Forestry Commission

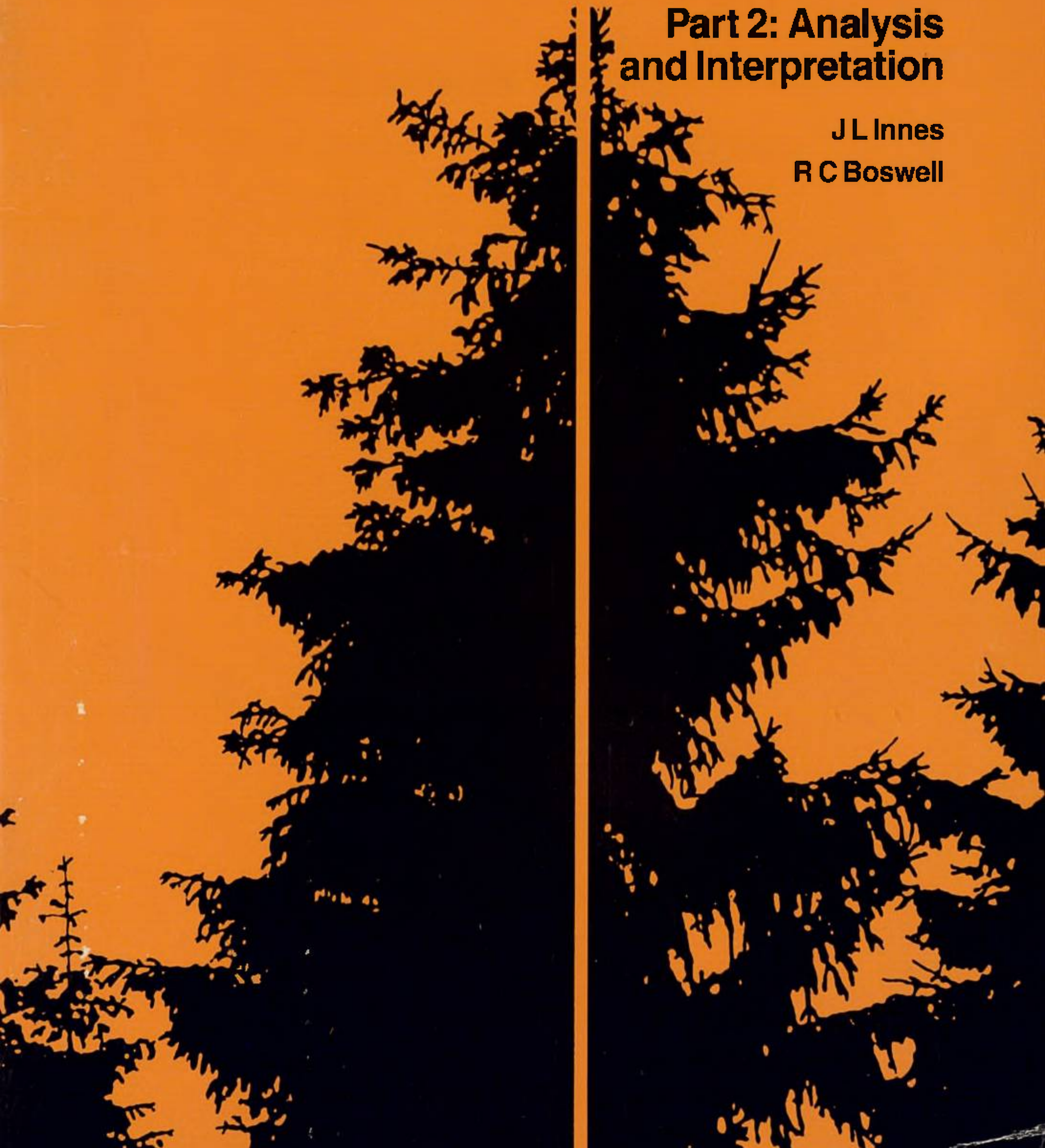
Bulletin 79

Forest Health Surveys 1987

Part 2: Analysis and Interpretation

J L Innes

R C Boswell



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Part 2: Analysis and Interpretation

J. L. Innes and R. C. Boswell
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FRONT COVER: Composite silhouette of two Norway spruce (*Picea abies*) of different crown habits, showing the difference in light transmission. Left half, brush type; right half, comb type.

Contents

Forest Health Surveys 1987

Part 2: Analysis and Interpretation

J.L. Innes and R.C. Boswell
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Abstract

The crown appearance of five British tree species, Sitka spruce, Norway spruce, Scots pine, oak and beech, was assessed in 1987 using parameters such as crown density, amount of needle or leaf discoloration and crown dieback. Distinct spatial patterns exist in the crown parameters relating to three of these species. The appearance of Scots pine, oak and beech generally deteriorates towards the north and west of Britain. The two spruce species do not show this trend. The appearance of the trees is statistically related to a wide variety of environmental variables. Some of the explanatory variables examined in the analysis are pollutant levels and there is a general increase in the crown densities of Scots pine, oak and beech with increasing levels of most pollutants. This is entirely consistent with the many experimental studies that have shown that at relatively low levels of atmospheric pollution the growth of plants may be stimulated. The variables used in the study are all highly inter-correlated, placing severe limitations on the extent to which the statistical associations can be interpreted.

Introduction

The results of the 1987 survey of forest health have already been published (Innes and Boswell, 1987). The aim of this part of the report is to interpret as far as possible these results by attempting to establish the cause(s) of the low crown densities and the crown discoloration observed in five of our most important tree species: Sitka spruce, Norway spruce, Scots pine, beech and oak. The low densities and the discoloration were observed during the 1987 survey which was undertaken between late July and early September 1987. Some problems arising from a second survey of forest health carried out in 1987 are discussed in Appendix I.

The results presented in *Part 1* have given rise to concern as the overall figures for crown density and crown discoloration are similar to those published in European countries where forest decline is believed to be a major environmental problem. Most scientists now consider that a variety of stresses are responsible for this decline although the relative importance of different stresses remains uncertain. In some cases, there is good evidence that air pollution is the primary factor causing injury to trees (e.g. Materna, 1982; Keller, 1984; Roelofs *et al.*, 1985) and in many others, strong circumstantial evidence suggests that air pollution is at least involved (e.g. Feiler, 1985; Flückiger *et al.*, 1986). Consequently, this report places particular emphasis on the possible effects of air pollution on crown density and other crown parameters. However, many other factors affect the appearance of tree crowns and it is important not to ignore the extent to which these have affected the present appearance of our trees.

Rationale for the Current Approach

Crown density is the basic index used in surveys of forest health throughout Europe. It is influenced by a number of factors, of which pollution is only one. Consequently, there is a major problem in separating any changes in crown density attributable to pollution from those attributable to other factors. The situation is further complicated by indirect effects of pollution: while the levels of pollution at a particular site may not affect a tree directly, they may affect either the response of the tree to some other factor affecting crown density or they may directly affect that factor itself.

Trend Analysis

As a result of the difficulties mentioned above, it is not possible to infer a pollution effect from the summary statistics alone. Instead, it is necessary to see whether any pattern is present in the data, either spatial or temporal.

At present, no comment can be made on the temporal changes seen in crown density in Britain over the period 1984–1987 other than to say that a substantial proportion of the changes is attributable to changes in survey technique and observer perception. Major changes in observer perception occurred between 1985 and 1986 and it is believed that substantial changes also occurred between 1986 and 1987. The latter can be attributed to the introduction of a detailed training course and the use of a more comprehensive set of photographic standards. It has not been possible to quantify the extent of these changes in perception and it is therefore impossible to determine the extent of any real change in crown condition over the past 4 years.

Even now that the problem of changes in observer perception has been largely resolved it is likely that it will be impossible to make a confident statement on temporal trends in forest appearance for some considerable time. This is because substantial year-to-year variations in crown density are thought to occur, particularly in broadleaves. When such variations occur in conifers, they are likely to have persistent lag effects (Innes, 1988). Lag effects may also occur in broadleaves, but they are yet to be fully evaluated. Other countries face the same problems, particularly those that do not have a fixed reference point (such as a photograph of an ideal tree) which they can use as a standard through time.

Consequently, the emphasis currently has to be placed on spatial trends. Forest health surveys provide data on the appearance of forests over a broad geographical area. If pollution is an important factor affecting the appearance of trees, then it might be expected that in those areas with high levels of pollution, the appearance of the trees will be worse. The basic approach used in this study is an attempt to use any pattern in the distribution of crown density and crown discoloration to identify an association with one or more variables, ranging from topographic indices, such as distance from the sea, to indices of pollution such as the rate of nitrate deposition. Particular emphasis has been placed on determining whether any association exists between the patterns of individual pollutants and the pattern of crown density and crown discoloration.

The limitations of analysis by association

One of the most widely accepted techniques for determining whether or not an association exists between a target index and one or more variables is multiple regression and its associated correlation analysis. However, the approach has a serious limitation and this must be considered when examining the results presented in this report.

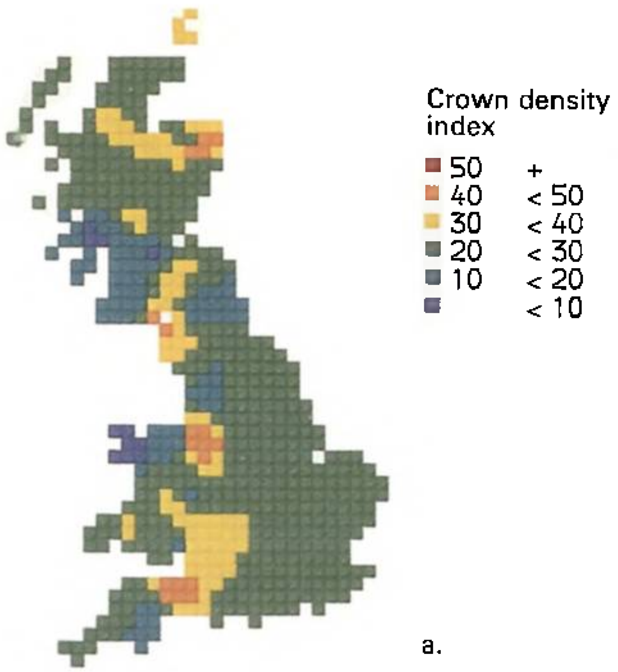
Many of the variables that we have used are highly intercorrelated. Consequently, while significant statistical associations may be demonstrated, these do not necessarily imply that there is a functional relationship between the explanatory variable and the crown parameter. The reverse is also true. The absence of a statistical relationship between a crown parameter and an explanatory variable does not rule out the possibility that a functional relationship exists between the two.

