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Windthrow Probability as a Function of Stand Characteristics and Shelter

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In 1981 a storm caused windthrow of 3 million cubic meters of softwood in Denmark, equal to the normal removals of three years. The object of the present analysis is to determine the way in which the probability of windthrow depends on parameters that can be affected by forest management, viz. rotation age, thinning programme, choice of species, spatial distribution of stands and drainage. An empirical data set from 612 stands is used in the estimations. It is found that the windthrow probability is negatively affected by tree diameter, drainage, the time since last thinning and the protection from other stands. The probability increases with tree height, age and relative thinning volume in the latest thinning. Picea is more stable than Abies and Pseudotsuga.

INTRODUCTION

Windthrow has a significant impact on the profitability of forestry. This is true not only in Denmark, where 3 million cubic meters of softwood blew down during a storm in 1981. As the normal removals of softwood per annum amount to 1.2 million cubic meters, this was the greatest disaster to date in Danish forestry. The object of the present analysis is to estimate the relationship between the windthrow probability and parameters that fully or partly can be affected through the forest management strategy.

Helles (1983) gives a detailed presentation of the literature in this field, and some of the more essential parts are discussed below. The theory of the windthrow problem consists of several topics. It is suggested that they be classified as follows:

a. *Stability theory*. Brünig (1974), Holten (1904), Møller (1957), Wangler (1976).
b. *Stability estimation*. Bazzigher & Schmid (1969), Kohlstock & Lockow (1981), Neustein (1971), Persson (1975).
c. *Wind theory*. Alexander (1964), Odin (1976).
d. *Wind tunnel experiments*. Fraser (1964), Hütte (1968).
e. *Valuation*. Madsen (1984 and 1985).
f. *Normative theory*. Holten (1904), Neckelmann (1981 and 1982), Persson (1975), Schretzenmayr et al. (1974).

In the present analysis it is possible to test some of the ideas put forward in the literature.

Stability theory and estimation

Brünig (1974) suggests that windthrow probability is an increasing function of the ratio between tree height and diameter at 1.3 meters, a claim supported by a technical strength calculation. This hypothesis is supported by the present analysis (cf. Fig. 2).

Holten (1904) claims that stability increases when the distance between trees is small

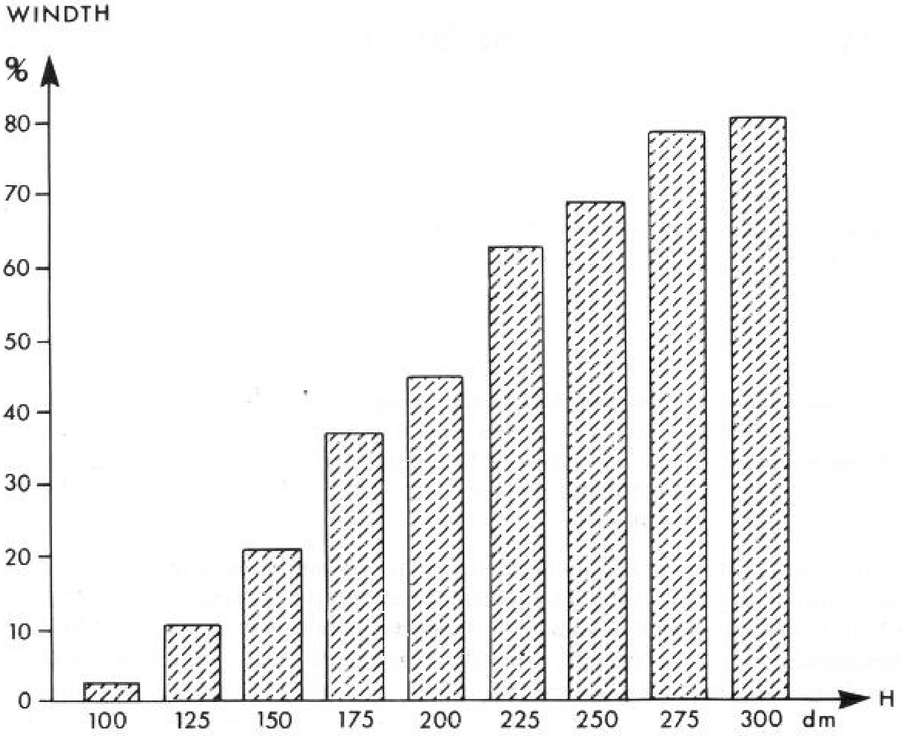

Fig. 1. The observed windthrow percentage (WINDTH) in different height classes.

since their root systems are connected. However, when the distance decreases, the ratio height/diameter will be positively affected, which in turn diminishes stability (cf. Fig. 2). On the other hand, it is an experienced fact that stands which have never been thinned are comparatively stable (cf. Fig. 3).

