Quantitative assessment of the relative importance and cooperative effects of factors influencing forest instability[1]

M. S. O CINNEIDE[2]

1. Introduction

CONSIDERABLE progress has been made in recognising the factors that lead to windblow in forest plantations. These may be classified into three broad groups, (a) those relating to characteristics of individual tree species, (b) those relating to composition and structure of forest plantations, and (c) environmental variables. The first two groups are largely the concern of the botanist and the silviculturist and are not considered in this paper. Environmental variables shown to be significant to windblow processes include bedrock, soil-type, slope, altitude, exposure, and aspect. This paper assesses the relative importance of these variables and explores their co-operative effects on forest instability.

2. Approaches to the Study of Windblow

Research on windblow has been carried out along two distinct but complementary lines. One has dealt primarily with the factors affecting the resistance of trees to wind damage. The second line pursues the processes of windthrow, such as the forces that wind applies to trees and the forces that a tree can resist. The latter approach has the advantage of being a direct observational or experimental method and is consequently more focussed on the processes *per se*, whereas the former generally is circumstantial and comes after the processes have occurred. The direct observational method is, however, wrought with many difficulties including the inconvenience of having to observe the study area during storms. Because of this, much work along this line has retreated from the forest to the greater comfort of laboratories where an effort is made to simulate natural conditions. This research has been executed along the first of these lines as it is by

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1. Paper delivered at Wind Risk Symposium, Pomeroy, Co. Tyrone, 1st-3rd May, 1974.
2. Department of Geography, University College, Galway. (Present address: National College of Physical Education, Limerick).

far the best method for the individual researcher with limited resources, while capable of yielding valuable insights as to the nature of windblow.

3. Field Investigations

Choice of a suitable field study area was guided by the foslowing criteria: (a) wind damage should be a frequent occurrence; (b) forests established on sites that exhibit a wide range of the environmental variables affecting windthrow should exist; (c) existence of data on wind damage was deemed highly desirable. The coniferous plantations of Northern Ireland met these criteria well and were chosen without hesitation.

Windblow data collerted in 1969 by the Ministry of Agriculture, Northern Ireland were made available to this author. A total of 2,590 sample plots, 0.04 hectares (one-tenth acre) in size, were investigated. Intensity of windthrow and windsnap together with the level of variables believed to be significant to wind damage were recorded. Data for 33 of these plots were unacceptable because of incompleteness and ambiguity. Because of the huge sample size it was deemed unnecessary to substitute for these plots. Consequently, a total of 2,557 plots were available for analysis.

4. Analytical Difficulties

A great number of variables are involved in the processes of windthrow. The major difficulty is one of determining which variables are most functionally related to the phenomenon and under what conditions and through which intervening processes do these functional relationships find their greatest manifestation. This research is primarily associated with the inductive phase of model development in as much as *ex post facto* explanations of the relationships found within the data form the basis for developing much more specific hypotheses (middle-range theory) to be tested later.

Because of the large number of potential explanatory variables the task of isolating the relationships within the data is not easy. Among the complicating factors are:

(a) Interactions and intercorrelations between the causal variables. Many of the factors involved do not produce their effects simply. Rather, interaction of a high order with those of other factors are involved. Thus some factors tend to augment the effects of other factors in such a way that the combined effects are greater than the sum of the individual effects. This phenomenon is known in ecology parlance as synergism. Some factors tend to nullify the effects of other factors thus making detection difficult. Because of intercorrelations between the causal variables it is difficult to establish to which variable can variation in the dependent variable be rightly attributed.

(b) Measurability difficulties. Some of the variables involved cannot be quantitatively measured on a continuous scale, but at best on an ordinal scale and in some cases on a purely nominal scale. The nonparametric nature of these variables defies the fruitful application of many conventional mathematical models to the problem.

(c) Stratification in sampling. To ensure reasonable representation of minority conditions it was necessary to stratify the original sample despite its huge size. This renders the significance tests usually employed in multivariate analysis models inapplicable.

(d) Nonlinearity. The absence of linear relationships between many of the causal variables and the dependent variables all but eliminates the possibility of devising a simple model that adequately explains the dependent variables.

(e) Spatial autocorrelation. This makes void the assumption of independence between observations.

(f) The highly skewed nature of the dependent variables. As most parametric statistical models assume normality they could not be properly applied to the present data without considerable transformations inevitably resulting in information loss.

(g) The meristic nature of the dependent variable. As windthrow could only assume integer values it does not meet the assumptions of many statistical models.

