# Some factors influencing the stability of Sitka in Northern Ireland[1]

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## 1. Introduction

1.1 In 1969 forest management in Northern Ireland was still influenced by the aftermath of the catastrophic winds which had occurred 10 years earlier. Although the number and volume of trees wind damaged was substantially diminished there was still an important proportion of the total production which could be attributed to these phenomenal conditions. Because of this it was decided that a survey should be conducted with a view to identifying and evaluating those site factors which pre-disposed stands to risk of wind damage. An examination of existing sample plots provided the readiest means of assessing damage and recording the appropriate site factors. The effective period covered was probably from 1965 to 1969. Some supplementary evidence was gathered following the gales of January 1974 and is included where appropriate.

1.2 During that period the annual summaries of the monthly weather reports of the Meteorological Office (Anon 1968, 1969, 1970, 1971) indicated that the number of gales and the maximum wind speeds recorded were not abnormal. Nor did any catastrophic amount of wind damage occur. The survey was, therefore, concerned with the attritional damage of the type that can continue from year to year within stands on sites that are susceptible, rather than with the dramatic and extensive damage that results from catastrophic winds occurring at long intervals of time.

1.3 The survey was of an observational character. This was because, while man power resources were available the laboratory facilities which would have been required for detailed scientific examination of, for example, soil physical and chemical characteristics were then unable to cope with this volume of work. At the same time the amount of data that could be analysed was limited by the capacity of existing computer services. It was, however, fortunate that Dr. Michael Kennedy (M. S. O Cinneide) of University College, Galway, was able to undertake a sophisticated

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statistical analysis of the data and his paper is one of those presented in this issue.

## 2. Stand Management

2.1 Although it was not possible to obtain reliable information about the relationship between thinning practice and wind damage the survey was able to produce information on certain other management aspects. The amount of damage recorded in relation to these factors is given in Table 1. Along with the other site factors discussed in the following sections a chi-squared test was applied to this information and a figure of 2943.51 was obtained which, on the face of it, would indicate a high degree of relationship between these management aspects and the amount of windthrow recorded. In this particular case the test is not valid as the results may indicate only that there is, say, a high proportion of edge relative to the total area of plantation or that the plantations are intensively drained. However a subsequent investigation, following the storm of January 1974, into the causes of windthrow of single trees on 85 sites in the North and West of the Province indicated that only 11% of the throw could not be attributed to direct association with artificial features such as drains, racks, plough scores on roads, which accounted for 77%, and natural features such as flush areas or rock outcrops which accounted for the remainder. In these circumstances it was considered that there was a validity in the findings of the survey even though strict statistical testing was not possible.

2.2 Of the factors recorded in Table 1 the most important is that of windthrow-creep. This term signifies the gradual increase in extent of a windthrow area that occurs from year to year, and

TABLE 1
NUMBERS AND PROPORTIONS OF WINDTHROWN TREES IN RELATION TO CERTAIN MISCELLANEOUS SITE FACTORS

| Factor | No. of trees thrown | No. of trees not thrown | Total Number | Proportion thrown % | No. of plots |
|---|---|---|---|---|---|
| Exposed edge | 63 | 879 | 879 | 7·16 | 19 |
| Drain edge ... | 217 | 26,729 | 26,946 | 0.18 | 291 |
| Road edge ... | 15 | 493 | 508 | 2.·95 | 15 |
| Rack or ride ... | 24 | 1,618 | 1,642 | 1·46 | 21 |
| Windtrhrow creep | 307 | 1,971 | 2,278 | 13·48 | 59 |
| Springs or flush | 12 | 1,119 | 1,131 | 1·06 | 4 |
| Any combination | 115 | 3,060 | 3,175 | 3·62 | 29 |
| No abnormality | 14 | 31,298 | 31,312 | 0·04 | 483 |

the implication is that once the canopy of the forest has been broken by windthrow the chances of further damage occurring in the same area are considerably increased. Future management of any stand which has had the canopy broken by windthrow must take into account this very substantial increase in the probability of further damage — it is unlikely that remedial measures regarding the basic site factors can be taken at this stage but it may be possible to lengthen thinning cycles, or to stop thinning altogether, or to bring forward the date of felling.

2.3 The second most important factor is that of proximity to plantation edges. Sample plot location instructions require that plots which fall on the edge of plantations are in fact sited there and are, if need be, semi-circular in shape. In practice this is very seldom done and it is more usual for plots to be located 10 metres approximately from the actual edge of the plantation. The windthrown trees recorded in the survey are not therefore those of the actual edge of the plantation but of a belt about 20 metres or so in width along the edge. In fact it would seem from observation that the actual edge trees are more stable than those to the immediate interior of the plantation. This may be due to the alteration of wind patterns at the edge of the forest — the windthrow resulting from the eddy caused by this disturbance.

2.4 To a certain extent this suggestion is supported by observational evidence in edge zone windthrown areas where the direction of fall is frequently variable indicating a downward rather than a horizontal wind movement. In general it may be concluded that the edge zone is more vulnerable than elsewhere and management should take account of this susceptibility.