Møller (1957) gives two reasons why windthrow probability increases with age. First, trees get more diseases and parasites when age increases. Second, tree height increases for a longer time than does root depth. The present analysis supports Møller's theory (cf. Fig. 2).

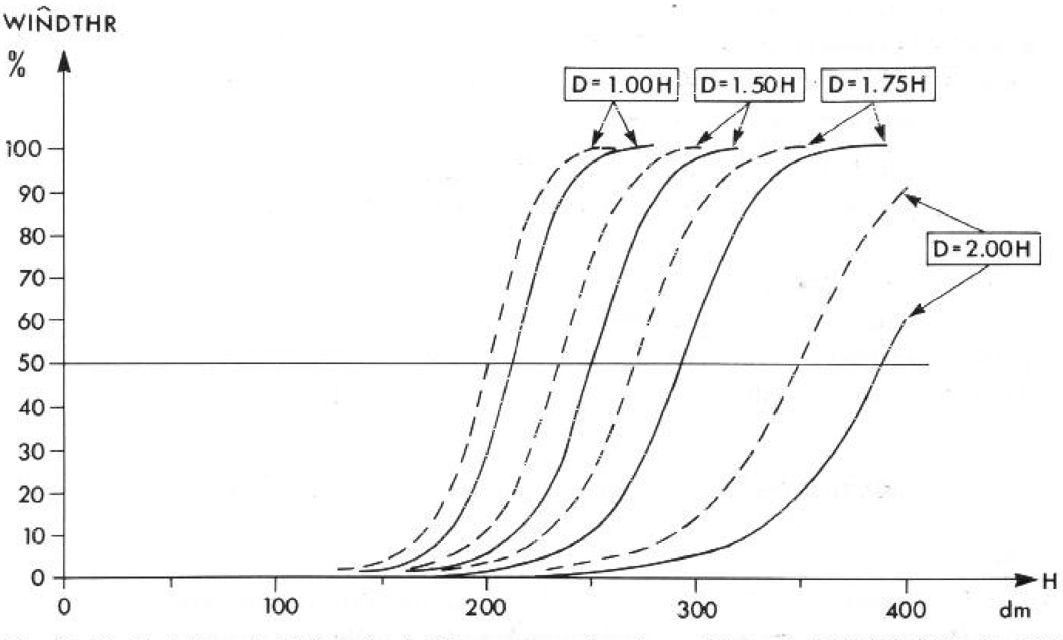

Fig. 2. Predicted probability of windthrow as a function of tree height (DRAIN=2, PICEA=1, HU1/VOL=0.1, TDIF=10, NVOL=208 NH=164, FBELT=17). Two different height–age relations are investigated; solid line, H=5.00×AGE; dotted line, H=3.33×AGE.

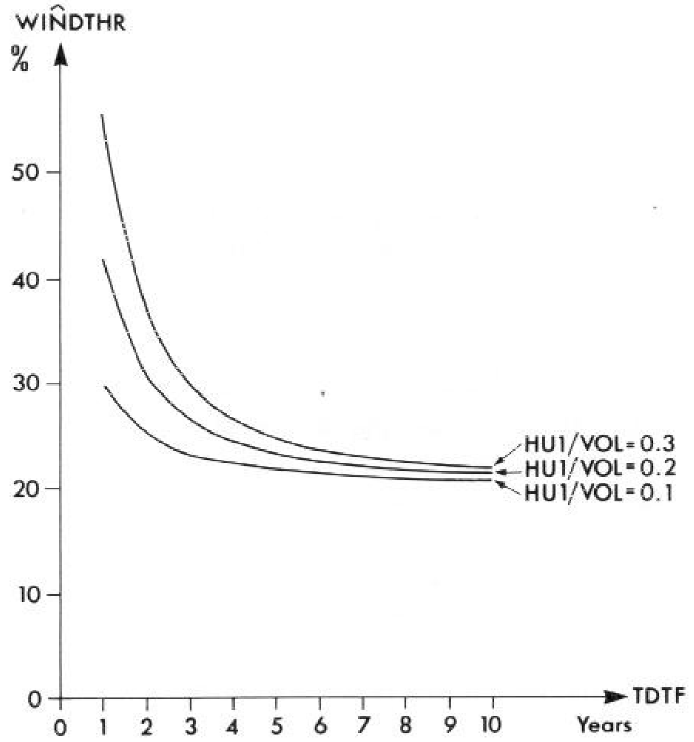

Fig. 3. Predicted probability of windthrow as a function of the time from the latest thinning (D=234, H=199, DRAIN=2, PICEA=1, AGE=47, NVOL=208, NH=164, FBELT=17).