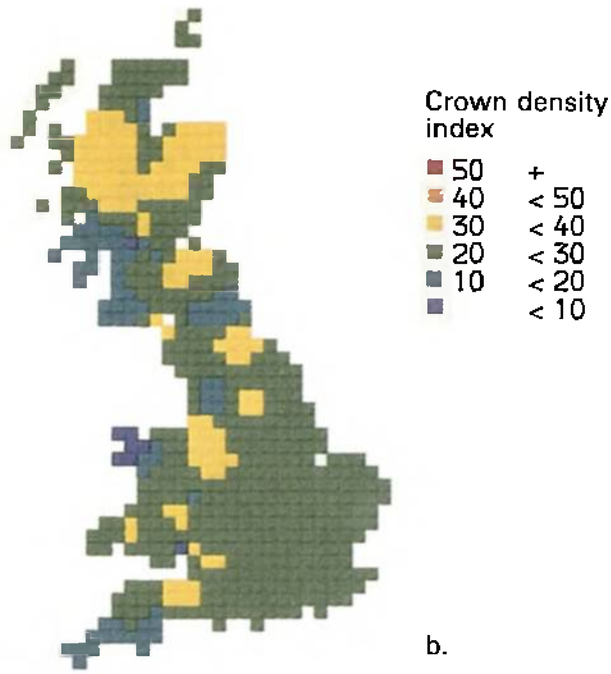
This problem is common to all studies of this type although here it is aggravated by the absence of any visual feature of the tree that can be specifically associated with pollution. A great deal of work is currently underway which is aimed at identifying any biochemical or physiological parameters that might provide an indication of potential pollution impact (e.g. Cape *et al.*, 1988).

Geographical Variation in Crown Condition

In order to determine any spatial pattern in the indices used in the forest survey, maps have been prepared showing the distribution of various crown indices in each of the five species. The maps were prepared using the mean of a particular index for each site, and interpolating to a 20 by 20 km grid (Figures 1 to 5). The accuracy of these maps is dependent on the density and distribution of sample plots. The most reliable maps are those for Norway spruce and Scots pine. Sitka spruce is relatively rare in the south-east and the accuracy of the map east of a line from Bournemouth to Scarborough is therefore questionable. For the two spruce species, we know that tree age is related to crown density (Figure 6). In order to make maximum use of the available data, the effects of age have therefore been removed using simple regression and the maps of the adjusted crown density indices are also presented.

Both broadleaf species have very few plots (31 for oak and 29 for beech) and the sample sizes may well be inadequate for the type of presentation and analysis adopted here. The maps for these two species should





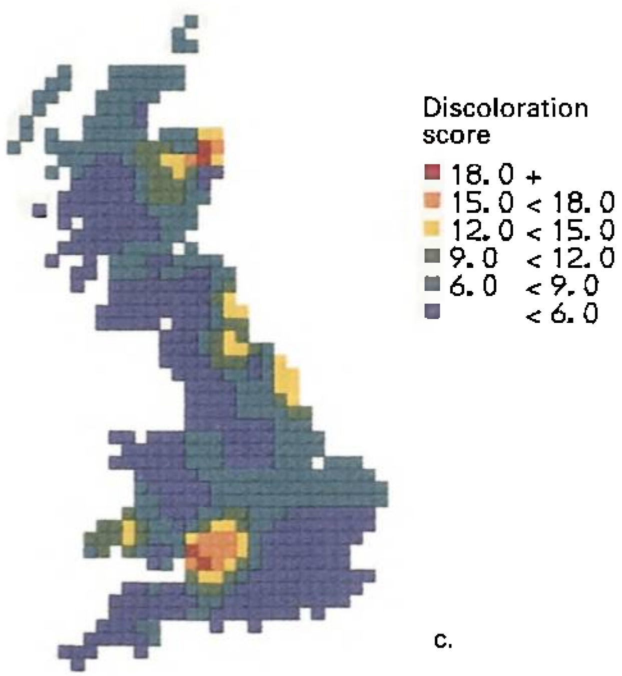


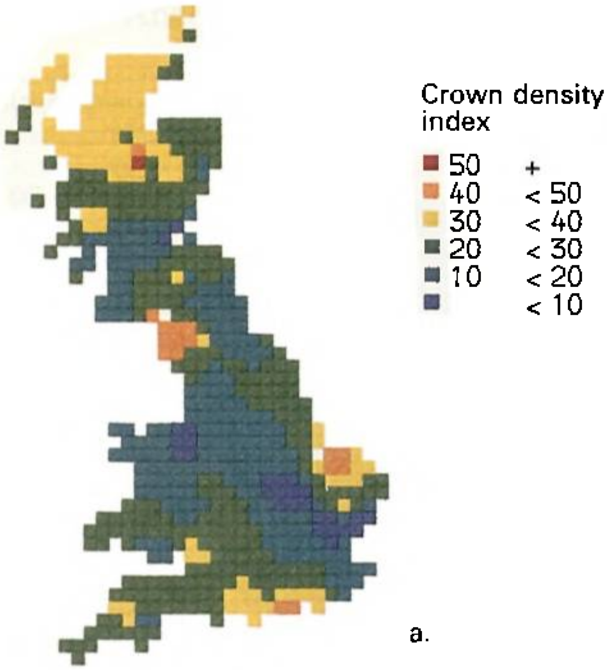
Figure 1. Patterns of crown indices in Sitka spruce:

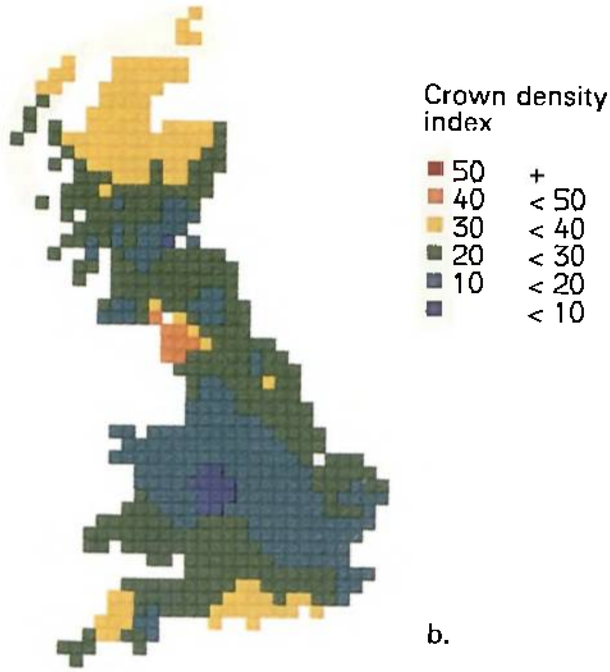
a. crown density

b. crown density after taking age into account

c. crown discoloration.

See Table 2 for derivation of indices.





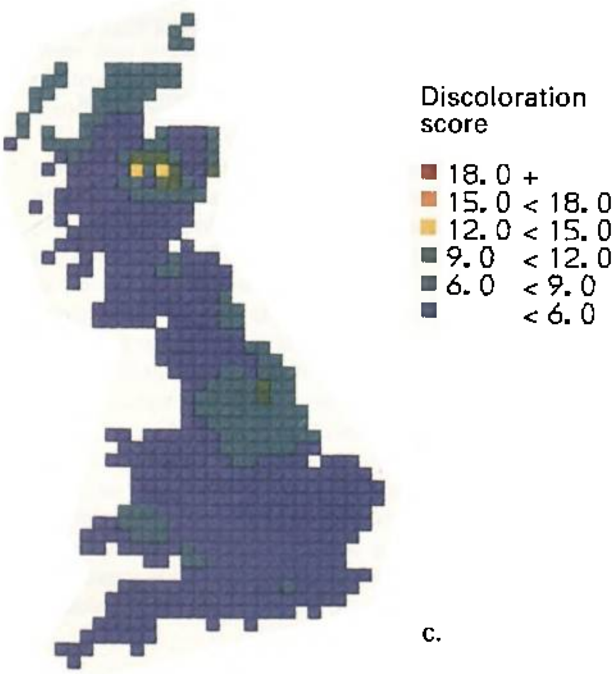
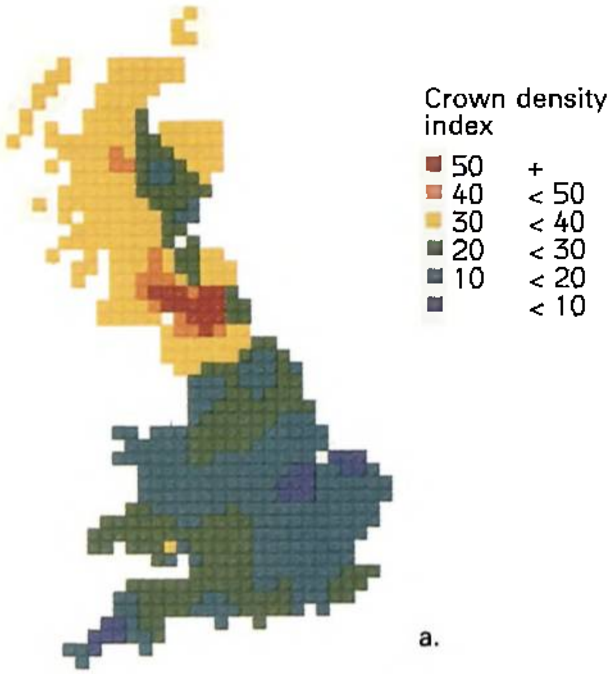


Figure 2. Patterns of crown indices in Norway spruce:

a. crown density

b. crown density after taking age into account

c. crown discoloration.



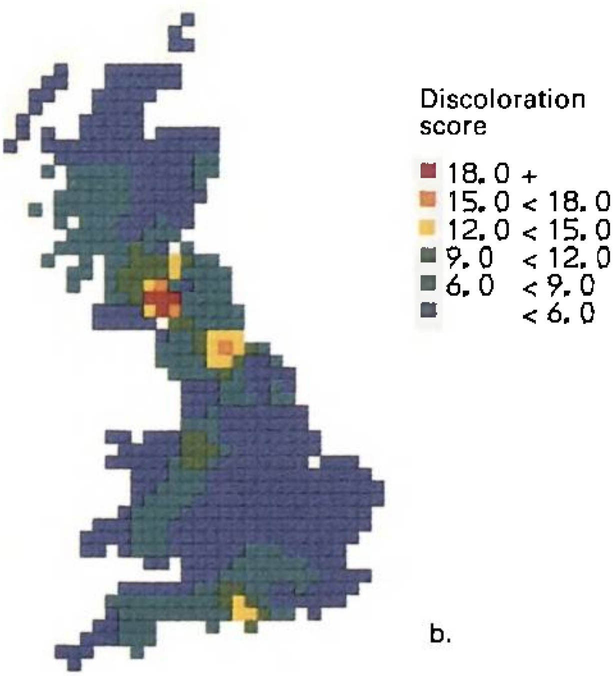


Figure 3. Patterns of crown indices in Scots pine:

a. crown density

b. crown discoloration.

