zonation of Ireland, based on limited exposure Flag Data.

2. *Site elevation.* Mean windspeeds increase with elevation, and the frequency of gale events also rises at higher elevations, both affecting the recurrence of potentially damaging winds, and windthrow vulnerability of particular sites.

3. *Site topex.* The topography of forest areas affects windthrow vulnerability. In particular, the nature of surrounding topography will influence local windspeeds and turbulent wind structure. The precise relationships between wind structure and topography are poorly understood at present, but effects such as the upslope acceleration of wind, flow separation over hilltops with strong leeslope turbulence, and the funnelling of wind up valleys are all likely to be important in determining the windthrow vulnerability of any particular location in a forest area. In order to take some account of topographic effects on windflow, the simplified system of topex was developed (Malcolm and Studholme, 1972). This system involves the measurement and summation of 8 skyline angles, spaced at 45 degrees, for each assessment point. Sheltered sites, having substantial surrounding high ground, subtend a large cumulative skyline angle, and a correspondingly high topex score.

The particular influence of topography on wind conditions will depend on the wind direction prevailing, but topex in its basic form does not incorporate a directional weighting. Nevertheless, topex remains a useful index for quantifying local site exposure, and topex assessments are relatively simple to carry out for incorporation in WHC appraisals.

4. *Soil types.* Soil type exerts a major influence on the windthrow vulnerability of forest areas by affecting root develop and tree anchorage. Endemic damage in Britain is most commonly observed on soil types with physical characteristics which impede vertical soil water movement and root development. In particular, the hazardous gley soils, with high bulk density, low hydraulic conductivity and prolonged winter waterlogging are associated with low soil shear strength and shallow tree root systems, and consequently with low resistance to uprooting of trees during windloading. Although it is recognised that site preparation will strongly influence root architecture and hence the resistive anchorage of trees to overturning forces under windloading, it is possible to adopt a simplified approach to characterising the soil/rooting status of forest areas, based on soil type alone. Most forest areas have detailed soil maps available, and component scores for WHC purposes can be attributed to each soil type. Even in the absence of a detailed soil survey, it is possible to simply classify forest sites by their approximate rooting depth potential, and derive appropriate scores for WHC in this way.

Windzone + Elevation + Topex + Soil

↓

Combined Score Total

↓

Windthrow Hazard Class

↓

Estimated Critical Height

Fig 3 Schematic Derivation of WHC of any Forest Site

By assessing each of these 4 variables, calculating their appropriate scores, and adding these together, the WHC of the site is found as shown in Fig 3. Details of appropriate scores to match particular site conditions are contained in Forestry Commission Leaflet Number 85 (Miller, 1985) referred to previously. A total of 6 windthrow hazard classes is recognised, covering the full spectrum

Table 1 Estimated Critical Heights (M) for 6 WHCs under different thinning methods.

WHC	Selective Thin	Systematic Thin	Non Thin
1	25	25	28
2	22	22	25
3	19	18	22
4	16	14	19
5	13	12	16
6	10	9	13

of windthrow vulnerability of forest sites from highly windfirm to highly unstable. Each hazard class is associated with a critical height, indicating the stage when initial endemic windthrow is likely to arise. Critical heights, shown in Table 1, relate principally to stands which have been treated by selective or systematic thinning at management table times and intensity, or stands managed as non thin. Stand management practices which may confer increased stability, such as non-thin management, or wider spacing, will be associated with increased critical height, and in the case of non-thin management, the increase in critical height is of the order of 3m, or equivalent to a reduction of one hazard class in stands so managed. Conversely, very heavy or delayed thinning and systematic thinning practices are often detrimental to stand stability, and reductions in the calculated critical heights are appropriate for the higher windthrow classes, where the adoption of harsh thinning regimes can precipitate early onset of windthrow. Insufficient information exists at present to quantify precisely the effects of different thinning and spacing or respacing practices on critical heights in each of the 6 windthrow hazard classes, but local estimates of these effects can be used to modify the critical heights indicated by WHC.