2.5 For the reasons given in paragraph 2.1 it is less easy to assess the influence of the next group of factors — that including drains, roads, racks and rides. The survey recorded whether or not any one of these factors was present in the plot, it did not record whether there was a direct relationship with windthrown trees although subsequent observation tends to confirm that such a direct relationship does exist.

2.6 As it is the information available is only sufficient to say that these factors do have an effect on increasing the susceptibility of any site to wind damage, and that there would seem to be a strong indication that the major interruption in the canopy resulting from the presence of a road would be twice as dangerous as the minor interruption caused by racks or rides. This would, however, be influenced to a large extent by the date of construction of the road relative to the age of the plantation and the information gathered regarding the causes of damage to single trees following the gales of January 1974 indicated that only 3% of thrown trees were associated with roads. This compared with 35% of thrown trees which were on rack sides.

2.7 The presence of drains, which do not usually affect the form of the canopy, is less serious and in this instance the increase in instability can be attributed to the interference with the root system. This is to a certain extent confirmed by the 1974 survey which showed that 22% of all single trees that were thrown were on drain edges and 20% were directly associated with plough scores. In both cases the development of eccentric root systems was very marked. A general conclusion from this would be that, given that the rooting system is such that the stand is inherently unstable, then the canopy form is of very great importance and the greater the interruption in the canopy the greater will be the amount of windthrow that can be expected.

2.8 Finally it is worth noting that the presence of springs or flush areas are of importance. There is no evidence to indicate that the presence of springs or flush areas have any influence on rooting patterns although it may be so. Observation would suggest that if there is an influence it is not great. It is suggested that the likeliest reason for the increase in windthrow on these areas is the difference in growth pattern found on them. Flushes and spring lines are frequently associated with increased growth rate which involves a substantial and usually abrupt change in the canopy form presenting an increase in resistance to wind; and, because of increased stem length, causing relatively greater bending moments (with less mutual support) than is experienced by trees in the matrix of the stand. If this assumption is correct then remedial treatment must be aimed at producing as regular a canopy as possible within the stand and this may be achieved by judicious use of fertilisers over the non-flushed areas.

## 3. The Influence of Soil Type

3.1 The amount of damage recorded in the various plots is given in Table 2. When the number of windthrown trees is compared with the number not affected, in relation to the various soil types recognised, a chi-squared figure of 116.23 is arrived at which is sufficiently high to indicate that damage varies significantly with soil type.

3.2 The main reason for this would appear to lie in the rooting patterns developed on the various soils. On brown earths and podzols Sitka roots are abundant to depths in excess of 50 cm although, because most of these soils are shallow, it is not usual

TABLE 2
NUMBERS AND PROPORTIONS OF WINDTHROWN TREES IN RELATION TO THE MAJOR SOIL TYPES

| Soil Type | No. of trees thrown | No. not thrown | Total | Proportion thrown % | No. of Plots |
|---|---|---|---|---|---|
| Brown Earth ... | 1 | 2,056 | 2,057 | 0·05 | 28 |
| Podzol ... ... | 4 | 1,209 | 1,213 | 0·33 | 32 |
| Iron Pan ... | 2 | 1,193 | 1,195 | 0·17 | 27 |
| Gley ... ... | 223 | 12,558 | 12,781 | 1·74 | 239 |
| Peaty Gley ... | 395 | 30,604 | 30,999 | 1·27 | 379 |
| Valley Peat ... | 2 | 691 | 693 | 0·29 | 22 |
| Blanket Peat ... | 139 | 18,284 | 18,423 | 0·75 | 177 |
| TOTALS ... ... | 766 | 66,595 | 67,361 | 1·14 | 904 |

to find much rooting beyond 1m. On gleys root penetration is common to a depth of 35 cm but diminishes rapidly below that and on peaty gleys the abundance of roots diminishes after 30 cm is reached — Table 3 refers. Iron pan soils are usually characterised by the presence of a discontinuous pan and most trees have root systems which can penetrate this at one or more points. The pans are usually at depths of around 25 to 35 cm which would make them comparable in terms of stability with the gleys were it not for this characteristic.

3.3 Rooting development may be restricted either physically or chemically. In the first instance soil bulk densities of over 1.5 have been shown to prevent root penetration. The pan horizon of an iron pan soil would have a density in excess of this but for most other forest soils of Northern Ireland the normal density range would be from approximately 0.6 to 1.3 — well below the range in which root growth might be inhibited. Chemical impedance is possible and some evidence of what may be manganese toxicity has been found in the more acid soils although a similar effect could be caused by the inhibition of growth hormones in flooded roots as suggested by Phillips (1964).

3.4 However the most likely cause of this variation in rooting pattern is the retardation of root growth by inadequate oxygenation. As Sutton (1969) records in a review of literature ". . . inadequate oxygenation is well known (c.f. Barker, 1919; Heinicke, 1932; Leyton and Rousseau, 1958). Aeration was shown by Loehwing (1931) to influence total root surface area, size of root hair zone, degree of vascular differentiation, and fibrousness in roots of several aquatic and terrestrial species. Gail and Long

(1935) demonstrated that distribution of main laterals, number of laterals, and length of tap root of Pinus contorta and P ponderosa were influenced strongly by degree of aeration. Elongation of roots of P sylvestris and Picea abies grown in aerobic unsterilised distilled water or peat extracts from various bogs was ten times that of plants grown in unaerobic conditions (Huikari, 1959) . . . Such evaluations of soil aeration based on gas-phase composition fail to allow for the effect of any liquid surrounding the root. Water thicknesses of 0.08 to 0.35 mm around a root will be sufficient to limit oxygen supply at soil porosities between 0.2 and 0.5 when the oxygen concentration in the pores is in equilibrium with atmospheric oxygen (Letey and Stolzy, 1967)." It would seem, therefore, that rooting is likely to be more closely related to profile drainage characteristics than to other factors.