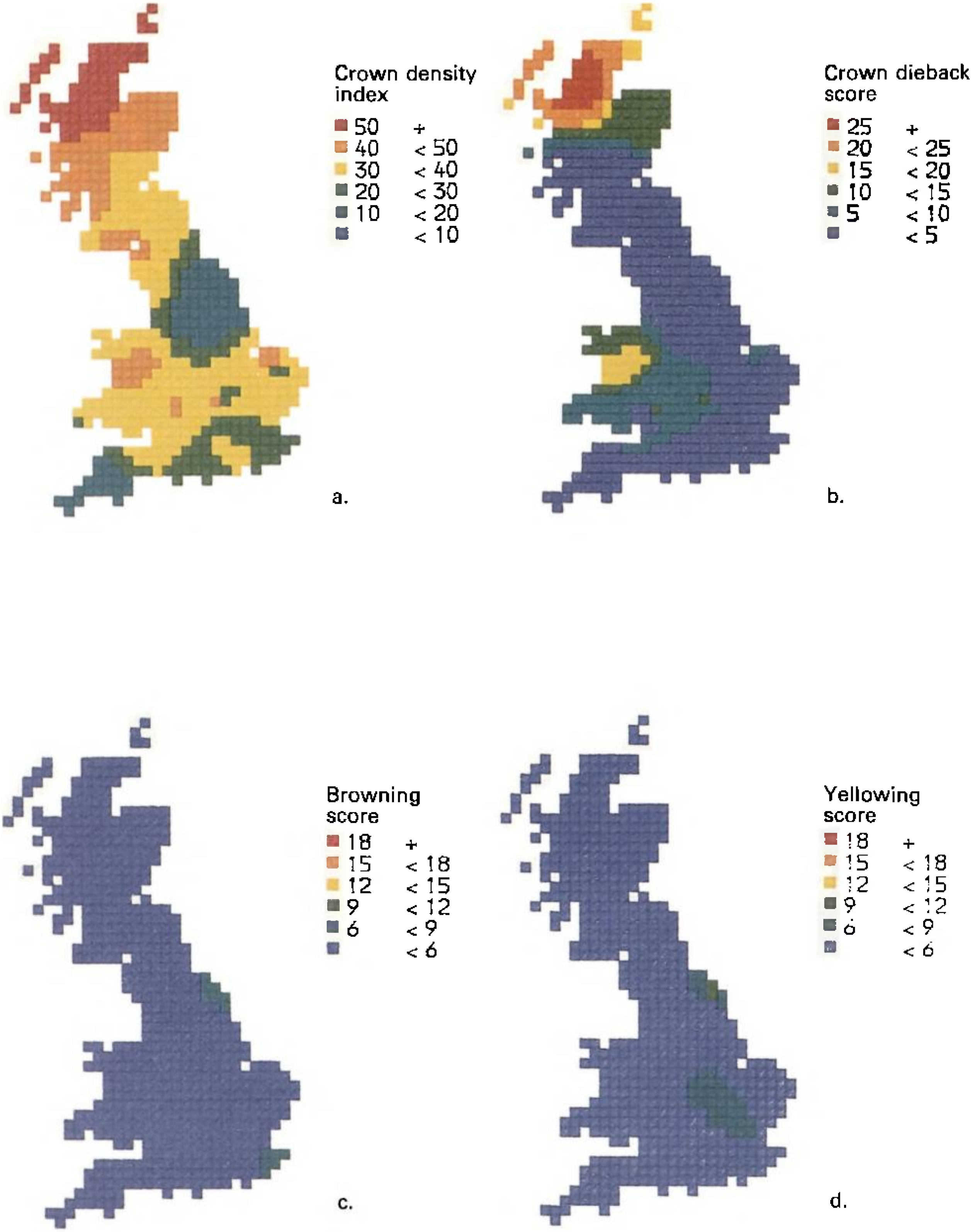

Crown density index
50 +
40 < 50
30 < 40
20 < 30
10 < 20
< 10
a.
Crown dieback score
25 +
20 < 25
15 < 20
10 < 15
5 < 10
< 5
b.
Browning score
18 +
15 < 18
12 < 15
9 < 12
6 < 9
< 6
c.
Yellowing score
18 +
15 < 18
12 < 15
9 < 12
6 < 9
< 6
d.

Figure 4. Patterns of crown indices in oak:

a. crown density

b. crown dieback

c. browning of leaves

d. yellowing of leaves.

therefore be viewed with considerable caution as it is possible that some of the patterns apparent on the maps for oak and beech are an artefact of the low density of sampling points. We are currently reviewing techniques for quantifying the accuracy of the maps and future reports will cover this problem in more detail.

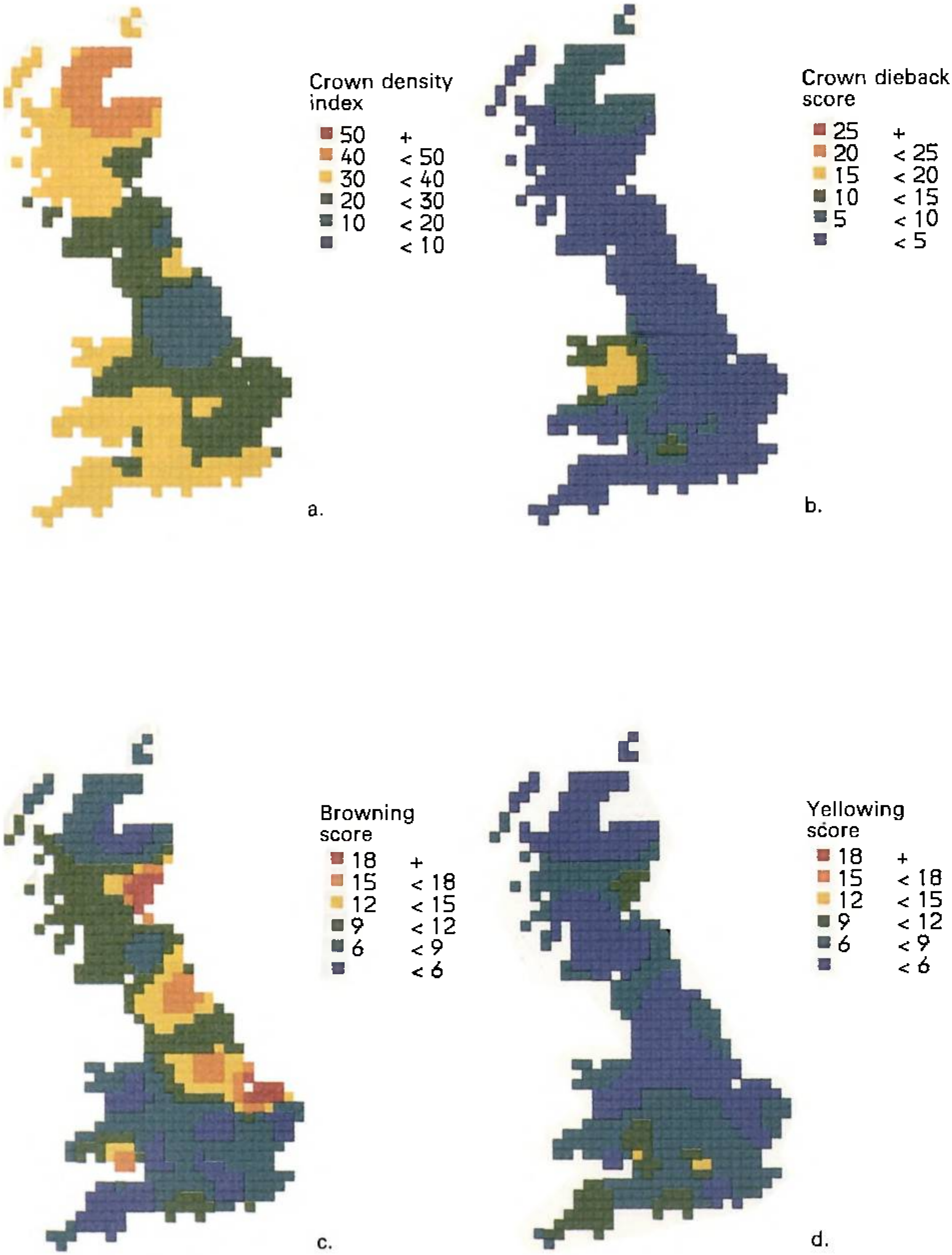
Possible Factors Affecting Crown Appearance

A wide variety of factors could be responsible for the patterns shown in Figures 1 to 5. These explanatory variables can be divided into several types depending on whether they are specific to individual trees (e.g. differences in crown density according to genetic constitution), sites (e.g. distance from sea) or groups of sites (most climatic and pollution factors). In the following analysis, a wide variety of such variables have been used and their derivation is described in the following sections.

Measured topographic variables

In an attempt to predict climatic variables for sites within Great Britain, White and Smith (1982) measured a number of indices which were considered to reflect the geographical position, site topography and the effects of the sea at each location. As climate is known to have a strong influence on tree growth, the same variables were assessed for each of the 264 plots used in the survey. The variables, and their derivation, are as follows:

i. Grid easting (EAST). Taken from Ordnance Survey maps to the nearest 100 m. In both this and the following index, the origin is the south-west corner of OS square SW, i.e. to the south-west of Land's End.
ii. Grid northing (NORTH). Taken from Ordnance Survey maps to the nearest 100 m.
iii. Distance from sea (DFS). Distance from the plot to the nearest point where the sea is more than 10 km wide, to the nearest km.
iv. Elevation (ELEV). Average altitude of plot, to nearest 1 m, read from 1:50 000 Ordnance Survey maps.
v. Slope due east or west (SLOW). The angle of slope between two points within 0.5 km east and west of the plot. Westerly slopes are negative, easterly ones are positive.
vi. Slope due north or south (SLOS). As for SLOW, with northerly slopes positive and southerly slopes negative.



Crown density index
50 +
40 < 50
30 < 40
20 < 30
10 < 20
< 10
a.
Crown dieback score
25 +
20 < 25
15 < 20
10 < 15
5 < 10
< 5
b.
Browning score
18 +
15 < 18
12 < 15
9 < 12
6 < 9
< 6
c.
Yellowing score
18 +
15 < 18
12 < 15
9 < 12
6 < 9
< 6
d.

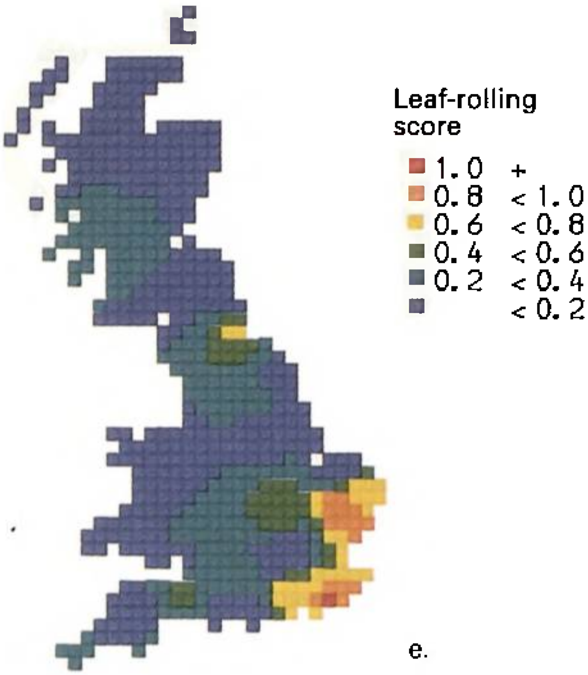


Figure 5. Patterns of crown indices in beech:

a. crown density

b. crown dieback

c. browning of leaves

d. yellowing of leaves

e. frequency of rolled leaves.

vii. Change of slope through the site (VERT). A measure of the degree of convexity or concavity of the slope which the plot is on.

viii. Change of direction of contour line passing through the site (HOR). A measure of whether the plot lies in a valley (one extreme) or on the brow of a hill (the other extreme).

ix. The ruggedness of the site (RUG). Equivalent to ELE4 of White and Smith (1982). Based on the sum of the four differences in altitude from the plot to the highest, or lowest, location within 10 km in each of the north-west, north-east, south-east and south-west quadrants.

x. Distance to the west coast (DFSW). This index provides an indication of oceanic impact at the site and is measured to the nearest 1 km.

xi. Distance to the east coast (DFSE), measured to the nearest 1 km.

xii. Highest elevation at any distance due west (HEW).

xiii. Highest elevation at any distance due east (HEE).

xiv. Average slope of the plot (SSLOPE). This is an extra index not used by White and Smith (1982).