Wangler (1976) suggests that the observation of Norway spruce (*Picea abies* L.) being easily blown down may be due to the fact that this species is usually planted on clayey soils suffering from bad drainage. Under such conditions the root system will become shallow and, therefore, give low stability. Drainage was an important parameter in the present analysis. However, spruce (*Picea abies* L. + *P. sitchensis* Bong) was found to be significantly more stable than *Abies* (*alba* Mill + *nordmanniana* Spach + *grandis* Lind.) and Douglas fir (*Pseudotsuga menziesii* Mirbel), (cf. Fig. 4) but the number of clay observations was small and the dummy variable for clay was not significant.

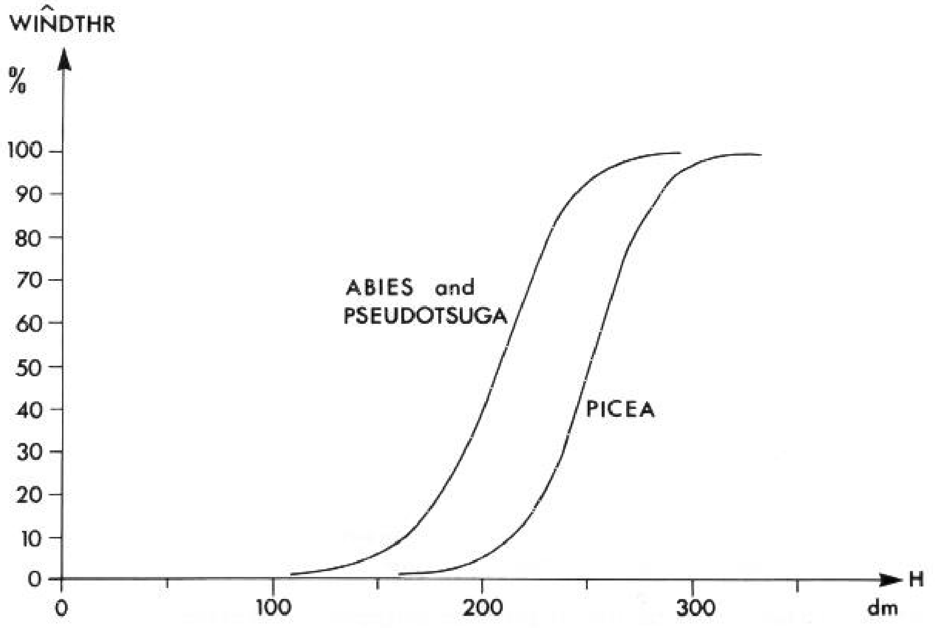

Fig. 4. Predicted probability of windthrow as a function of tree height and species (DRAIN=2, HU1/VOL=0.1, TDIF=10, NVOL=208, NH=164, FBELT=17, D=1.5 H, AGE=0.2 H).

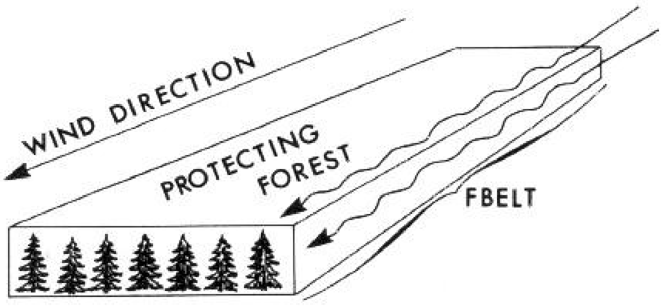

Fig. 5. The parameter PROTECT represents the wind protection obtained from the neighbour stands in the wind direction.