TABLE 3
NUMBER OF PLOTS SHOWING WIND DAMAGE ON CERTAIN SOIL TYPES AND THE DEPTH OF ROOT PLATES OF WINDTHROWN TREES

| Soil Type | Rooting Depth (cm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 10–14 | 15–19 | 20–24 | 25–29 | 30–34 | 35–39 | 40–44 | 45–49 | 50+ |
| Brown Earth | | | 3 | 3 | 4 | 2 | 1 | 6 | 11 |
| Gley ... ... ... | 5 | 8 | 3 | 11 | 12 | 9 | 9 | 7 | 5 |
| Peaty Gley ... ... | 2 | 6 | 13 | 21 | 17 | 13 | 10 | 4 | 10 |
| TOTAL ... ... | 7 | 14 | 16 | 32 | 29 | 22 | 19 | 11 | 15 |

3.5 The principal effect of this restriction is to produce a set of circumstances in which the liability to damage increases rapidly for unstable trees and less quickly for deep rooting trees. Broadly speaking this means that for any given wind force the poorer the profile drainage the greater will be the extent of damage and, with increasing wind force, the rate of damage on the unstable site will increase much faster than will the rate of damage on the stable site. Returning to Table 2 it will be seen that we can divide the Northern Ireland forest soils into four broad groups for the purpose of classification of wind damage risk. The first group, where the risk is outstandingly great, is that comprising the gleys and the peaty gleys. The indication is that the gleys with a proportion damaged of 1.74% present a greater problem from the point of view of stability than do the peaty gleys, with a proportion damaged of 1.27%.

3.6 The second broad grouping of soil types are the various climatic peats referred to under the general heading of blanket peat in Table 2. The indication here is that with a proportion damaged of 0.75% the risk is only half that of the gleys and peaty gleys. It is unlikely that this increased stability on the blanket peats can be attributed to deeper rooting although there is some evidence that horizontal systems are more extensive. The prime cause may lie in the complex interlocking of the peat fibre at all levels from the mineral soil upwards combined with the extensive development of a fine root system for the Sitka under the highly acid conditions of the peat. This contrasts sharply with the characteristic separation of the top soil — which is usually about 25 cm in depth — from the sub-soil on gleys.

3.7 The third grouping of soil types, which include the valley peats, podozols and iron soils, show proportions damaged of 0.29%, 0.33% and 0.17% respectively — in effect this group can be expected to show approximately half the amount of damage relative to the climatic peats. In this group improved stability is related to the improved rooting conditions. The valley peats are usually highly eutrophic and the water supply is normally telluric — both factors contributing to the development of a stable root system. Podozols are free draining and would normally be highly stable but tend under Northern Ireland conditions to be shallow and weakly developed manganese pans are not uncommon. As has been mentioned in Paragraph 3.3 the iron pan soils usually have discontinuous pans and some degree of through rooting is possible.

3.8 The fourth group, that of the brown earth, has a proportion damaged of 0.05% which may be considered negligible and consequently forest management need not be concerned with wind risk on this type. The low level of windthrow on these soils can be attributed to the development of a deep and stable root system and it is worth noting that the proportion of wind break is highest on this soil type.

## 4. The Influence of Slope

4.1 The amount of damage recorded in relation to the slope of the ground, as measured from a height of 1.4 m on the highest tree to the same height on the opposite tree on the plot margin through the plot centre, is given in Table 4. Application of the chi-squared test to this table gives a result of 238.77 which is sufficiently high to indicate that there is a significant statistical relationship between the angle of slope and the amount of windthrow that has occurred.

4.2 An examination of the data indicates that by far the largest proportion of damage occurs on slopes between 5 and 9 degrees — there being approximately twice as much damage here as there is to be found on level ground or on the next steeper class of slope, that from 10 to 14 degrees. The amount of damage occurring on slopes in excess of 14 degrees is negligible and windthrow does not appear to be a risk that would normally influence management decisions in areas with steep slopes but it is worth noting that topographical influences can be of considerable importance and land form is most likely to be a factor in wind damage where the terrain is steepest.