Derived climatic data

White and Smith (1982) used the above indices to estimate a number of climatic variables. However, not all of these are thought to be relevant to tree growth. Very often, those that are can be characterised by a few relatively simple variables (Denton and Barnes, 1987). In this analysis, mean seasonal precipitation and temperature indices have been calculated using the multiple regression equations presented by White and Smith (1982). The models provide a good indication of mean air temperature for each season (93–96 per cent variation accounted for). Mean rainfall is less good (65–67 per cent variation accounted for), reflecting its high degree of spatial variation.

Equations for mean wind speed were also provided by White and Smith (1982) but the models account for very little of the variation and have not been adopted in this study. Wind is known to be an important factor affecting tree growth in Britain (see, for example, Pears, 1967 and Dixon and Grace, 1984) and the use of some index such as that proposed by Miller *et al.* (1987), based on a combination of the rate of tatter-flag destruction and altitude, is being investigated. Wind speed will be included when a suitable index has been identified. For the present analysis, as wind speed is essentially controlled by geographic and topographic factors, the inclusion of these in the analysis should take any wind effects into account.

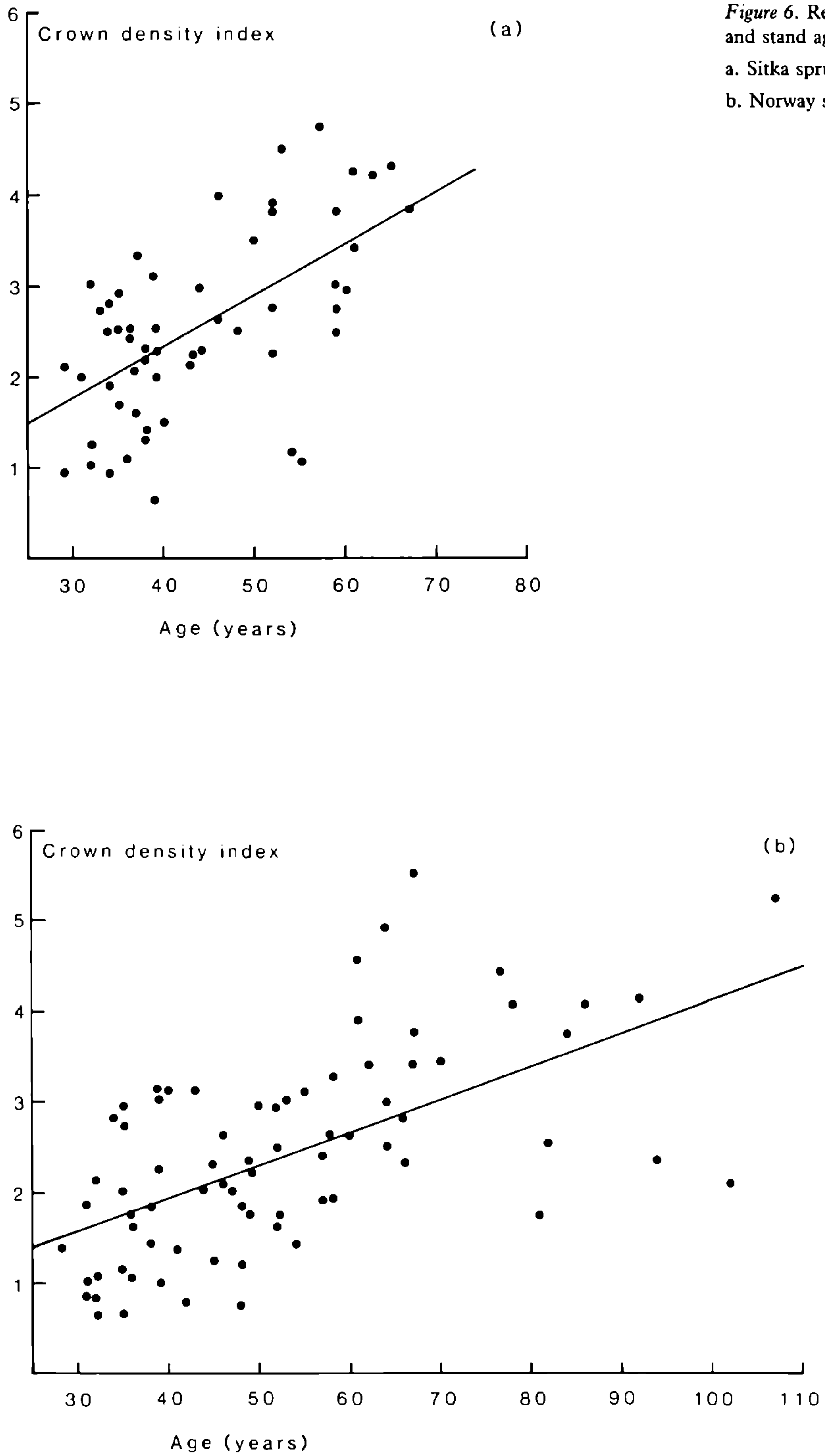


Figure 6. Relationship between crown density and stand age in

a. Sitka spruce

b. Norway spruce.

Modelled pollution variables (based on emission data)

Detailed information for a large number of pollutants has been supplied by the Modelling and Assessments Group at the United Kingdom Atomic Energy Authority at Harwell. A trajectory model was used to estimate the pollutant concentrations and rates of deposition at each of the 264 plots. The variables used are listed in Table 1. Whereas some of the modelled patterns of pollutant distribution fit measured data quite well, other models (e.g. that for ammonia deposition) have a relatively poor fit. The model for the distribution of mean annual ozone levels is currently under considerable debate and lacks any detailed verification. As more measurements become available for the United Kingdom, it is likely that a number of refinements will be made to all the models. In addition, it will be possible to map peak ozone concentrations, which may have more biological significance than mean annual concentrations. Full details of the trajectory model and the derivation of the pollution levels are given in Derwent *et al.* (1987).

Modelled pollution variables (based on deposition measurements)

Data for pollutant concentrations in rainfall were obtained from Warren Spring Laboratory. The data from the secondary network for 1986, the first year of operation, were used. This network consists of 60 bulk precipitation collectors (i.e. those which are continuously open) located throughout the United Kingdom. The sites used in the network were chosen to provide details of the regional patterns of precipitation composition (Devenish, 1986).

The data from the 60 sites have been used to develop spatial models of deposition. The actual deposition field was calculated using the Meteorological Office 1941–70 mean annual precipitation data. Using interpolation procedures, deposition figures were calculated for each 20 by 20 km square in the United Kingdom by staff at Warren Spring Laboratory, and it is these data that have been used to represent the deposition of pollutants at each plot. The pollutants used in the analysis are listed in Table 1 and maps showing their distributions are given in Appendix 2.

The values in the deposition field do not take into account any deposition of pollutants that may occur as a result of cloud water coming into contact with trees (a phenomenon known as occult deposition). This is important at higher altitudes (Dollard *et al.*, 1983) but, as yet, there is insufficient information to enable this form of deposition to be incorporated into the deposition field. There are also indications that the concentration of pollutants in rainfall increases with increasing altitude but, again, there are insufficient data to incorporate this phenomenon into the present analysis. When such information becomes available, it will, of course, be incorporated.

Regression and Correlation Analysis

As stated above, the basic techniques used in this study are simple and multiple correlation analysis and multiple regression analysis. The correlations between the measured tree indices (Table 2) and the range of explanatory variables are given for individual tree species in Figures 7 to 11. As in Figures 1 to 5, various crown parameters have been examined.

Sitka spruce

The correlation between crown density and stand age is readily apparent, with density decreasing with increasing stand age. The only other significant ($p < 0.05$) correlation for crown density is with the north-south slope in the vicinity of the plot (SLOS). Crown density is higher where the lie of the land is south-facing than where it is north-facing. The amount of discoloration within the crowns increases with increasing distance from the west coast.

Norway spruce

As with Sitka spruce, there is a clear correlation between crown density and stand age. No other variable is significantly correlated with crown density. Similarly, none of the variables used in this study are correlated with crown discoloration.

Scots pine

The patterns of correlation are totally different for Scots pine. Many of the variables are significantly correlated with crown density, although no correlations were found between discoloration and any of the variables. Crown density decreases northwards and westwards and this is reflected in the climatic correlations, with crown density being lower in areas with higher rainfall and lower temperatures. Crown density is also lower at higher elevations, on steeper slopes and in more rugged terrain.

Most of the modelled pollutant levels are significantly correlated with crown density, with crowns being denser in areas with higher levels of pollution. The exception is with long-term ozone levels: crown density is lower in those parts of Britain with higher mean ozone concentrations. The correlations with the measured deposition data indicate that crown density

Table 1. Pollution data used in analysis

From Harwell Laboratory (all values are modelled):

HNOx	Mean annual concentration of oxides of nitrogen (ppb).
HNO2	Mean annual concentration of nitrogen dioxide (ppb).
HHNO3	Mean annual concentration of gaseous nitric acid (ppb).
HNae	Mean annual concentration of nitrate aerosol (ppb).
HNO3	Mean annual concentration of nitric oxide (ppb).
HNH3	Mean annual concentration of ammonia (ppb).
HNH4ae	Mean annual concentration of ammonium aerosol (ppb).
HSO2	Mean annual concentration of sulphur dioxide (ppb).
HSO4ae	Mean annual concentration of sulphate aerosol (ppb).
HNO3r	Mean annual concentration of nitrate in rain (mg N l^{-1}).
HSO4r	Mean annual concentration of sulphate in rain (mg S l^{-1}).
HNH4r	Mean annual concentration of ammonium in rain (mg N l^{-1}).
HtdryS	Total dry deposition of sulphur (kg S ha^{-1} yr^{-1}).
HtwetS	Total wet deposition of sulphur (kg S ha^{-1} yr^{-1}).
HO3	Mean annual ozone concentration (ppb).
HdryNO3	Dry nitrate deposition (kg N ha^{-1} yr^{-1}).
HwetNO3	Wet nitrate deposition (kg N ha^{-1} yr^{-1}).
HdryNH4	Dry ammonium deposition (kg N ha^{-1} yr^{-1}).
HwetNH4	Wet ammonium deposition (kg N ha^{-1} yr^{-1}).