Bazzigher & Schmid (1969) could not find a significant difference of windthrow tendency between Norway spruce and silver fir (*Abies alba* L.). However, they did observe that Scots pine (*Pinus silvestris* L.) and beech (*Fagus silvatica* L.) were more resistant to winds than Norway spruce and Sitka spruce. They also noticed that the differences partly depended on the health of the root system. With a healthy root system, Norway spruce did not have a higher windthrow tendency than the most stable species. In the present analysis, *Picea* was found significantly more stable than *Abies* and *Pseudotsuga* (cf. Fig. 4).

Kohlstock & Lockow (1981) claim that the windthrow probability is an increasing function of the thinning volume. They do not find any significant differences between various thinning patterns. Their claim is consistent with the present analysis. The most significant functional form of the relationship is found in Appendix 1.

Neustein (1971) presents a three-level wind risk classification based on topography and soil. Persson (1975) estimates the relationships between different stand characteristics and windthrow percentage. He claims that the wind protection from other stands should be taken into account as an explanatory variable. In the present analysis, a wind protection

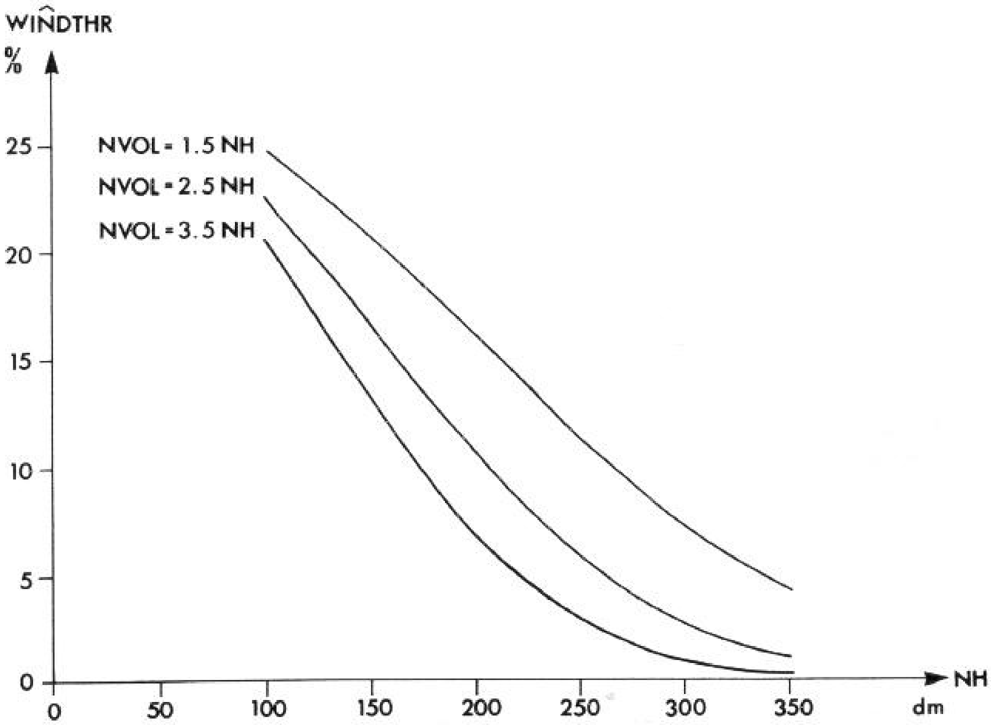

Fig. 6. Predicted probability of windthrow as a function of the tree height in the neighbour stand in the wind direction (D=234, H=199, DRAIN=2, PICEA=1, AGE=47, HU1/VOL=0.1, TDIF=10, FBELT=17).