TABLE 4

NUMBER AND PROPORTION OF WINDTHROWN TREES IN RELATION TO THE GROUND SLOPE OF THE SAMPLE PLOTS

| Slope (in degrees) | No. of trees thrown | No. not thrown | Total | Proportion thrown % | No. of plots |
|---|---|---|---|---|---|
| 0– 4 ... ... | 226 | 31,765 | 31,991 | 0·71 | 349 |
| 5– 9 ... ... | 461 | 23,217 | 23,678 | 1·95 | 347 |
| 10–14 ... ... | 75 | 7,352 | 7,427 | 1·01 | 128 |
| 15–19 ... ... | 3 | 2,981 | 2,984 | 0·10 | 52 |
| 20–24 ... ... | 2 | 1,282 | 1,284 | 0·16 | 31 |
| 24+ ... ... | 0 | 507 | 507 | 0·00 | 14 |
| Total ... ... | 767 | 67,104 | 67,871 | 1·13 | 921 |

4.3 In broad terms, therefore, it is possible to divide the forest into three risk classes from the point of view of slope: with the reservation that there may be topographical influences of which account should be taken. The first class in which the risk is as high as it is on gleysols, is represented by slopes of 5 to 9 degrees. The second group, with a degree of risk approximately half that of the first, is represented by relatively level ground and slopes from 10 degrees to 14 degrees. The third group, in which the risk appears very small (but where the influence of topography may be large), is represented by all steeper slopes.

4.4 In attempting to attribute the wind risk characteristics of various slopes to environmental factors one must return to the basic mechanics of windthrow which requires that the centre of gravity of the tree be displaced beyond the base before the tree can fall. The extent of the base is determined by the rooting system which in turn is influenced by the physical nature of the soil and the effect that has upon the soil hydrology. As has already been suggested it is the water in the soil that controls root development and under the limiting conditions imposed by high winter water tables deep rooting is prevented on most forest soils. On steeper slopes drainage is improved through the natural downhill movement of water and soil depths are frequently increased through the process of solifluction from upper slopes. These factors together contribute to lessening the restrictions on root development and hence increasing stability.

4.5 This may appear to be a somewhat contradictory statement in view of the substantial increase in stability of trees on more or less level ground compared with those on slopes of 5 to 9 degrees. There are, however, two reasons for this increase in stability; both based on the profile drainage characteristics of the site. In the first instance, at higher elevations, iron pan formation is common, following leaching of the better drained soils, and elsewhere unsorted and unstratified glacial deposits inhibit water movement down the profile. Under these conditions of poor drainage, and with the deterioration of climate at higher elevations, peat formation can be expected to proceed at a rapid rate and bogs are likely to be deeper here than lower down the hill. It has already been shown (Paragraph 3.6) that there appears to be characteristically more stability on deep peats than on the closely related peaty mineral soils.

4.6 The second probable reason for the increase in stability on relatively level ground may be attributed to the existence of limited areas of deep, well-drained lowland soils which would not normally form part of the forest estate but were acquired along with the more extensive areas of hill land usually purchased.

4.7 Because of the close relationship between the rooting pattern and stability, and the fact that root development is substantially influenced by profile drainage it would be reasonable to expect to find a relationship between soil type — which is determined to a great extent by profile drainage — and most other factors which are significantly related related to windthrow. An examination of the data given in Table 5 and the application of a chi-squared test to the observed and expected frequencies of soil types within each slope class indicates that there is a highly significant relationship between soil type and slope. The number of gleyed plots diminishes directly and rapidly with increasing slope. Peaty gleys are most common on slopes of 5 to 9 degrees and there are more peaty plots on the more or less level sites. In contrasting the freely drained soils with those characterised by impeded drainage — the brown earths with the gleys and peats — 74% of the plots on the latter types fell on slopes of less than 9 degrees compared with 44% of the former.

TABLE 5

NUMBER OF PLOTS OF FOUR MAJOR SOIL TYPES IN RELATIONSHIP TO SLOPE OF THE GROUND WITHIN THE PLOT

| Slope (in degrees) | Brown earth | Gley | Peaty gley | Peat | Total |
|---|---|---|---|---|---|
| 0– 4 ... ... | 118 | 250 | 164 | 164 | 696 |
| 5– 9 ... ... | 216 | 225 | 206 | 106 | 753 |
| 10–14 ... ... | 149 | 67 | 121 | 52 | 389 |
| 15–19 ... ... | 100 | 26 | 50 | 12 | 188 |
| 20–24 ... ... | 112 | 13 | 13 | 5 | 143 |
| 25–29 ... ... | 49 | 5 | 3 | 10 | 67 |
| 30–34 ... ... | 17 | 1 | 1 | | 19 |
| 35–39 ... ... | 4 | 2 | 1 | | 7 |
| 40–44 ... ... | | | | | 0 |
| 45–49 ... ... | 1 | | | | 1 |
| Totals ... ... | 766 | 589 | 559 | 349 | 2,263 |

4.8 Reference now to Table 2 shows that of all Sitka spruce production forest in 1969 68% was planted on gleys and peaty gleys, 20% on blanket peats and the remainder (including 3% on brown earths) on other soil types. Given that increasing peat depth appears to have a favourable influence on stability then the reduction in windthrow on level ground as compared with the moderate slopes can be attributed to the higher proportion of deeper peats on these sites.

**5. The Influence of Aspect**

5.1 The amount of damage recorded in relation to the aspect of the plot assessed from a central position and taking into account the general topography of the vicinity is given in Table 6. When the number of trees windthrown is compared to the number unaffected by wind a chi-squared figure of 264.66 is derived indicating a highly significant statistical relationship between aspect and wind damage.