Assessment methods

Although it is theoretically possible to assess the WHC distribution for a complex forest area, simply as a desk exercise (assuming detailed soil survey and topex maps are available), many forest managers will be faced with a field survey committment to define soil and topex variations over their forest areas. It is normally desirable to combine soil and topex assessments into a single survey, and the intensity of sampling is determined mainly by the variation in soil and topography across the forest area being surveyed. Vegetation changes are useful indicators for soil survey, and topex sweeps should be carried out at points, coinciding with soil pits, approximating with a grid at intervals not exceeding 500 m. The use of a prismatic compass and optical clinometer are normally required for topex assessment, and clear visibility to ensure accurate location of the skyline is essential. Topex assessments of thicket and polestage stands are particularly problematic due to restricted visibility to the skyline. Windthrow hazard maps are normally the final product of the assessment. These are prepared by overlaying soil and topex maps, one of which must contain contours to derive the elevation score, and by numerical interpolation of the WHC component scores, the boundaries between windthrow hazard classes can be drawn.

Predictive precision of the windthrow hazard classification

Validation surveys carried out in forests in the uplands of Britain indicate a fair precision of the system, with average observed height of the onset of damage falling reasonably close to the estimated height derived from windthrow hazard classification. Fig 4 illustrates the results of a series of validation surveys, comparing actual critical heights with the calculated critical heights for 5 WHCs. There is the possibility of some bias in these validation surveys, since mainly wind damaged stands were surveyed, with undamaged stands tending to be ignored by local managers and not identified to the surveyors.

Applications of windthrow hazard classification

It is important to appreciate that the WHC is a rather crude method of predicting the differential vulnerability to endemic windthrow within extensive forest areas. The system necessarily involves many simplifications, which limit both its predictive precision, and the range of applications. In particular, WHC is designed to predict the 'average' response of many individual compartments to the highly variable and uncertain effects of gales. Inevitably, some stands will become unstable at an earlier stage than expected, and others will endure well beyond the critical height calculated by the WHC method. For this reason, WHC is of relatively little value in the management of individual compartments or small isolated forest areas, and its main application in Britain is to assist in regional timber production forecasting. In this role, early wind damage in some locations is