These difficulties led to a search for a model capable of (a) handling a large number of explanatory variables, (b) showing how these variables interacted with one another to determine the distribution of the dependent variable, and (c) doing (a) and (b) with nonparametric data and without the assumptions of normality, homoscedacity, linearity, and additivity. Conventional multivariate models such as those employed in regression and factor analysis clearly do not meet the criteria. The Automatic Interaction Detection (AID) model developed at the Institute for Social Research, The University of Michigan (Sonquist and Morgan, 1964), was designed specifically for this type of problem. The basic idea in the model is the sequential identification and segregation of subgroups one at a time, nonsymmetrically, so as to select the set of subgroups that will reduce the error in predicting the dependent variable as much as possible relative to the number of groups. The model is described briefly by Sonquist (1970, p. 20):

The technique is a step-wise application of a one-way analysis of variance model. Its objective is to partition the sample into a series of non-overlapping sub-groups whose means explain more of the variance in the dependent variable than any other such set of subgroups. The algorithm actually implemented is as follows:

1. Select that as yet unspilt and untried sample group, group i, which has the largest total sum of squares. (The total input sample is considered the first, and indeed only, group at the start).

2. Fnd the division of the Ck classes of any single predictor Xk such that combining classes to form the partition p of this group i into two non-overlapping sub-groups on this basis provides the largest reduction in the unexplained sum of squares. Consider all possible binary splits on all predictors with the restrictions that (a) the classes of each predictor are ordered into descending sequence, using their means as a key and (b) observations belonging to classes which are not contiguous (after sorting) are not placed together in one of the new groups to be formed. Restriction (a) may be removed, by option, for any predictor Xk.

3. For a partition p on variable k over group i actually to take place after completion of step 2 it is required that the between group sum of squares associated with this partition be larger than an arbitary constant Q. It is also required that the total sume of squares for group i be larger than an arbitrary constant P. If neither of these criteria are met, group i is not capable of being split and the next most promising group (having the maximum total sum of squares) is selected via step 1.

4. If there are no more unsplit groups such that requirements P and Q are met or if the number of currently unsplit groups exceeds an arbitrary integer R, the process terminates.

This model was deemed appropriate and has been employed in the following analysis.

5. Analysis and Findings

Parent material, soil-type, slope of terrain, altitude, exposure, aspect, species, and age of trees were employed as predictor variables in the AID analysis. Slope, altitude, exposure, and age of trees were monotonically constrained; all possible splits based on the remaining four variables were permissable. For a split to occur, a reduction in the unexplained sum of squares amounting to one per cent of the initial total sum of squares had to be achieved. Splits resulting in group membership of less than 10 were prohibited. Groups with less than $1x10^{-5}$ of the initial total sum of squares were not considered eligible for splitting.

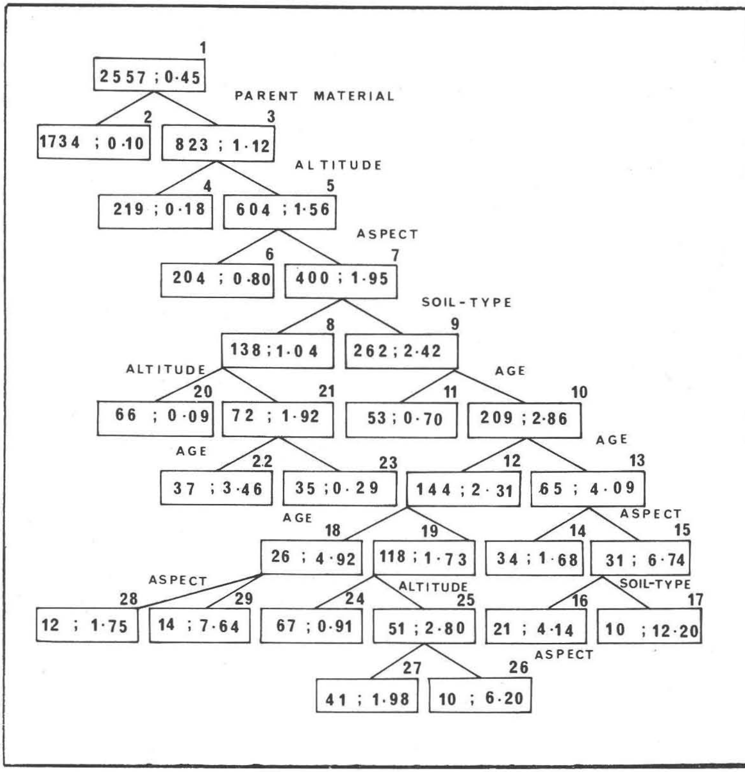

Figure 1: Summary of AID analysis of windthrow. The entry on the left in each box refers to the number of sample quadrats; the entry on the right is the mean number of trees thrown in these quadrats. The group number is listed beside each group. The variable used to perform each binary split is also shown.