5.2 Examination of this table indicates that two broad risk classes are discernible. The least risk is encountered on slopes

TABLE 6
NUMBERS AND PROPORTIONS OF WINDTHROWN TREES IN RELATION TO THE ASPECT OF THE PLOT

| Aspect | No. of trees thrown | No. not thrown | Total | Proportion thrown % | No. of plots |
|---|---|---|---|---|---|
| N ... ... | 180 | 7,200 | 7,380 | 2.44 | 123 |
| NE ... ... | 223 | 17,361 | 17,584 | 1·27 | 179 |
| E ... ... | 50 | 14,885 | 14,935 | 0·33 | 136 |
| SE ... ... | 116 | 5,864 | 5,980 | 1·94 | 86 |
| S ... ... | 34 | 4,341 | 4,375 | 0·78 | 74 |
| SW ... ... | 26 | 3,801 | 3,827 | 0·68 | 78 |
| W ... ... | 38 | 5,563 | 5,601 | 0·68 | 81 |
| NW ... ... | 98 | 7,378 | 7,476 | 1·31 | 141 |
| Flat ... ... | 2 | 713 | 713 | 0·28 | 23 |

facing the south, south-west and the west; and there would appear to be twice as much chance of windthrow occurring on slopes with aspects ranging from north-westerly through north to south-easterly. There are anomalies within this range. The northerly aspect would appear to be twice as risk prone as the rest of the group and, if the figures are to be taken literally, there would appear to be virtually no risk from wind if an easterly aspect is chosen for planting. However the assessment of espect is essentially based on a broad subjective judgement with some assistance from the compass and any grouping of aspects with a view to allocation to risk classes must be made with this in mind.

TABLE 7
RELATIONSHIP BETWEEN THE DIRECTION OF THE WIND AND THE NUMBER OF PLOTS WITH DAMAGE

| Wind from | Number of plots with damage | Proportion of total (%) |
|---|---|---|
| S ... ... ... | 7 | 2·8 |
| SW ... ... ... | 41 | 16·6 |
| W ... ... ... | 70 | 28·3 |
| NW ... ... ... | 54 | 21·9 |
| N ... ... ... | 39 | 15·8 |
| NE ... ... ... | 6 | 2·4 |
| E ... ... ... | 4 | 1·6 |
| SE ... ... ... | 10 | 4·1 |

5.3 If these broad groups are considered in relation to the information concerning wind direction given in Table 7 it will be seen that there is a general relationship between the aspect factor and wind direction. Winds from north through west to south-west account for 88% of all damage — and 87% of all damage occurs on slopes with aspects from north-west through north to south-east. If it is suggested that there is a relationship between damage and lee slopes then a contingency table, Table 8 can be constructed. Application of the chi-squared test to these figures gives a result of 187.88 which would suggest that the relationship is a real one.

TABLE 8
RELATIONSHIP BETWEEN WIND DIRECTION AND LEE SLOPE DAMAGE

| Wind from | S | SW | W | NW | N | NE | E | SE |
|---|---|---|---|---|---|---|---|---|
| Number of plots damaged | 7 | 41 | 70 | 54 | 39 | 6 | 4 | 10 |
| Number of trees damaged | 180 | 223 | 50 | 116 | 34 | 26 | 38 | 98 |
| Aspect | N | NE | E | SE | S | SW | W | NW |

5.4 Gloyne (1968) has suggested that the obstruction to flow of wind by the major geographic features of the Earth's surface, such as the Rocky Mountains, can impose recognisably distinct readjustments of the pressure field but in the British Isles the only such case of importance is the now well documented lee-wave phenomenon. This arises when an air-stream of particular velocity and temperature structure in the vertical blows across a range of suitably spaced hills which may be only a few hundred feet in height. Sympathetic undulations are set up in the upper current and strong surface winds are induced which blow down lee slopes. In more mountainous country, where the lee-wave phenomenon is absent, damage may still be markedly associated with lee slopes (Aanensen, 1965). In these circumstances it is not uncommon to find that a point about one third of the way down the lee-slope experiences more severe damage than elsewhere. This is generally attributed to the effects of turbulence. In either event lee slopes are more susceptible than windward slopes.

5.5 In addition to the influence of wind there are two other factors that can be taken into account when attempting to explain the greater susceptibility to wind damage of trees on northern and eastern slopes. The first is that the total solar daily energy available is limited and the net amount received by unit area of ground is related to the angle of incidence of the suns rays. In broad terms south facing slopes can be expected to receive substantially more energy than north facing slopes. Most of the energy received is dissipated in the evaporation of water but insufficient energy is available to evaporate all water at all times and north slopes are less favoured in this respect than others, and there is therefore a greater tendency for peat formation to occur there. As has been shown peaty mineral soils are likely to be inherently unstable.