From Warren Spring Laboratory:

WHc	Precipitation weighted annual mean hydrogen ion concentration (μeq l^{-1}) for 1986.
WHd	Wet deposited acidity (g H^+ m^{-2}) for 1986.
WSO4c	Precipitation weighted annual mean non-marine sulphate concentration (μeq l^{-1}) for 1986.
WSO4d	Wet deposited non-marine sulphate (g S m^{-2}) for 1986.
WtSO4c	Precipitation weighted annual mean total sulphate concentration (μeq l^{-1}) for 1986.
WtSO4d	Wet deposited sulphate (g S m^{-2}) for 1986.
WNO3c	Precipitation weighted annual mean nitrate concentration (μeq l^{-1}) for 1986.
WNO3d	Wet deposited nitrate (g N m^{-2}) for 1986.
WNH4c	Precipitation weighted annual mean ammonium concentration (μeq^{-1}) for 1986.
WNH4d	Wet deposited ammonium (g N m^{-2}) for 1986.
WdryS	Modelled dry deposited sulphur deposition (g S m^{-2}) for 1983.
WSO2c	Modelled near-surface sulphur dioxide concentrations (μg S m^{-3}) for 1983.

Some of these measures were combined in an attempt to reduce the size of the data set:

HtwdS	HtdryS + HtwetS
HwdNO3	HdryNO3 + HwetNO3
HwdNH4	HdryHN4 + HwetNH4
TS	HtdryS + HtwetS + WtSO4d − WSO4d

This enabled HtdryS, HtwetS, HdryNO3, HwetNO3, HdryHN4, HwetNH4, WtSO4d and WSO4d to be excluded from the analysis.

Table 2. Derivation of reponse variables used to represent crown condition (all indices are site means)

Crown density
Crown density is scored in 10% classes with class 0 representing no reduction in density and class 9 being 90–100% below that of a 'perfect' tree. For the index, class 0 was taken as 5, class 1 as 15, class 2 as 25 and so on. It is important to note that as the index increases in value, crown density decreases.
Crown discoloration
Crown discoloration is scored in 4 classes: 0–10%, 11–25%, 26–60% and >60%. For the index, class 0 was taken as 5, class 1 as 18, class 2 as 43 and class 3 as 80. A high index therefore indicates a large amount of discoloration in the crown.
Crown dieback
Crown dieback was scored in 4 classes: 0, 1–10%, 11–30% and >30%. For the index, class 0 was taken as 0, class 1 as 5, class 2 as 20 and class 3 as 45. A high index therefore indicates a large amount of dieback in the crown.
Leaf-rolling
The frequency of leaf-rolling was assessed in three classes: none, rare or common. For the index, these were scored as 0, 1 and 2. The degree of rolling was assessed in four classes: none, light, moderate and severe. For the index, these were scored as 0, 1, 2, and 3.

increases with increasing concentrations of some pollutants, but not with total deposition. This reflects the gradients in concentration and total deposition, the latter being strongly influenced by total rainfall.

Oak

Crown densities in oak are lower in areas with more rugged terrain and in areas with higher summer rainfall. Densities are generally higher in those areas with higher modelled levels of pollution. The exception is again with mean ozone levels, with crown densities being lowest in those areas with high long-term levels of ozone. With the measured pollution data, correlations exist with pollutant concentration in rainfall but not with total deposition.

The extent of crown die-back is greatest in areas with high summer rainfall and cool summer temperatures, otherwise, no signficant correlations were found.

Browning of leaves decreases with increasing distance from the east coast and is higher in areas with higher rainfall acidity. The only correlation obtained for leaf yellowing is with a topographic variable, with yellowing being greater on concave slopes.

Beech

Crown densities of beech are strongly correlated with a number of pollution variables, with densities being highest in areas with higher modelled levels of pollution. Mean ozone levels again show the reverse, with crown densities being lower in areas with higher long-term ozone levels. In contrast to Scots pine and oak, correlations exist between both concentration and total deposition of the measured pollutants, the exception being with levels of ammonia deposition.

Crown dieback increases with increasing distance from the east coast and is higher in more rugged areas. It is also greater in areas with higher rainfall. The only pollutant variable that dieback is correlated with is total modelled ammonia deposition, with dieback being greater in areas with higher levels of total ammonia deposition.

Browning of beech leaves decreases with increasing distance from the east coast but shows no relation with distance from the west coast or distance to the nearest coast. It is also greater in areas with lower levels of modelled ammonia deposition. Yellowing of leaves is not significantly correlated with any of the variables examined.

The extent of leaf-rolling was recorded in 1987 and the degree of this increases eastwards and also increases in areas with higher spring temperatures. It is lower in areas with higher summer rainfall.

Figure 7. Correlation diagrams for: a. crown density and b. crown discoloration of Sitka spruce.