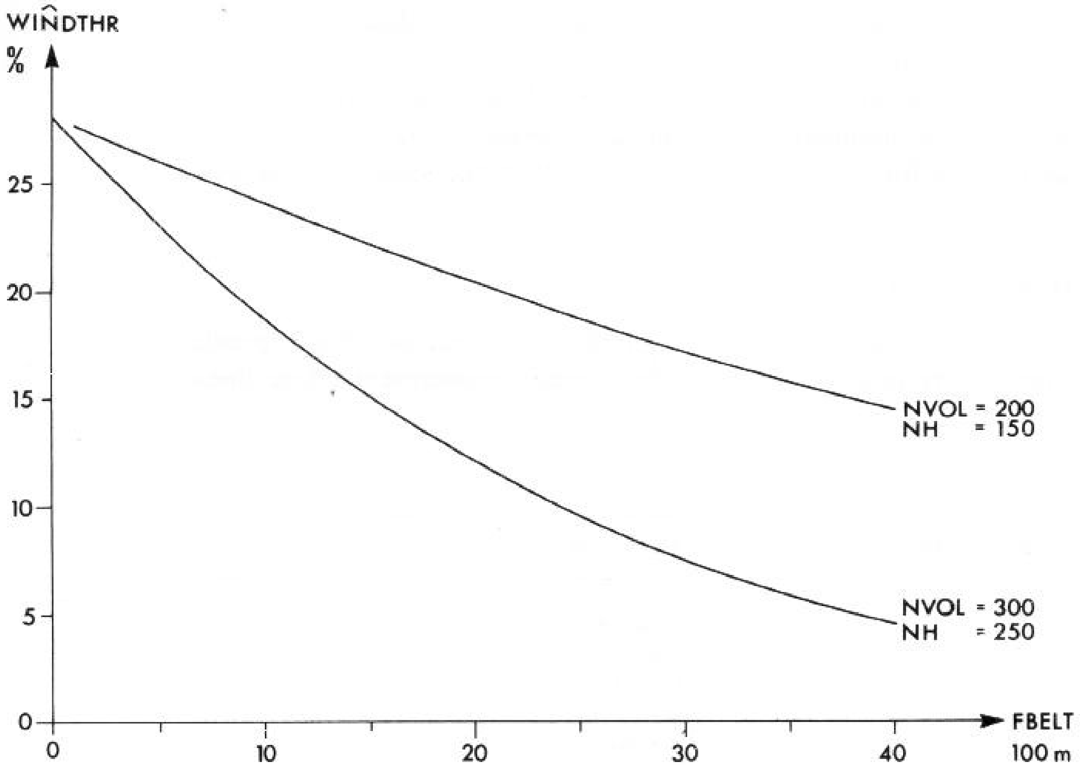

Fig. 7. Predicted probability of windthrow as a function of the distance to the end of the forest in the wind direction (D=234, H=199, DRAIN=2, PICEA=1, AGE=47, HU1/VOL=0.1, TDIF=10).

index derived from the characteristics of the neighbouring stands in the wind direction was found highly significant (cf. Figs. 5, 6 and 7).

Normative theory

Schretzenmayr et al. (1974) discuss the treatment of the protecting (and unprotected) fringe of the forest in the main wind direction. They state that this outer stand should not be thinned after an age of 40 years in order to avoid windthrow. This protecting stand should consist of trees with much space, which implies that they grow resistant to winds. Both of these ideas are consistent with the present empirical findings. A larger distance between trees would decrease the height/diameter ratio. The time since the latest thinning also affects the windthrow probability (cf. Figs. 2 and 3).

Neckelmann (1981 and 1982) suggests that Japanese larch (*Larix leptolepsis* Gord) be the protecting species. Holten (1904) finds that many species should be found in the forest, because then the whole forest will not blow down since the species may have different stability.

Persson (1975) highlights many important relationships between stand parameters that can be affected through management and the windthrow probability. A similar ambition is held in the present analysis.

The empirical data

Since the wind conditions can be expected to vary geographically, three different forest districts were used in the investigation. The forest districts were Esrum, Frederiksborg and Nødebo, all owned by the Danish government. The observation areas are represented in Table 1. Within each observation area, every coniferous stand with a height exceeding

10 meters was included in the analysis as one observation. A short description of the empirical material is given in Table 2.

Table 3 shows how the different species are distributed over the forest districts. Obviously, *Picea abies* strongly dominates the empirical material. In Fig. 1, the observed windthrow percentage is given for different height classes. Note the similarities between Fig. 1 and Fig. 2.

THE MODEL AND THE RESULTS

When the problem is to estimate the probability of windthrow, a linear model may predict probabilities that are below zero or above one. In a first attempt to analyse the data, linear

Table 1. *Investigation area*

Forest district	No. of obs.	Area (ha)	Observation area
Esrum	255	270	Ostrup skovpart Trustrup skovpart
Frederiksborg	223	299	Store Dyrehave Præstevang
Nødebo	134	160	Grib Skov
Total	612	729	

Table 2. *Some statistics based on the 612 observations*

Parameter		Sample mean	Standard deviation
H	Stand height, Hg (dm)	199	44
D	Stand diameter, Dg (mm)	234	74
VOL	Stand density (m^3/ha)[a]	321	81
DRAIN	Drainage[a]	1.40	0.86
AGE	Age of stand (years)[a]	47.2	12.3
NVOL	Density in neighbour stand (m^3/ha)[a]	208	144
NH	Height in neighbour stand (dm)[a]	164	91
FBELT	Distance to end of forest (100 m)[a]	17.3	11.0
WINDTH	Windthrow percentage (%)[a]	45.2	40.0
HU1	Latest thinning volume (m^3/ha)[a]	28.9	30.0

[a] More information is found in Appendix 1.