5.6 The second factor which renders lee-slope forest unstable is related to the positive geotropism shown by most roots. By the concentration of growth hormones, through gratívational influence, in the lower parts of meristematic regions roots grown downwards. Where the development of the vertical system is inhibited through the presence of a restricting sub-stratum, the horizontal system may demonstrate the same characteristic, but to a lesser extent, by the downhill orientation of roots on slopes. Scale drawings of typical root systems are given in Fig 1. In terms of susceptibility to wind damage this means that lee-slope trees are generally inefficiently anchored to the soil on the uphill side and are there-

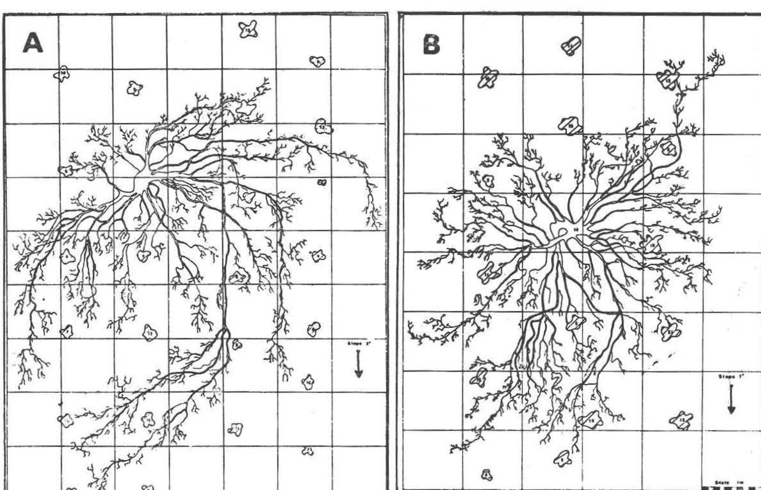


Figure 1: Plans of the horizontal rooting systems of Sitka spruce, aged 21 yeare in Lisnaskea Forest. A on 3° slope, B on 7° slope. The plans ars divided into 1 m. squares.

fore inherently more unstable than those on the windward slope which have improved anchorage.

**6. Influence of Altitude**

6.1 The amount of damage recorded in relation to the altitude of the plot as estimated from the 6" Ordnance Survey map is given in Table 9. When the number of trees thrown is compared with the number unaffected by wind for each altitudinal class a chi-squared figure of 84.97 is derived indicating that there is a significant statistical relationship.

TABLE 9
RELATIONSHIP BETWEEN THE NUMBER AND PROPORTION OF WINDTHROWN TREES IN RELATION TO THE ESTIMATED ALTITUDE

| Altitude above OD | No. of trees thrown | No. of trees not thrown | Total | Proportion thrown % | No. of plots |
|---|---|---|---|---|---|
| 0 – 150′ | 1 | 805 | 806 | 0·12 | 25 |
| 151′– 300′ | 16 | 2,085 | 2,101 | 0·76 | 62 |
| 301′– 450′ | 2 | 3,581 | 3,583 | 0·06 | 48 |
| 451′– 600′ | 81 | 4,487 | 4,568 | 1·77 | 113 |
| 601′– 750′ | 182 | 12,733 | 12,955 | 1·40 | 187 |
| 751′– 900′ | 412 | 34,789 | 35,210 | 1·17 | 265 |
| 901′–1,050′ | 56 | 5,893 | 5,949 | 0·94 | 136 |
| 1,051′–1,200′ | 17 | 1,888 | 1,905 | 0·89 | 60 |
| Above 1,200′ | 0 | 794 | 794 | 0·00 | 25 |

6.2 Examination of the data in Table 9 indicates that, with the exception of the anomaly in the 300' to 450' zone (which may be fortuitous and ascribed to the small number of plots), the proportion of damage increases with increasing altitude reaching a maximum at between 451' and 600' and thereafter decreasing until a point is reached at the highest elevations where no damage at all occurs. In general terms this trend follows expected soil development patterns with the better drained soils, usual at lower elevations, giving way to gleys and then to shallow peaty mineral soils and finally, on the highest regions, to deep peat. Again, as with aspect, the role of climate is important. Increasing elevation brings in turn decreasing temperatures and increasing rainfall — both factors which play a predominant part in the processes of peat formation.

6.3 Although it is suggested that soil type is a better indicator of site susceptibility to wind change than altitude it is worth noting that elevation and wind strength and gustiness are related. At altitudes of 2,000 to 3,000 feet winds are governed by pressure gradients and by the rotation of the earth (Gloyne 1963). Below that level friction, and other forces, reduce wind speed but increase gustiness. At the lowest levels, below 450', a degree of shelter exists and in forests at these levels the effect of gustiness is reduced. Because of this, and the generally better rooting conditions at these lower altitudes, risk of wind damage is reduced. At the highest elevations gustiness is reduced and wind speed increased. Trees tabituated to high wind speeds tend to develop root systems adapted to their habitat and this, combined with a greater stability found on deep peat — which is more common at high elevations — would explain the reduction in damage.

**7. The Influence of the Solid Geology**

7.1 The amount of damage recorded in relation to the parent material from which the soil of the plots was derived, as determined by an examination of the stones found in the plot area, is given in Table 10. When the number of windthrown trees is compared with the number of unaffected in relation to parent material a chi-squared figure of 914.70 is derived indicating a highly significant statistical relationship between windthrow and the solid geology.