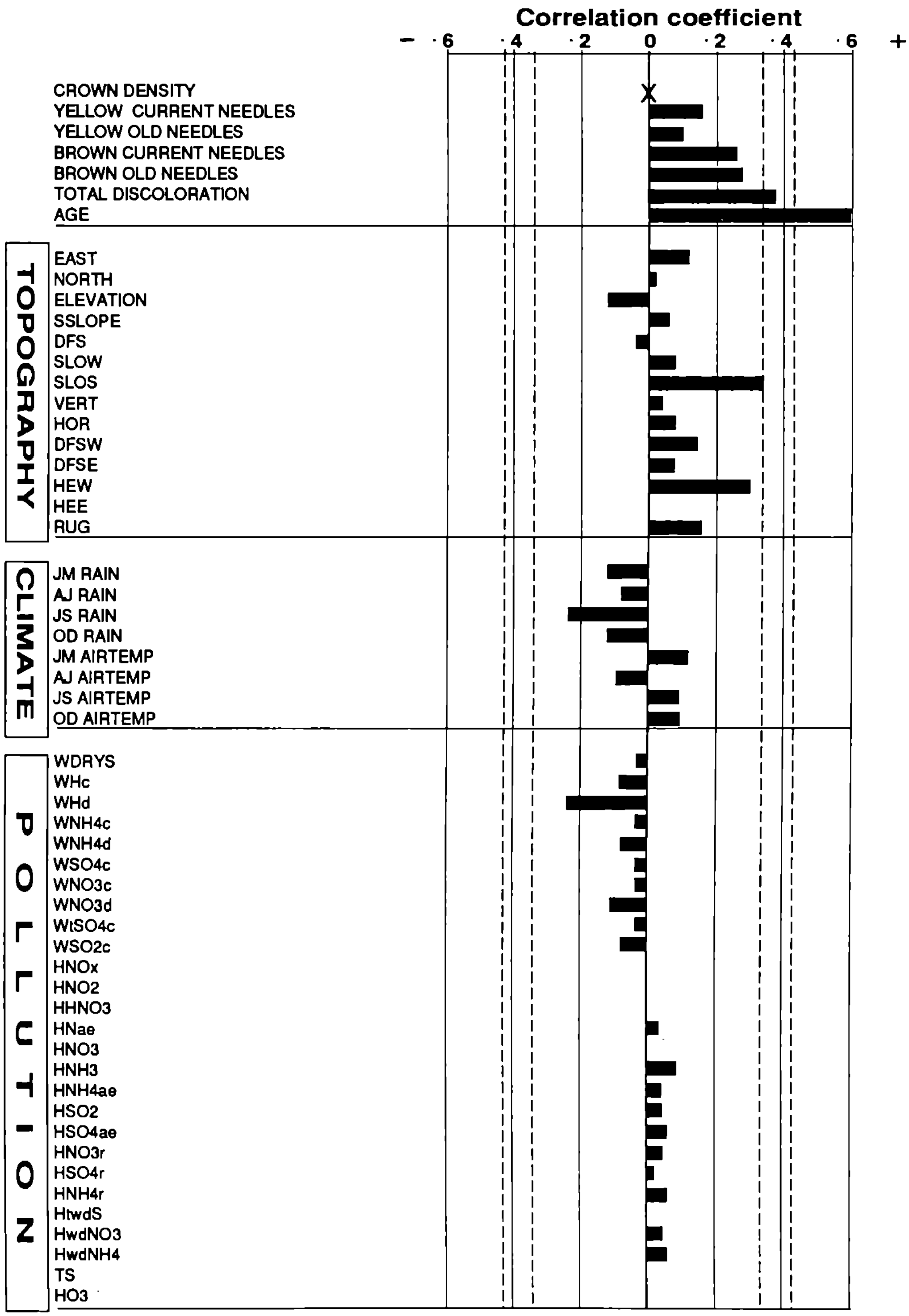


Figure 7a. Sitka spruce – crown density

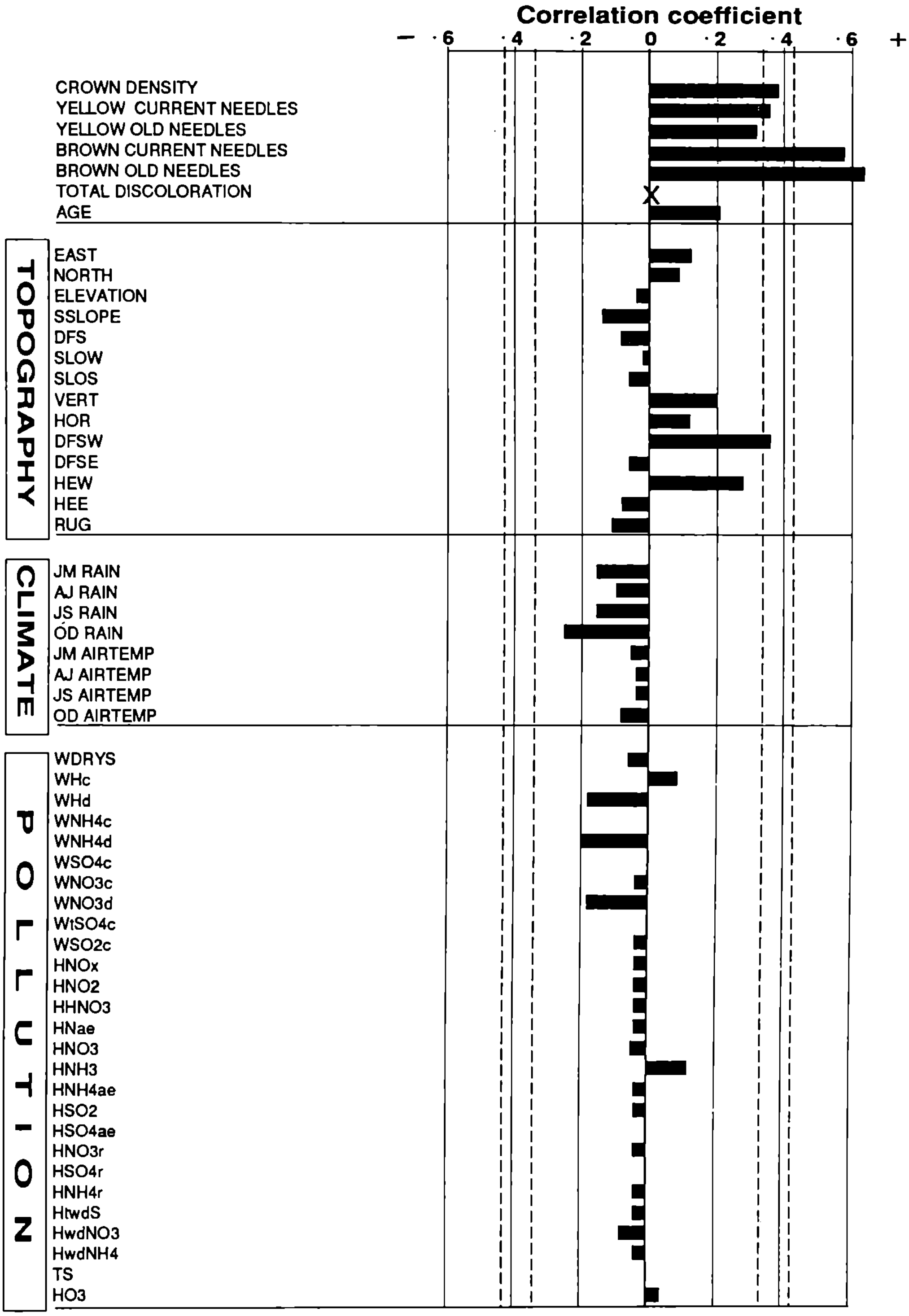


Figure 7b. Sitka spruce – total discoloration

Figure 8. Correlation diagrams for: a. crown density and b. crown discoloration in Norway spruce.

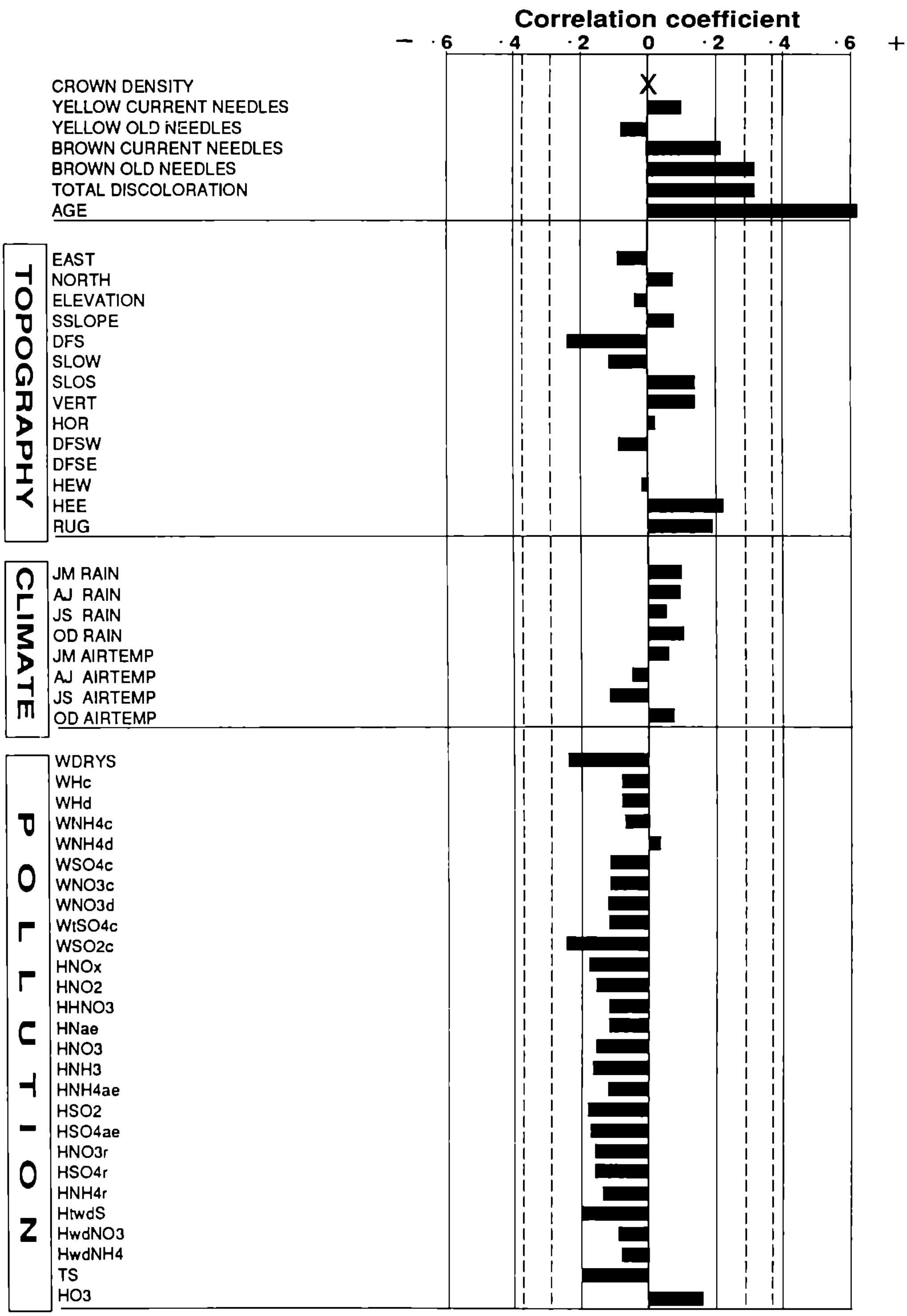


Figure 8a. Norway spruce – crown density

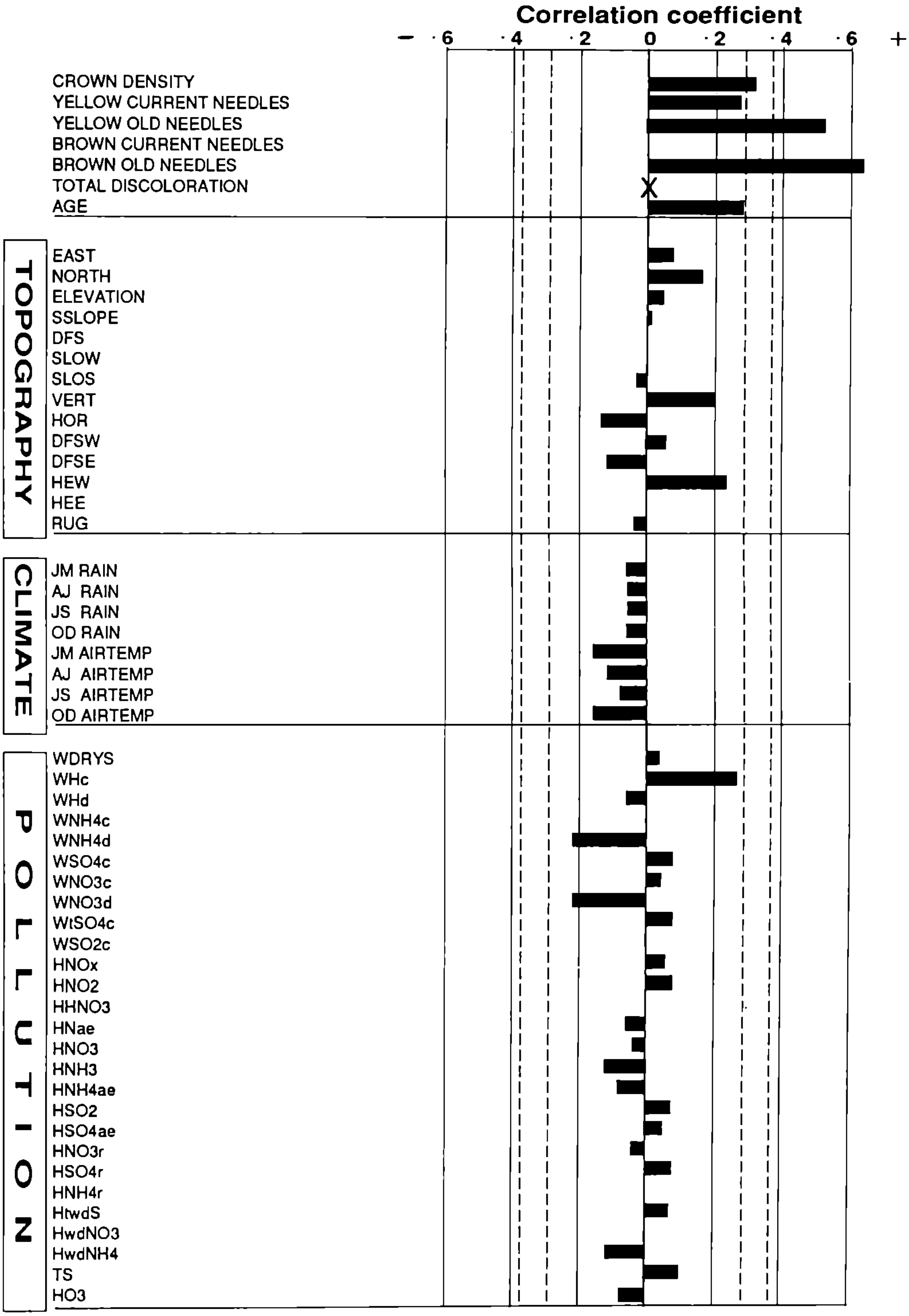


Figure 8b. Norway spruce – total discoloration

Figure 9. Correlation diagrams for: a. crown density and b. crown discoloration in Scots pine.