Table 3. *Percentage of the investigation are covered with different species*

	Species			
District	*Picea abies*	*Pseudotsuga menziesii*	*Picea sitchensis*	*Abies alba* and *Abies nordmanniana*
Esrum	97.2	1.6	0.0	1.2
Frederiksborg	59.2	19.7	17.5	3.6
Nødebo	88.6	9.0	1.0	1.4
Total	82.2	9.7	6.0	2.1

models were applied (Andersen & Helles, 1984; Helles, 1984). A frequently used specification is the logistic probability function. A short guide to the theory of the estimation of this function is given in Appendix 2. In the present analysis, the logistic model is used with the parameters as defined in Appendix 1. The estimated coefficients, standard deviations and t-values are shown together with more information in Appendix 3, where also the resulting windthrow probability function is explicitly expressed. This function is used in the construction of the figures in the present section.

Height, diameter and age

The sensitivity of the windthrow probability to changes in tree height, diameter and age is shown in Fig. 2. The different curves represent various height/diameter ratios and age/height ratios. It is seen that windthrow probability increases with height, decreases with diameter and increases with age.

Obviously, the windthrow probability can be reduced by increasing the space of each tree because this will decrease the height/diameter ratio. (On the other hand, the stand may give less wind protection when the trees grow far from each other. Hence, thinning will affect the windthrow probability at least in two ways.) The optimal rotation age is *probably* reduced in most cases. However, felling of one stand affects the probability of windthrow in other stands (cf. Fig. 5).

Thinning pattern

As shown in Fig. 3 the probability of windthrow increases with the relative thinning volume and decreases with the time since the latest thinning. What can be learned from Figs. 2 and 3 is that the stand should not be thinned too strongly at a high age. The last thinning should be made when the stand is still comparatively young. The number of remaining stems should be small in order to decrease the height/diameter ratio (cf. Fig. 2): a reverse consideration is, of course, that of the stem form from an industrial point of view.

Tree species

The probability of windthrow is strongly affected by the choice of tree species. Fig. 4 shows that if one stand consists of *Picea* and another of *Abies* or *Pseudotsuga*, and if the tree height of the Picea stand is about 4 meters higher than the other, then the probability of windthrow is approximately equal in the two stands (*ceteris paribus*).

Protection from other stands

Odin (1976) has investigated the wind profiles and the reduction of the wind speed as a function of forest conditions such as the distance to the forest edge.

Stands in the wind direction will reduce wind velocity. The hypothesis is that standing volume multiplied by distance to the end of the forest provides a measure of the change of wind velocity. Because of irregularities of terrain etc., the wind velocity increases with distance from the ground. Furthermore, if the wind does not blow horisontally but sometimes turns downwards to some extent, then the protection increases with the height of the neighbouring stand. This is why the protection index also contains the height of the neighbouring stand. The purely multiplicative definition of the index PROTECT was also supported by a nonlinear estimation.

As shown in Fig. 6 the probability of windthrow is strongly dependent on the height of the neighbouring stand in the wind direction. However, the three different curves show that the density of this stand is also important.

The distance to the end of the forest and this parameter's impact on the windthrow probability are demonstrated in Fig. 7. It is seen that stands in the wind direction give protection at large distances. This is reasonable if we assume that the wind velocity decreases continuously during the movement through the forest. From this it can be learned that it is important to keep large areas under tree cover. Clearcuts should probably take place simultaneously over large forest areas irrespective of small differences in age and "optimal rotation age". It is also seen that height and density of the neighbouring stand play an important role.

DISCUSSION

The main results obtained are:

(*a*) A single model was constructed, by which it was possible to test many hypotheses from the literature.

(*b*) The wind protection was analysed explicitly thanks to measurements in stands in the wind direction.

(*c*) It was possible to "optimize" functional forms for wind protection and for the influence of thinnings thanks to a large number of observations and to nonlinear optimization routines.