TABLE 10
RELATIONSHIP BETWEEN THE NUMBER AND PROPORTION OF WINDTHROWN TREES IN RELATION TO THE PARENT MATERIAL FROM WHICH THE PLOT SOIL WAS DERIVED

| Parent Material | No. of trees damaged | No. of trees not damaged | Total | Proportion damaged | No. of plots |
|---|---|---|---|---|---|
| Basalt ... ... | 560 | 44,991 | 45,551 | 1·23 | 396 |
| Triassic associates of Basalts ... | 113 | 998 | 1,111 | 10·17 | 35 |
| Schists ... ... | 37 | 8,748 | 8,785 | 0·42 | 242 |
| Carboniferous ... | 48 | 8,713 | 8,761 | 0·55 | 159 |
| Old Red sandstone | 0 | 181 | 181 | 0·00 | 6 |
| Granite ... ... | 4 | 2,231 | 2,235 | 0·18 | 57 |
| Silurian ... ... | 5 | 1,242 | 1,247 | 0·40 | 36 |

7.2 If the results for the Triassic soils and the Old Red Standstone are set aside — the number of plots are small and they are concentrated largely in two separate forests where the management may have influenced the degree of risk — then three broad risk classes can be identified. The lowest is represented by those soils derived from granites of South Down. The next class, where the risk is apparently twice as great, is formed from soils derived from schists, Silurian rocks, and the wide variety of Carboniferous strata. The highest rick class is on soils formed from basalts.

7.3 At first sight this would appear to be a reasonable conclusion. Basalts tend to weather to fine particles which might be expected to produce a heavy soil. The sedimentary and metamorphic rocks contain a proportion of hard quartzitic materials which should improve soil structure, and hence drainage, and the crystalline structure of the granites usually produces sandy, well drained soil. However these statements imply normal particle sorting such as occurs under the usual conditions of profile development. This is not the case with most of the Northern Ireland forest soils where the parent material is in the form of glacially deposited, unsorted and unstratified rock fragments. The granitic soils were furthest from the centres of distribution of the last ice advance and are least affected, most other soils are very widely evolved from glacial till which, because of its structure, is inherently poorly drained. This being the case we must look further to explain the apparent difference in susceptibility to windthrow of forests on soils derived from various parent materials.

7.4 In the early days of forestry in Northern Ireland, prior to 1930, acquisitions were limited mainly to old woodland sites associated with the larger estates. These were mostly well drained, lowland soils. During the 1930-1940 period further acquisitions were made in what was then marginal agricultural land on the poorer drained sites at higher altitudes. For historical reasons these acquisitions were largely concentrated on the basalt plateaux of Antrim and Derry, and, to a certain extent, the schistoze soils of the Sperrins. The first major acquisitions of carboniferous soils were made after 1940.

7.5 Historically the acquisition of forest land in all of the major geological regions has shown much the same pattern — well drained sites are acquired first, then gleyed soils, followed by the peaty soils of the upper middle slopes and finally the deep peats of the high elevations. This pattern has meant that the forests of the basalt plateaux were at a stage of growth and management which rendered them highly susceptible, and it is this factor of age (or more properly of height) rather than the nature of the parent material, which may influence the analysis.

7.6 Table 11 shows the relative proportion of the major soil groups in relation to parent material of those plots that were included in the survey. As only production forest was involved this reflects the position about 1955. The current position will indicate little change in the basalts, schists and pranites but soils of the Silurian, and in particular the Carboniferous series, will show a substantial increase in the peaty gleys and the peats. This trend has been accentuated in the last 20 years as techniques have been developed that make afforestation, and hence acquisition, of high altitude peats possible.

TABLE 11
RELATIVE PROPORTION OF SOIL TYPES FOR THE MAJOR GEOLOGICAL ZONES

| | Parent Material | | | | |
|---|---|---|---|---|---|
| Soil Type | Basalt | Schist | Carbon-iferous | Silurian | Granite |
| Brown earths and other well drained soils | 14 | 13 | 38 | 80 | 44 |
| Gleys ... ... | 35 | 15 | 49 | 8 | 12 |
| Peaty gleys ... | 31 | 51 | 6 | 7 | 11 |
| Peats ... ... | 20 | 20 | 6 | 5 | 33 |

**8. The Relationship Between Site Fertility and Windthrow**

8.1 The amount of damage recorded in relation to the fartility of the site as measured by the estimated yield in cubic metres per hectare per annum for the rotation of the maximum mean annual increment and determined from the top-height/age relationships of the Forestry Commission Management Tables (Forestry Commission Booklet No. 34 HMSO 1971) is given in Table 12. Application of a chi-squared test to this information gives a result of 1192.79 which indicates that there is a very significant statistical relationship between the amount of damage and the yield class.

8.2 The 1970 Inventory Survey of Northern Ireland's State Forests indicated that the mean yield class for Sitka spruce on peat soils was 9.3, for peaty-gleys the mean was 11.8 and on gleys yield averaged 14.6. As has already been shown in Section 4 there is a strong relationship between soil type and stand stability, with the peats being substantially more stable than the peaty-gleys which are marginally more stable than the gleys. This finding would confirm the general trend of Table 12 up to yield class 16. On the more fertile sites in yield classes 16 to 20 productivity can be associated with the existence of spring lines or extensive flushes and these have been shown, in paragraph 2.8 to be among the sites with a greater susceptibility to wind damage.