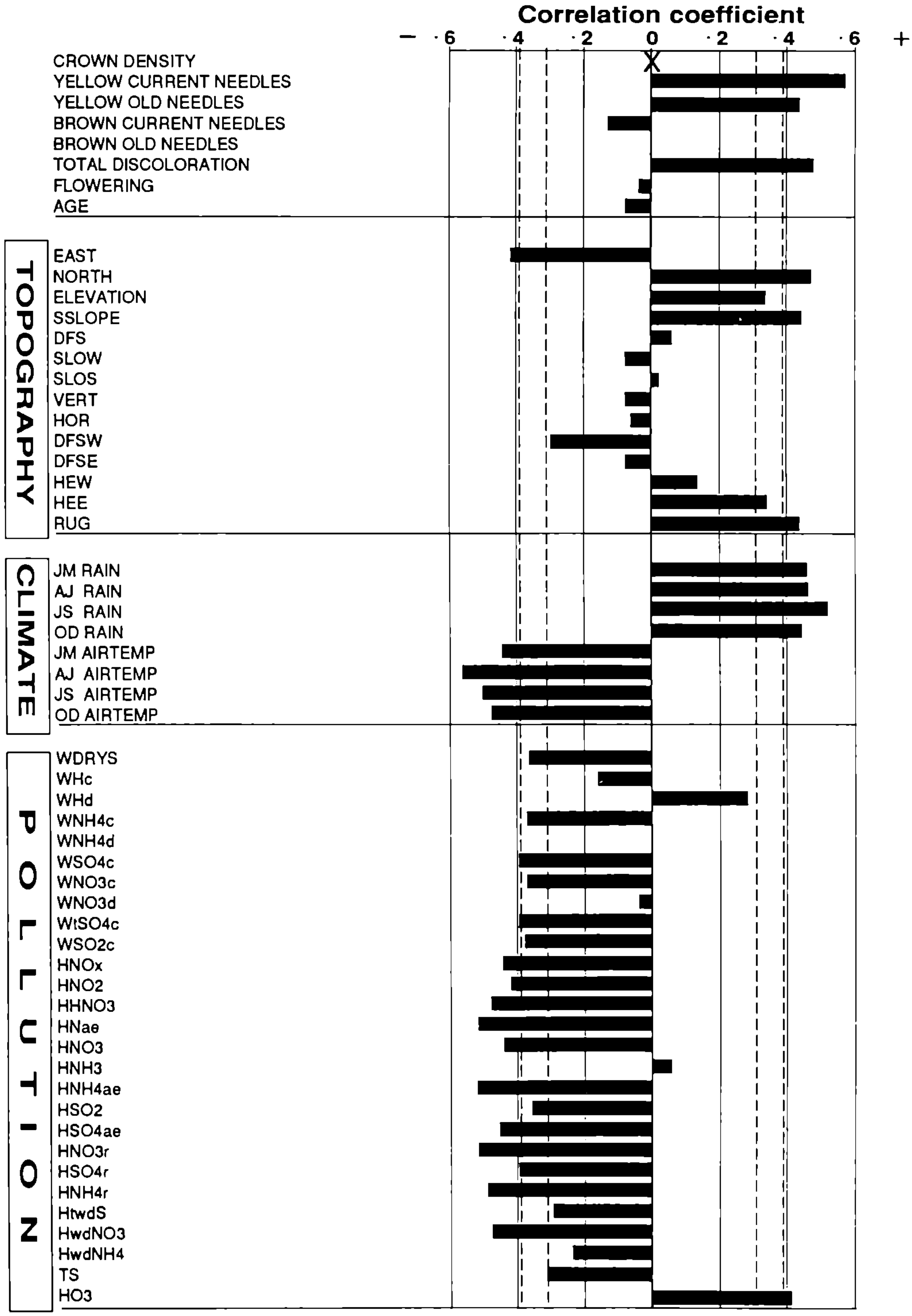


Figure 9a. Scots pine – crown density

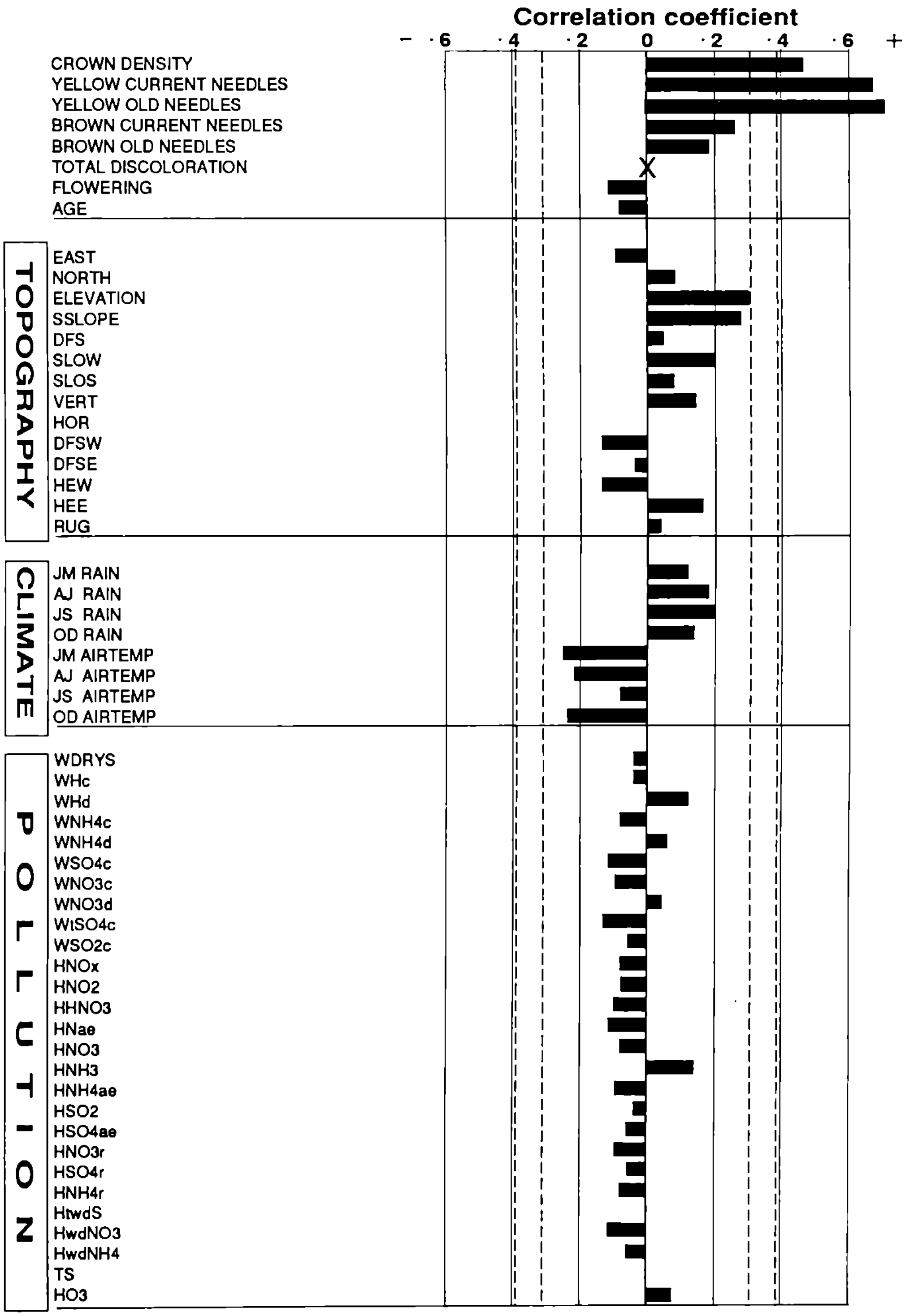


Figure 9b. Scots pine – total discoloration

Figure 10. Correlation diagrams for: a. crown density, b. crown dieback, c. browning and d. yellowing in oak.