Figure 1 summarizes the results of the AID analysis. The parent group, i.e. the total sample, has 2557 sample quadrats with a mean of 0.45 thrown trees per quadrat. The most efficient single predictor is parent material. With the aid of that variable a binary split was performed which isolated all quadrats with basalt and all basaltic "associates" into group 3 and all remaining quadrats into group 2. The mean number of thrown trees per quadrat in the latter was only 0.10 while damage in the former group was 11 times greater with a mean of 1.12 thrown trees per plot.

Group 3 had the greatest total sum of squares after the first split. In the next iteration this group was subdivided with the aid of altitude. The 219 cases that constitute group 4 had an altitude of 137 metres or less. The mean number of thrown trees in this group was 0.18. Group 5, which consists of all cases of group 2 with an altitude greater than 137 metres, has 604 members with a mean of 1.56 thrown trees per plot. Plantations on basalt and basaltic "associates" situated at altitudes greater than 137 metres are approximately 9 times more vulnerable to windthrow than plantations on the same rocks at lower altitudes and almost 16 times more vulnerable than plantations on all other rock types irrespective of altitude.

Of the 3 candidate groups available for splitting at the end of the second iteration group 5 had the largest total sum of squares and was successfully split using aspect as the predictor variable. Quadrats with eastern, southern and southwestern aspects were isolated into group 6 while all remaining quadrats were placed in group 7. Group 6 consists of 204 cases with a mean of 0.80 thrown trees per quadrat. Group 7 is composed of 400 cases with a mean of 1.95 thrown trees per plot. Plots on basalt and basaltic "associates" at altitudes greater than 137 meters with northern, northeastern, southeastern, western and northwestern aspects experienced over twice as much windthrow as those on the same parent materials, at the same elevations, but with eastern, southern and southwestern aspects and almost 10 times as much windthrow as plots on parent materials other than basalt and basaltic "associates" irrespective of altitude or aspect.

Of the four candidate groups available for splitting at the end of the third iteration group 7 had the greatest total sum of squares. The most efficient predictor variable was soil-type and was used to subdivide group 7 into groups 8 and 9. Group 8 has 138 quadrats, 98 of which are peat and 40 of which are brown earths. The mean number of trees thrown per plot is 1.04. Group 9 has 262 members, 172 of which are peaty gleys, 80 of which are non-peaty gleys, and 10 of which are iron pan soils. The mean number of thrown trees per quadrat in this group is 2.42. Thus, plantations on basalt or basaltic "associates", at altitudes greater than 137 metres with northern, northeastern, southeastern, western and northwestern aspects, with gleys and iron pan soils were more than twice as heavily damaged as plantations on the same rocks, at the same altitudes, with the same aspects, but with peaty or brown earth soils. The intensity of damage in group 9 is over 24 times greater than that in group 2.

Of the five candidate groups available for splitting at the end of the fourth iteration, group 9 was found to have the greatest total sum of squares. The most efficient variable at reducing the sum of squares in a binary split was age of trees. Thus group 9 was subdivided into groups 10 and 11. Plantations 20 years old or more were classified in group 10 while plantations less than 20 years old were classified in group 11. The mean number of trees thrown in group 10 was 2.86 while a mean of 0.70 was thrown in group 11. Thus plantations on basalt or basaltic "associates", at altitudes greater than 137 metres, with northern, northeastern, southeastern, western and northwestern aspects, with gley and iron pan soils, and 20 years old or more are over four times as vulnerable to damage as plantations on same rocks, altitudes, aspects, and soils, but less than 20 years old. The intensity of damage in group 10 is 28 times greater than that in group 2.

At the end of the fifth iteration group 10 had the largest total sum of squares. The binary split which most successfully reduces the sum of squares was accomplished using age of trees as the independent variable. Thus group 10 was subdivided into groups 12 and 13. All quadrats aged between 20-24 years inclusive were isolated in group 13 with a mean of 4.09 thrown trees per quadrat. Plots 25 years old or more are classified in group 12 with an appreciably lower rate of damage than their younger counterparts.

At the end of the sixth iteration group 13 was the candidate group which qualified for splitting. The variable employed in the splitting was aspect; plots with a northern or northeastern aspect were classified in group 15 while the remaining plots, with south-east, west, and northwest aspects, were entered in group 14. Damage in the former was 4 times greater than that in the latter and over 57 times greater than that in group 2.