TABLE 12
NUMBERS AND PROPORTION OF TREES WINDTHROWN IN RELATION TO THE YIELD CLASS

| Yield class | No. of trees thrown | No. not thrown | Total | Proportion thrown % | No. of plots |
|---|---|---|---|---|---|
| 0 ... ... | 0 | 104 | 104 | 0 | 5 |
| 2 ... ... | 0 | 446 | 546 | 0 | 18 |
| 4 ... ... | 0 | 826 | 826 | 0 | 32 |
| 6 ... ... | 16 | 1,482 | 1,498 | 1·07 | 52 |
| 8 ... ... | 0 | 1,193 | 1,193 | 0 | 35 |
| 10 ... ... | 8 | 1,802 | 1,810 | 0·44 | 53 |
| 12 ... ... | 180 | 9,802 | 9,982 | 1·80 | 251 |
| 14 ... ... | 152 | 5,513 | 5,665 | 2·68 | 145 |
| 16 ... ... | 239 | 6,160 | 6,399 | 3·73 | 152 |
| 18 ... ... | 139 | 3,695 | 3,836 | 3·62 | 79 |
| 20 ... ... | 22 | 1,050 | 1,072 | 2·05 | 33 |
| 22 ... ... | 6 | 718 | 724 | 0·83 | 17 |
| 24 ... ... | 0 | 74 | 74 | 0 | 5 |

8.3 The highest yielding trees have two characteristics which may make a material contribution to the apparent increase in stability. The first is that for physiological reasons needles are seldom retained on the most vigorous trees beyond three years whereas on slower growing trees retention periods can be as much as 10 years and this combined with the characteristic production of two whorls of branches every year, more or less irrespective of vigour, means that the fast growing tree presents a much lower degree of wind resistance than does the slower growing trees. If this conclusion is valid it is another indication of the importance of the form and structure of the forest canopy.

## 9. The Relationship Between Exposure and Windthrow

9.1 The amount of damage recorded in relation to the exposure of the site as measured by the sum of the angles of inclination to the horizon at the eight main points of the compass from the plot centre (the Topex system) is given in Table 13. Application of a chi-squared test to this information gives a result of 1192.79 indicating a significant relationship between the topex rating and the amount of windthrow.

9.2 No measurement of topography was made during the survey owing to the practical difficulties involved in classification and assessment; but the Topex measure of exposure would perhaps be more correctly considered a measure of the relative topography. Exposure is compounded of many factoes and there are as many

TABLE 13

NUMBER AND PROPORTION OF WINDTHROWN TREES IN RELATION TO THE EXPOSURE OF THE PLOTS AS MEASURES BY THE TOPEX SYSTEM

| Exposure (degrees) | No. of trees thrown | No. not thrown | Total | Proportion thrown % | No. of plots |
|---|---|---|---|---|---|
| Severe (0–10) ... ... | 37 | 1,252 | 1,289 | 2·87 | 40 |
| Very exposed (11–30) ... ... | 693 | 53,839 | 54,532 | 1·27 | 630 |
| Moderate (31–60) ... ... | 33 | 10,910 | 10,943 | 0·30 | 220 |
| Sheltered (61–100) ... | 4 | 1,103 | 1,107 | 0·36 | 31 |
| Totals ... ... | 767 | 67,104 | 67,871 | 1·13 | 921 |

opinions regarding the degree of exposure of a site as there are factors involved. It is therefore useful to have a basic reference point and the Topex system does provide this although it has obvious faults — a site at the base of a cliff exposed to westerly gales could be rated as 'sheltered' when, from the point of view of tree growth, the only sensible classification would be 'severely exposed'. This would be a major drawback under certain conditions; but in Northern Ireland this problem does not arise with the exception of the escarpment faces of the basalt and Carboniferous plateaux. In most other areas of the country the system probably provides a fair evaluation of the relative topography and as such may be of value in site assessment.

9.3 Table 13 indicates that a Topex rating of 'severe' is likely to indicate a high degree of windthrow risk, sites in this class being more than twice as prone to damage as sites in the next class — 'very exposed'. 'Moderately exposed' sites and 'sheltered' sites are substantially less liable to damage. However, a significant proportion of trees are thrown in these areas and they cannot be accounted 'safe' from the point of view of stability. It is only in the 'very sheltered' sites — those with a Topex rating of over 100° — that wind risk might be considered negligable and as none of the plots examined fell into this class no firm conclusions can be drawn.

9.4 As well as being a measure of land form the Topex system is also related to altitude. With higher elevations the chances of a Topex rating for a plot to approach zero will become greater. It follows that there will be an increased proportion of peats and gleys in the lower ratings with an additional possibility of damage occurring. At the same time the lower Topex ratings indicate a low relief topography and, as has been shown, this characterises the type of country in which the lee-wave phenomenon is most marked with the consequential increase of wind damage risk on lee slopes. It would seem, therefore, that assessment of Topex ratings, while of doubtful use as a measure of exposure, can nevertheless serve a useful purpose in the estimation of wind risk.

**10. The Assessment of Windthrow Risk**

10.1 The survey gathered information on eight groups of factors which it was thought might influence the degree of risk of windthrow. The application of statistical tests to this data has shown that, with certain reservations, significant relationships exist, thus justifying the use of this type of site and management information in the assessment of that risk. A means of doing this is given in Dr. Kennedy's paper.

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