The main limitations of the analysis are:

(*d*) The observations relate to a year with an extraordinarily intense windthrow. This implies that the estimated probability function will overestimate the probability in an average year.

(*e*) The observations were made in three forest districts with higher windthrow percentage than the average for Denmark for the particular year. This also implies that the windthrow probabilities will be lower on the average than those predicted by the probability function.

(*f*) Only different species of conifers were under investigation. Hence, it is impossible to get a quantitative answer to the question under what conditions broadleaves should be preferred to conifers from the viewpoint of windthrow probability.

Some interesting ways in which to continue the windthrow research seem to be:

(*g*) The wind force, or possibly its extreme value, should be used as an explanatory variable in the probability function. This would, however, require wind force measurements on different locations during the storm. In Denmark it is not possible to use existing meteorological data.

(*h*) The probability distribution of the extreme values of wind force should be estimated for different areas.

(*i*) Different species of broadleaves and other species of conifers, e.g. *Pinus* and *Larix* should be investigated.

Suggestions *g–i* would make it possible to optimize the management of a specific forest area under the influence of stochastic winds.

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APPENDICES

A1. *Definition of parameters*

The parameters below were used in the present analysis.

AGE	Age of the individual stands (windthrown) under investigation (years)
BLOCK1	Forest district Esrum (dummy variable)
BLOCK2	Forest district Frederiksborg (dummy variable)
BLOCK3	Forest district Nødebo (default)
D	Stand diameter, Dg (mm)
D2	D^2
DRAIN	Drainage represented by a scale 0–3, where 0 = good drainage, 3 = bad drainage
FBELT	Distance from windthrown stand to the end of the forest in the wind direction (100 m) (compare Fig. 5)
H	Stand height, Hg (dm)
H2	H^2
HU1	Thinning volume in the latest thinning (m^3/ha)
NH	Height (Hg) of the neighbouring stand in the wind direction (dm)
NVOL	Stand density of the neighbouring stand in the wind direction (m^3/ha)
PICEA	Dummy variable for *Picea Abies* and *Picea sitchensis* (PICEA = 0 for *Pseudotsuga menziesii, Abies alba* and *Abies nordmanniana*)
PROTECT	Indicator of wind protection = (NH)(NVOL)(FBELT)
WINDTH	windthrow percentage (= volume thrown in the storm × 100/VOL)
WINDTHTR	LN((WINDTH/100+ε)/(1-WINDTH/100+ε)), $\varepsilon = 0.001$
TDIF	1981—year of the latest thinning (= years since latest thinning)
THINNING	Indicator of the influence of thinning on stability = (HU1/VOL)(1+ TDIF)$^{-1.686}$
VOL	Stand density of windthrown stand (m^3/ha) before windthrow

A2. *Estimation of the probability function*

The logit function was estimated along the lines suggested by Pindyck & Rubinfeld (1981). A short guide is given below. ϕ denotes the probability of windthrow and x is the vector of parameters.

$$\phi = F(z) = F(\alpha+\beta x) \quad (0<\phi<1)$$

$$\phi = 1/(1+e^{-z})$$

$$(1+e^{-z})\phi = 1$$

$$e^{-z} = (1-\phi)/\phi$$

$$e^{z} = \phi/(1-\phi)$$

$$z = \ln(\phi/(1-\phi))$$

$$y = \ln(\phi/(1-\phi)) = \alpha+\beta x$$

In some observations the measurements give the values of 0 and 100% probability of windthrow. This means that ϕ takes the value 0 or 1, respectively, implying that the logarithmic expression is not defined. It is likely that this problem to some extent depends

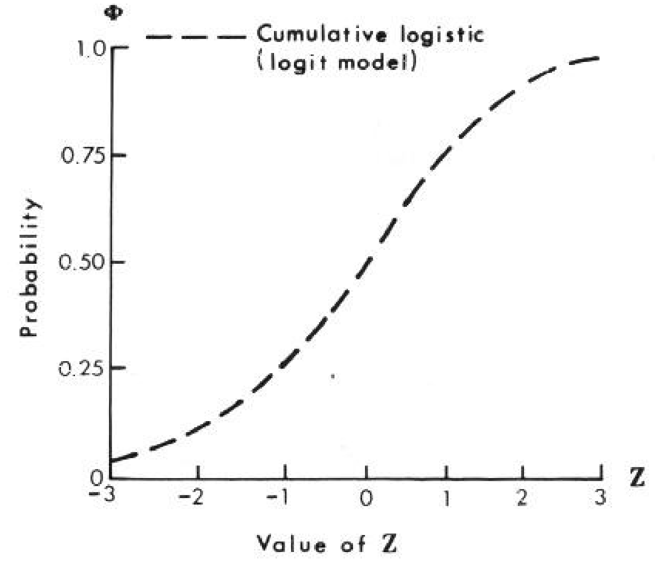

Fig. 8. The shape of the logit function $\phi=\phi(z)$.