At the end of the seventh iteration group 15 had the greatest unexplained total sum of squares. The most efficient variable in reducing this variation proved to be soil-type which was therefore employed to divide group 15 into groups 16 and 17. Group 16 consists of 21 quadrats all of which have peaty gley soils with a mean of 4.14 thrown trees per quadrat. Group 17 is composed of 10 quadrats all of which have nonpeaty gleys with a mean of 12.20 thrown trees per quadrat. The intensity of damage in group 17 is approximately 3 times that in group 16, 27 times that for the total sample, and 122 times that of group 2. It has by far the highest rate of damage of all the subgroups identified. Thus the most precarious position for a tree is (a) on a nonpeaty gley, (b) on a north or northeast facing slope, (c) in the 20-24 year age group, (d) at an altitude of 138 metres or greater, and (e) with a basaltic or basaltic "associate" parent material.

The ninth split resulted in the division of group 12 into groups 18 and 19 on the basis of age. All plots in group 18 were 35-44 years old. They experienced a mean of 4.92 thrown trees per plot which is actually higher than that among the 45-49 age-group previously segregated into group 13. The 118 members that constitute group 19 were aged 25-34 years and had experienced a mean of 1.73 thrown trees per plot.

The next iteration resulted in the subdivision of group 8 into groups 20 and 21 on the basis of altitude. The 66 plots in group 20 are at altitudes of 138-229 metres and had a mean of only 0.09 thrown trees per plot. Group 21 is composed of 72 quadrats, 69 of which are at altitudes of 230-320 metres and the remaining 3 having greater altitudes, with a mean of 1.92 thrown trees per quadrat.

The subdivision of group 21 into groups 22 and 23 using age as the discriminating variable constituted the next step. Group 22 is composed of plots in the 25-39 age-group while all 35 plots in group 23 were in the 15-24 age-group. The mean windthrow of 3.46 trees per plot in the former is over 11 times that of the latter, with a windthrow of 0.29 trees per plot.

The twelfth split was on group 19 and employed elevation as the predictor variable. Group 24 consists of 67 plots between 138 and 229 metres altitude and has a mean windthrow of 0.91 trees per plot. Group 25, with 51 plots situated between 230 and 320 metres altitude, had a mean of 2.80 thrown trees per plot.

The thirteenth successful iteration resulted in the division of group 25 into groups 26 and 27. Aspect was used as the discriminating variable. In group 26 are 41 plots having northeasterly, northerly, and northwesterly aspects and a mean windthrow of 1.98 thrown trees per plot. A mean windthrow of 6.20 trees per plot was recorded in the 10 plots that constitute group 27. These plots have southeasterly and westerly aspects.

The final split to occur was the segregation of group 18 into groups 28 and 29 on the basis of aspect. The 12 plots in group 28 have either northerly or southeasterly aspects and experienced a mean of 1.75 thrown trees per plot. In group 29 are 14 plots with northeasterly, northwesterly, and westerly aspects and having a mean windthrow of 7.64 trees per plot.

6. Conclusions

The more outstanding results of these splits include: (a) plots at higher altitudes are more vulnerable to windthrow than are those at lower levels; (b) plots on lee slopes are appreciably more vulnerable to windthrow than are those on windward sides; (c) plantations on gleyey soils are more prone to windthrow than are those on other soils; (d) although older plantations experience more windthrow than younger plantations, damage peaks in the middle part of the age range examined; (e) windthrow is not merely more intense but is found in younger plantations (i) at higher than at lower elevations, (ii) on leeward than on windward slopes, and (iii) on gleyey than on other soils; (f) advantages of favoured edaphic conditions are partly offset by disadvantages associated with high elevation; (g) high elevation plantations face less risk on windward than on leeward slopes; and (h) high elevation plantations on leeward slopes are much less liable to windthrow if established on brown earths, peats, or podzols than when on peaty and nonpeaty surface water gleys.

Parent material is the single most efficient discriminating variable between heavily and lightly damaged plantations. This does not imply that parent material is the primary causal factor in the determination of windthrow. Rather, its great predictive power is attributable to its spatial correspondence with a high incidence of (a) gleyey soils, (b) middle and high altitudes, (c) plantations on north, northeast, and east slopes, and (d) middle-aged plantations (Kennedy, 1973).

The analysis suggests that altitude is strongly related to windthrow, with plantations on middle slopes (138-274 m) being exceptionally vulnerable. Aspect is the next most significant variable with plantations on north, northeast and east slopes having heavy wind damage. Soil-type is ranked next in importance; most of the windthrow being associated with gley soils. Finally, age of plantation is significantly related to incidence of windthrow, with damage peaking in 20-39 years age-group.

Altitude, aspect, and soil-type are, in that order, the variables most functionally related to windthrow at the scale of Northern Ireland. Analysis of smaller areas reveal that these three variables are consistently among the most significant variables, but the order of importance is likely to change. These variables are strongly interactive such that the damage associated with a site possessing deleterious levels of all three variables (e.g. peaty gley at an altitude of 175 m on a northeast slope) is much greater than the sum of damages associated with these site attributes individually.

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