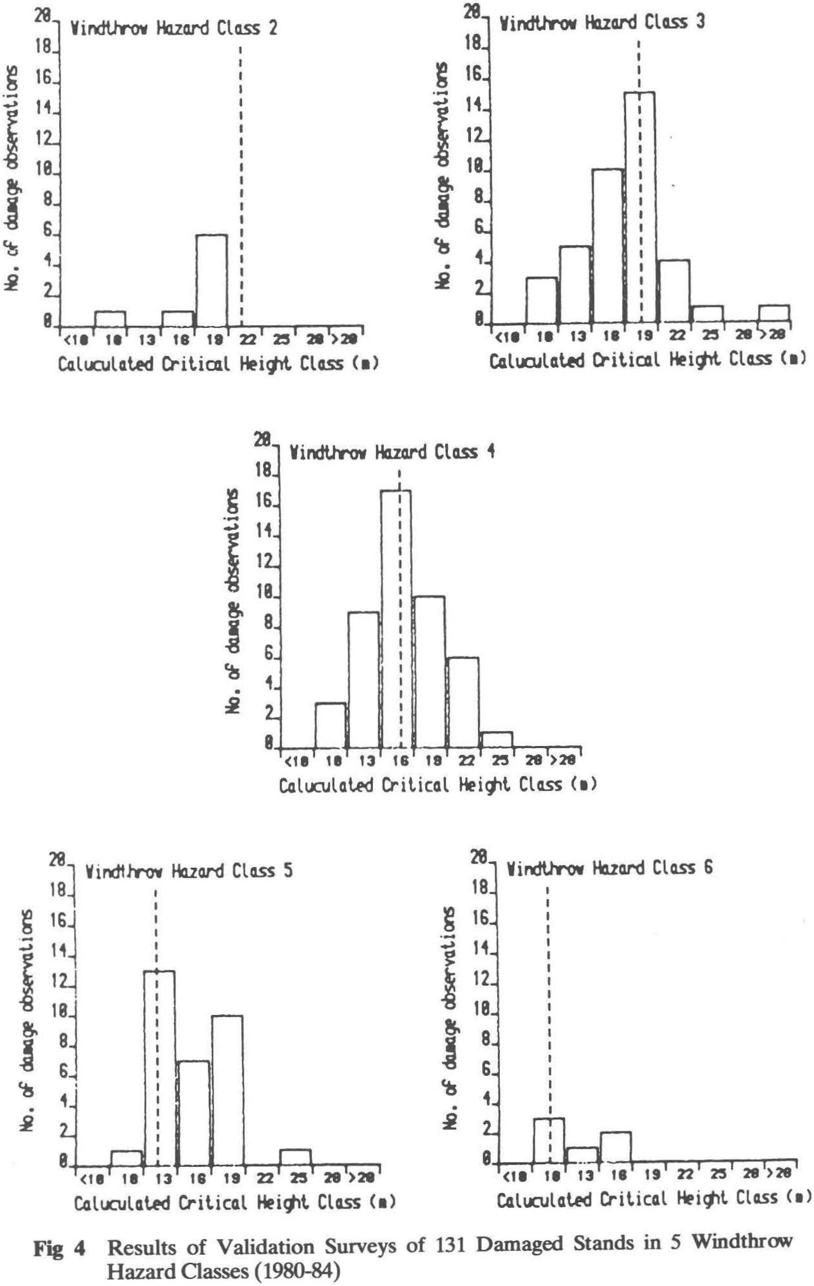

Fig 4 Results of Validation Surveys of 131 Damaged Stands in 5 Windthrow Hazard Classes (1980-84)

counterbalanced by other areas where windthrow does not develop as rapidly as expected. Overall, regional timber yields are close to that calculated by combining the WHC distributions for different forests, and the utility of the system is quite high. In addition to refining strategic marketing plans, regional managers are also able to plan ahead more realistically for harvesting resource changes necessary to accommodate thinning and clearcutting operations as affected by vulernability and the incidence of damage.

It is possible to use the WHC system, at a more local level, for operational planning.In Britain, the most vulnerable windthrow hazard classes 5 and 6 are normally scheduled for non-thin management. The intermediate hazard classes 3 and 4 require care in selecting the timing, pattern and intensity of thinning, and hazard classes 1 and 2, on windfirm sites, are fairly unconstrained in thining options. The definition of the WHC4/WHC5 boundary (thin/non-thin boundary) is clearly important, and the particular thinning methods to be employed in hazard classes 3 and 4 are strongly influenced by windthrow hazard. In this way, the WHC can assist in identifying sections of forest where harvesting activity will be concentrated in the future, and indicates appropriate operational methods, thereby incorporating windthrow vulnerability into harvesting resource allocation and local production planning. By combining local estimates of the rate of spread of wind damage with the calculated or observed critical heights for different WHCs, it is possible to predict approximate terminal heights, and adjust local or regional clearcutting plans to accommodate the shorter rotations from windthrow susceptible areas.

Limitations of windthrow hazard classification

As indicated previously, the windthrow hazard classification system described is a practical approximation intended to facilitate the broad zonation of forest areas, generally greater than 500 hectares in extent.

1. Knowledge of the WHC distribution gives a general indication of appropriate silvicultural treatment, but does not provide a satisfactory basis for detailed, subcompartment management prescriptions. Windthrow hazard is only one of several factors to be taken into account in deciding whether to thin or fell any individual stand. These decisions must accommodate the other demands and constraints applying to the forest area, and windthrow susceptibility is only one such constraint, and in many cases may not even be the primary one.

2.The WHC was primarily developed from observations of damage in pure Sitka spruce stands in the Scottish borders, with gently rolling terrain, and extensive areas of uniform gley soil. In these conditions, the predictive precision of WHC is high. In more complex topography, and with greater soil and species variation, precision of windthrow prediction is generally lower.

3. The WHC is based on the concept of critical height. Following initial damage windthrow usually spreads progressively through the stand over a period of years, until terminal damage levels are reached. Terminal heights are of much greater importance than critical heights, but it is not yet possible to predict these with a simplified system like the WHC. Although the rate of spread of windthrow appears to be controlled by broadly the same site factors that affect windthrown gaps. Local observation with map-form recording there is the additional problem of exposed edges in windthrown gaps. Local abservation with map-form recording of typical damage extension rates is the only feasible way to estimate terminal heights.

4. The WHC system described was derived from observations of wind damage in stands established between 1940-1960. Site preparation during this period involved either shallow single mouldboard ploughing, or combinations of shallow ploughing and spread turves, and tree spacing at establishment was between 1.5 and 1.8 m. Since 1960, there has been a progressive shift towards deeper ploughing, and double throw plough configurations, and in more recent years, the use of subsoiling techniques have become more common. It is probable that root architecture and tree anchorage will be different in these more recently developed techniques, and the resistance to overturning under windloading will alter. Similarly, the effects of wider spacing in more recently established crops will produce individual trees with different stem form and crown shapes which will alter their momentum absorption and dissipation characteristics under dynamic windloading. The extent to which these more recent changes in silvicultural practice will alter windthrow response and sustain the predictive precision of the WHC is uncertain, but as information from research experiments and field surveys of windthrow stand becomes available, it will be possible to modify WHC scoring to accommodate these factors.