on the method of registration. (The relative windthrow is registred in 10% classes.) Therefore we add ε (a very small figure) to the nominator and the denominator.

$$y=\ln((\phi+\varepsilon)/(1-\phi+\varepsilon))=\alpha+\beta x+s$$

This is the function estimated in the regressions. In the final regression ε was given the value 0.001. In order to investigate the effect of ε on the solution, another regression was made with $\varepsilon=0.002$. However, the qualitative results obtained were identical for the two values of ε. The significance levels (t-values) changed with a few percent and the value of R^2 changed with 0.0015. An inspection of the residual plots showed that the residuals (of the linear transformation) were not heteroscedastic. Furthermore, the residuals did not suggest nonlinear relationships not included in the present model.

A3. *Results from estimations*

Two different models are estimated below. In the first model, the coefficients of which are used in the numerical illustrations of this paper, the parameters BLOCK1 and BLOCK 2 are excluded. These parameters represent two different forest districts.

```
DEPENDENT VARIABLE   20              WINDTHTR
FROM      1- 1       UNTIL  612-     1
OBSERVATIONS              612        DEGREES OF FREEDOM     604
R**2                      0.39500375 RBAR**2             0.38799220
SSR                  7187.9235       SEE             3.4497153
DURBIN-WATSON             1.67732186
NO.       LABEL      VAR    LAG      COEFFICIENT     STAND. ERROR    T-STATISTIC
--------------------------------------------------------------------------------
1         CONSTANT    0      0       -7.223312       0.8679720       -8.322056
2         D2         22      0       -0.4185077E-04  0.9363786E-05   -4.469429
3         H2         21      0       0.2060133E-03   0.1982562E-04   10.39126
4         DRAIN       8      0       0.4920661       0.1640171       3.000091
5         PICEA      33      0       -2.649700       0.4699868       -5.637817
6         AGE         4      0       0.4371760E-01   0.2675620E-01   1.633925
7         THINNING   41      0       16.91235        2.465012        6.860962
8         PROTECT    40      0       -0.6967801E-06  0.1500339E-06   -4.644152
```

```
DEPENDENT VARIABLE  20              WINDTHTR
FROM      1- 1      UNTIL  612-     1
OBSERVATIONS           612          DEGREES OF FREEDOM       602
R**2                   0.41269494   RBAR**2               0.40391463
SSR                 6977.7356       SEE            3.4045444
DURBIN-WATSON          1.72425857
NO.       LABEL     VAR   LAG       COEFFICIENT  STAND. ERROR  T-STATISTIC
--------------------------------------------------------------------------

1         CONSTANT    0    0        -8.952871        0.9563530       -9.361471
2         D2         22    0        -0.4892862E-04   0.9467830E-05   -5.167881
3         H2         21    0        0.2147034E-03    0.1968428E-04   10.90736
4         DRAIN       8    0        0.4976513        0.1643951       3.027166
5         PICEA      33    0        -2.275525        0.4793263       -4.747341
6         AGE         4    0        0.5819751E-01    0.2668395E-01   2.180994
7         THINNING   41    0        15.98553         2.455747        6.509436
8         PROTECT    40    0        -.6702016E-06    0.1486799E-06   -4.507681
9         BLOCK1     17    0        0.5204643        0.3801356       1.369154
10        BLOCK2     18    0        1.568496         0.3935493       3.985513
```

In the numerical illustrations (the figures), the first estimation is used. The windthrow probability function takes the form

$$\phi = \frac{1}{1+e^{-z}}$$

where z is given by

$$\begin{aligned} z = {} & -7.22 - 0.0000419(\mathrm{D2}) + 0.000206(\mathrm{H2}) + 0.492(\mathrm{DRAIN}) \\ & -2.65\ (\mathrm{PICEA}) + 0.0437(\mathrm{AGE}) + 16.9(\mathrm{THINNING}) \\ & -0.000000697(\mathrm{PROTECT}) \end{aligned}$$

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