Future refinements of windthrow hazard classification

In its present form, WHC offers a useful means of incorporating windthrow vulnerability in production forecasting and harvesting planning. It is unlikely that further major improvements in the overall predictive precision could be achieved by fine tuning of the system, and in Britian, several adjustments to wind zonation boundaries and soil scoring have already been incorporated over the past 8 years since the inception of WHC system. Local modifications to the WHC, based on systematic observation of windthrow, may improve its local precision. Forestry Commission research is now tending to concentrate on means of improving windthrow resistance of stands, mainly by investigating the mechanisms of windthrow in plantations. Progress to effective preventive measures will almost certainly lead to improved windthrow prediction in established stands.

The main research project geared specifically to improving windthrow prediction concerns investigation of the airflow/topography interaction.Local windspeeds, surface shear stress, and turbulence levels are all affected by topographic configuration of the upwind fetch, and certain locations within any forest area will be subject to a higher incidence and recurrence of potentially damaging wind conditions. Research into these effects is being undertaken, using both fullscale wind recording in complex terrain, and by testing of scaled topographic models in boundary layer wind tunnels (Booth, 1974). In the future, it may be possible to routinely test topographic models of areas of up to 10,000 hectares in extent, using wind tunnel techniques, and use the results to improve WHC estimates of critical heights.

The second current research project which related to windthrow prediction concerns the question of windloading and momentum absortion in stands established under wider spacing. Widely spaced, or respaced stands on windthrow susceptible sites are likely to comprise individual trees with deeper crowns, and stems with a lower height to diameter ratio. The alteration to stem form produced by wider spacing is likely to confer considerable benefit to the trees stability (Petty and Swain, 1985): the centre of gravity will lie lower down the stem, and there will be less flexural response to windloading in the middle stem region. Under windloading, the crown mass will have a lower horizontal displacement, and contribute less to the overturning moment at the rootplate. Unfortunately, these resistive advantages are likely to be counterbalanced by increased 'windloading' on the larger crown area, and perhaps reduced crown contact to damp out tree swaying.

In addition, deeper wind penetration into the canopy will arise, and increased turbulence in the upper canopy may be generated due to the increased surface roughness in the wider spaced stand. The changes in aeromechanical coupling in low density stands must be adequately quantified, to determine where the balance of the stability advantage lies, on sites with severely restricted tree anchorage. In addition, the reduced timber quality in lower density stands (Hands,1985) will also influence the degree to which wider spacing/respacing can be adopted on windthrow susceptible sites. An investigation is currently in progress, to measure changes in turbulent wind structure and momentum transfer to widely spaced stands.

The use of boundary layer wind tunnels to simulate the forest/turbulence interaction is also being examined, using 1:75 scale model trees at various spacings, and with different shapes and flexibilities of stem and crown.Progress in this aeromechanical research should enable the definition of optimum stand density targets for plantations, to maximise rotation lengths and increase stand values on vulnerable sites.

Any possible improvements in the tree anchorage, resulting from the adoption of alternative site preparation methods which avoid or limit the use of open furrows and continuous plough ridges, will have implications in windthrow prediction. At present, the benefits of non-ploughing methods to root architecture and major stand stability are still to be fully demonstrated and quantified, but any improvements arising can be incorporated into the assessment of site windthrow hazard by soil score modification. Considerable research effort is being applied to the questions of mechanical interaction between tree, root and soil in upland spruce plantations to determine the most effective rooting configuration for improved stability (Coutts, 1983). It is intended that these investigations will precede and underlie any future shift in British forestry practice towards alternative site preparation techniques such as subsoiling, mounding or ridge replacement ploughing. Preliminary analyses of root systems do indicate some modest improvement in root spread on subsoiling. However the potential stability benefits from this improved rooting is counterbalanced by establishment penalites on subsoiling which limit the widespread adoption of the technique to more uniform surface water gley soils (Miller and Coutts, 1986).

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