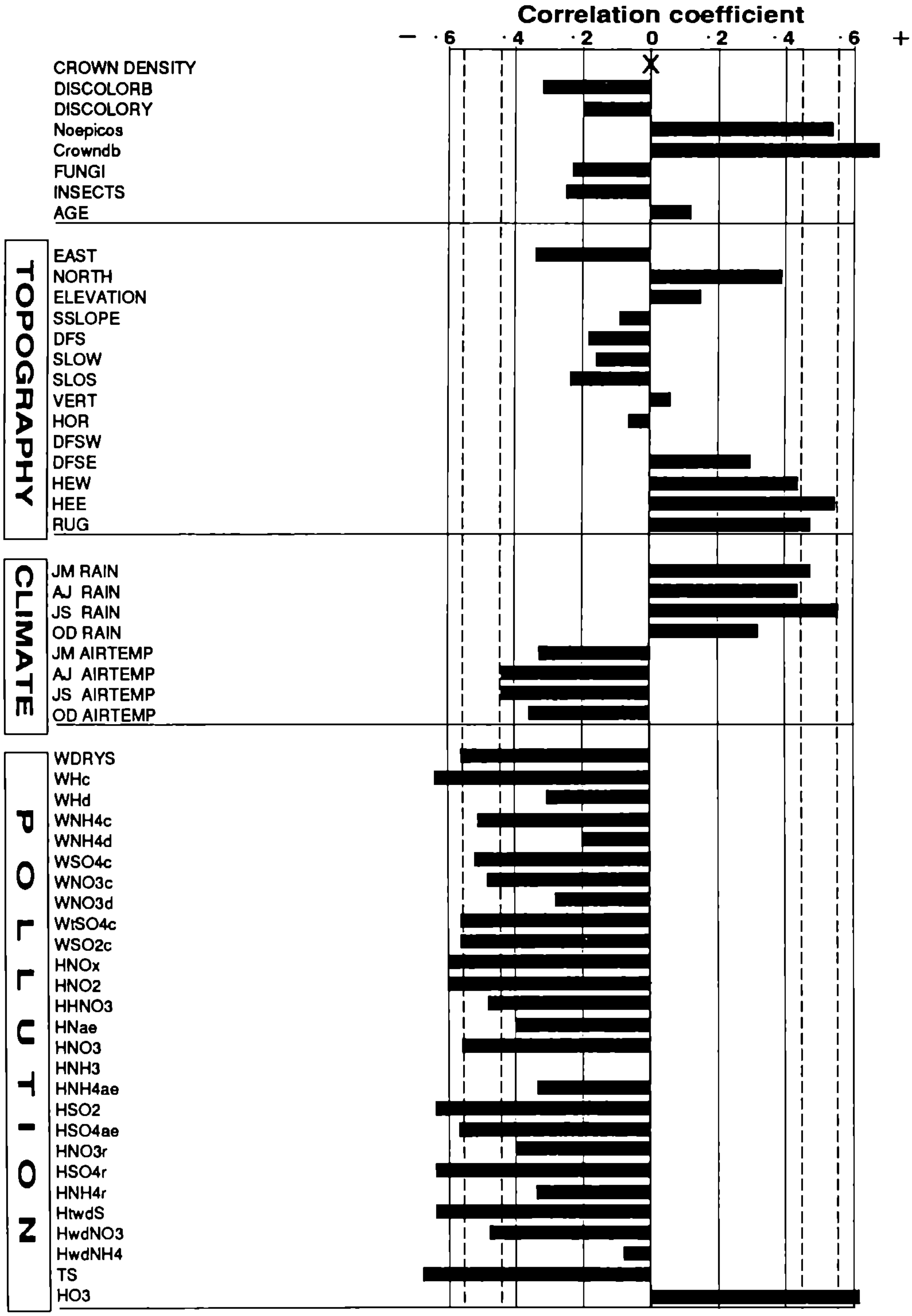


Figure 10a. Oak – crown density

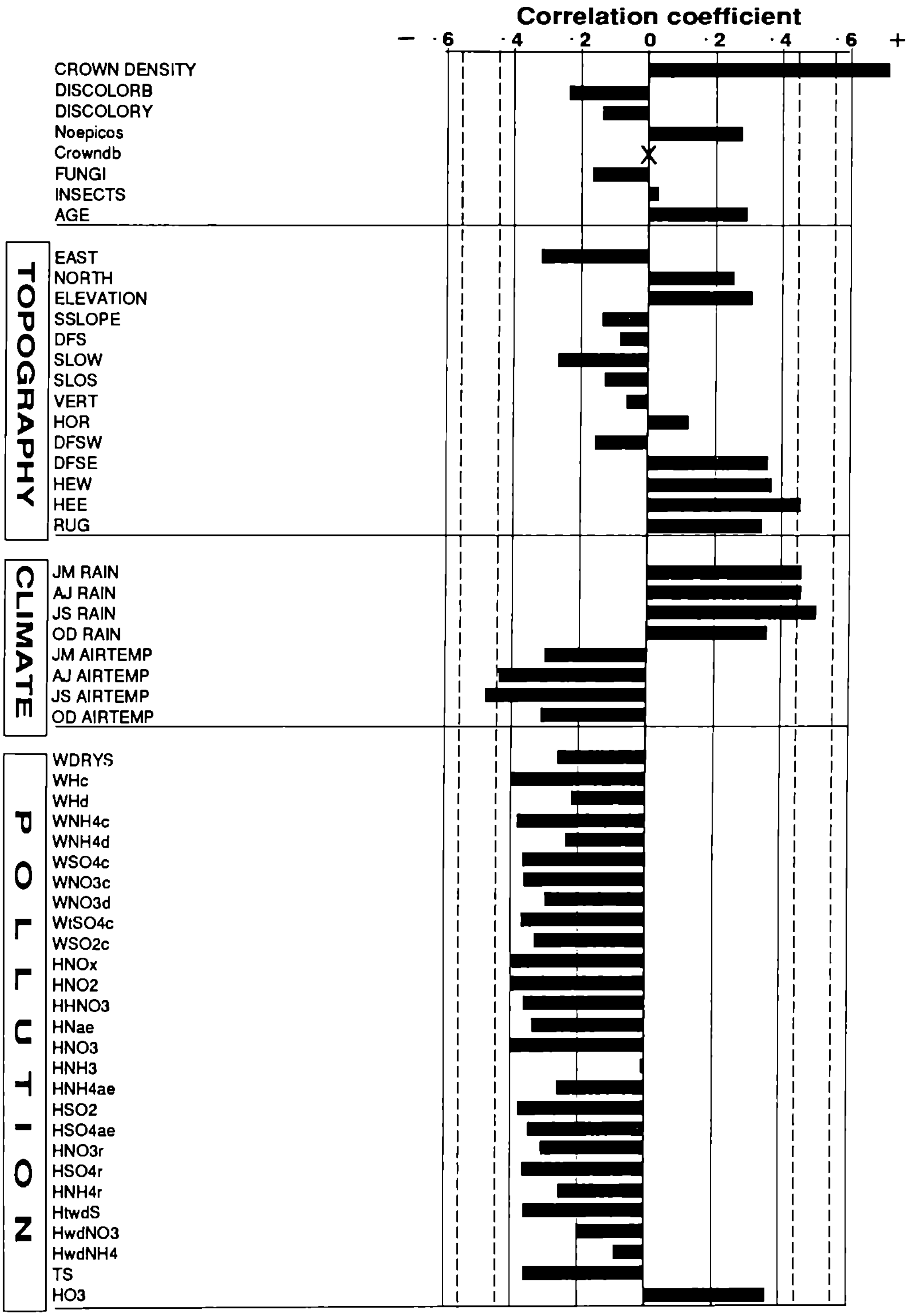


Figure 10b. Oak – crown dieback

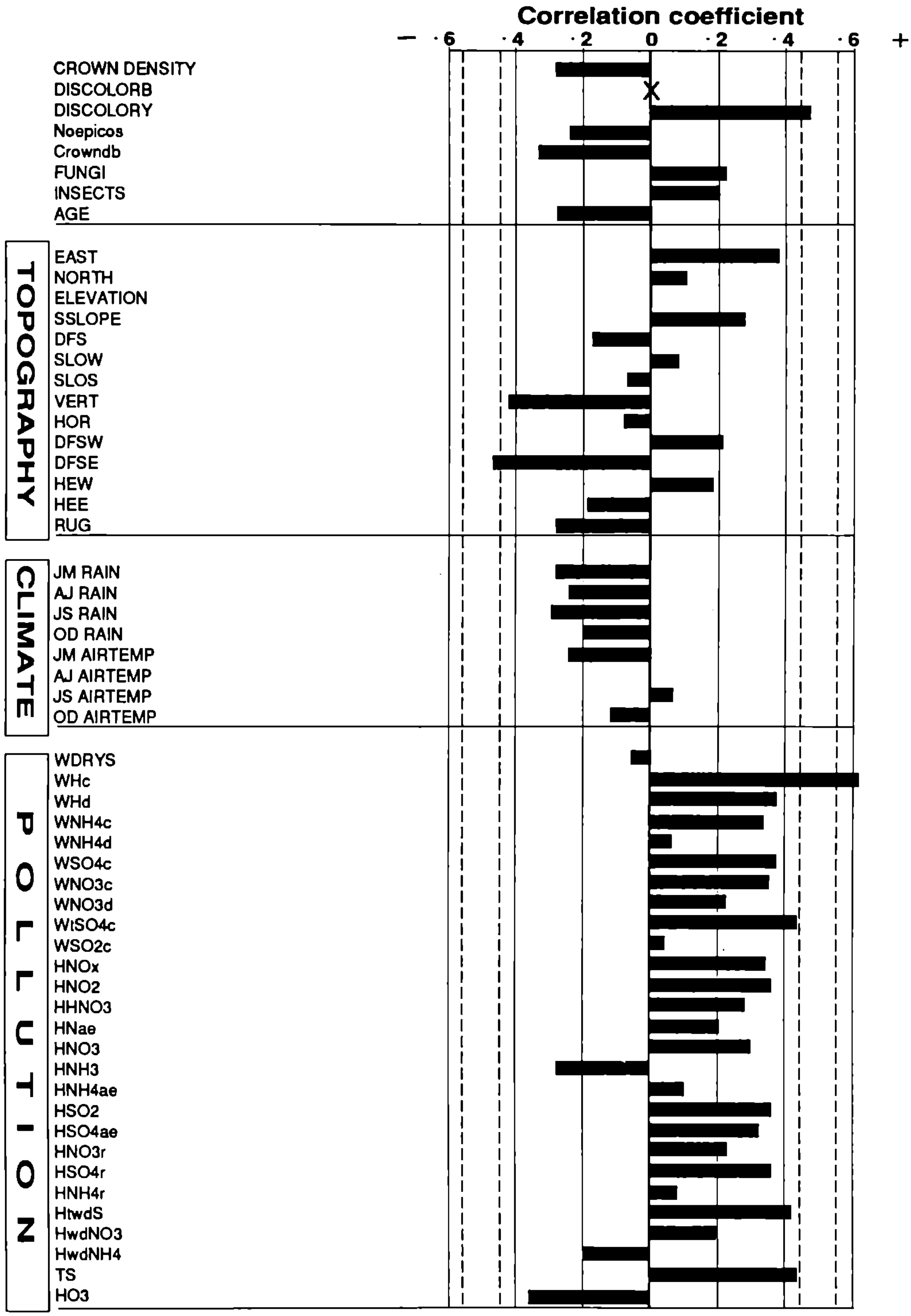


Figure 10c. Oak – browning

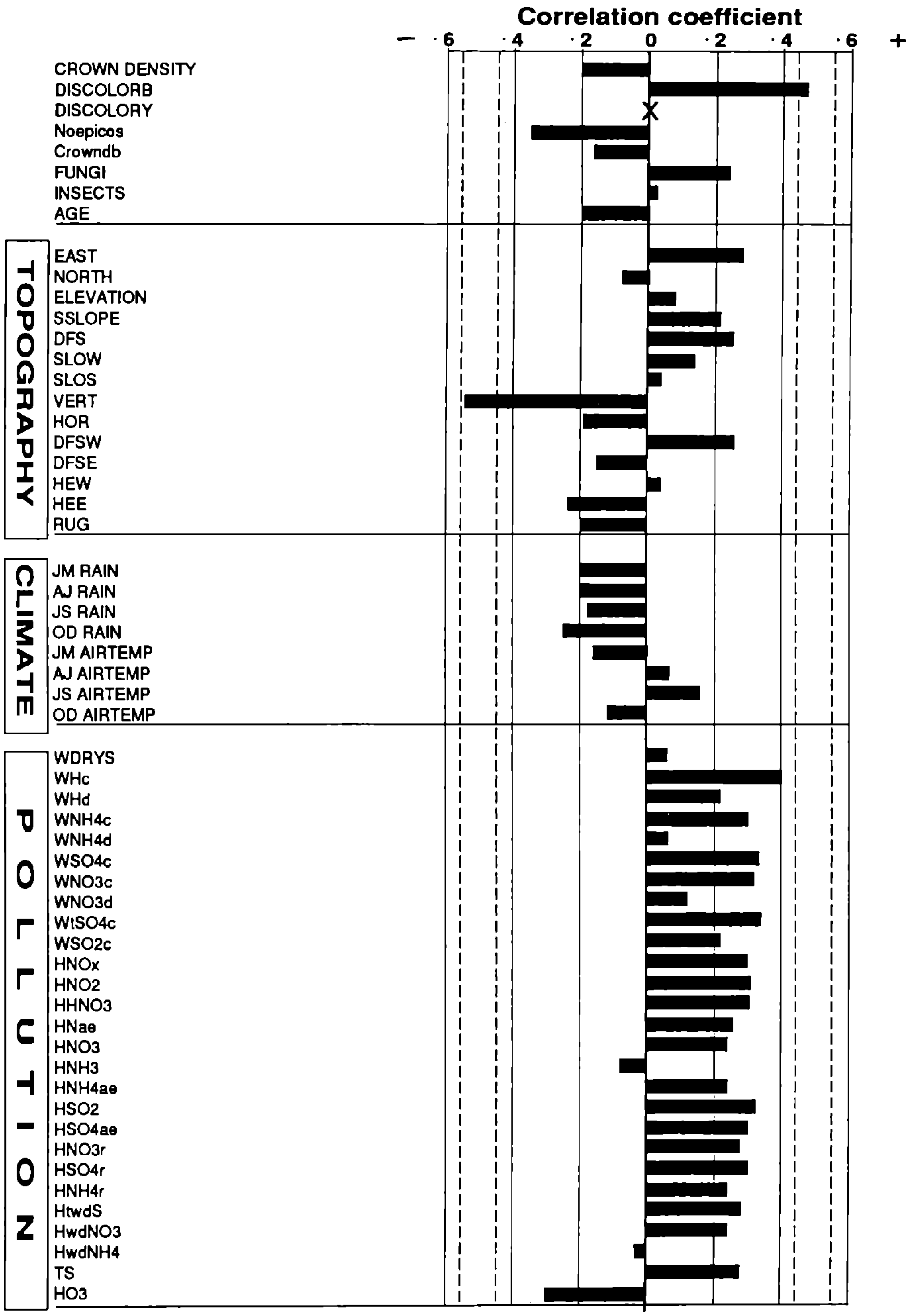


Figure 10d. Oak – yellowing

Figure 11. Correlation diagrams for: a. crown density, b. crown dieback, c. browning, d. yellowing and e. frequency of leaf-rolling in beech.

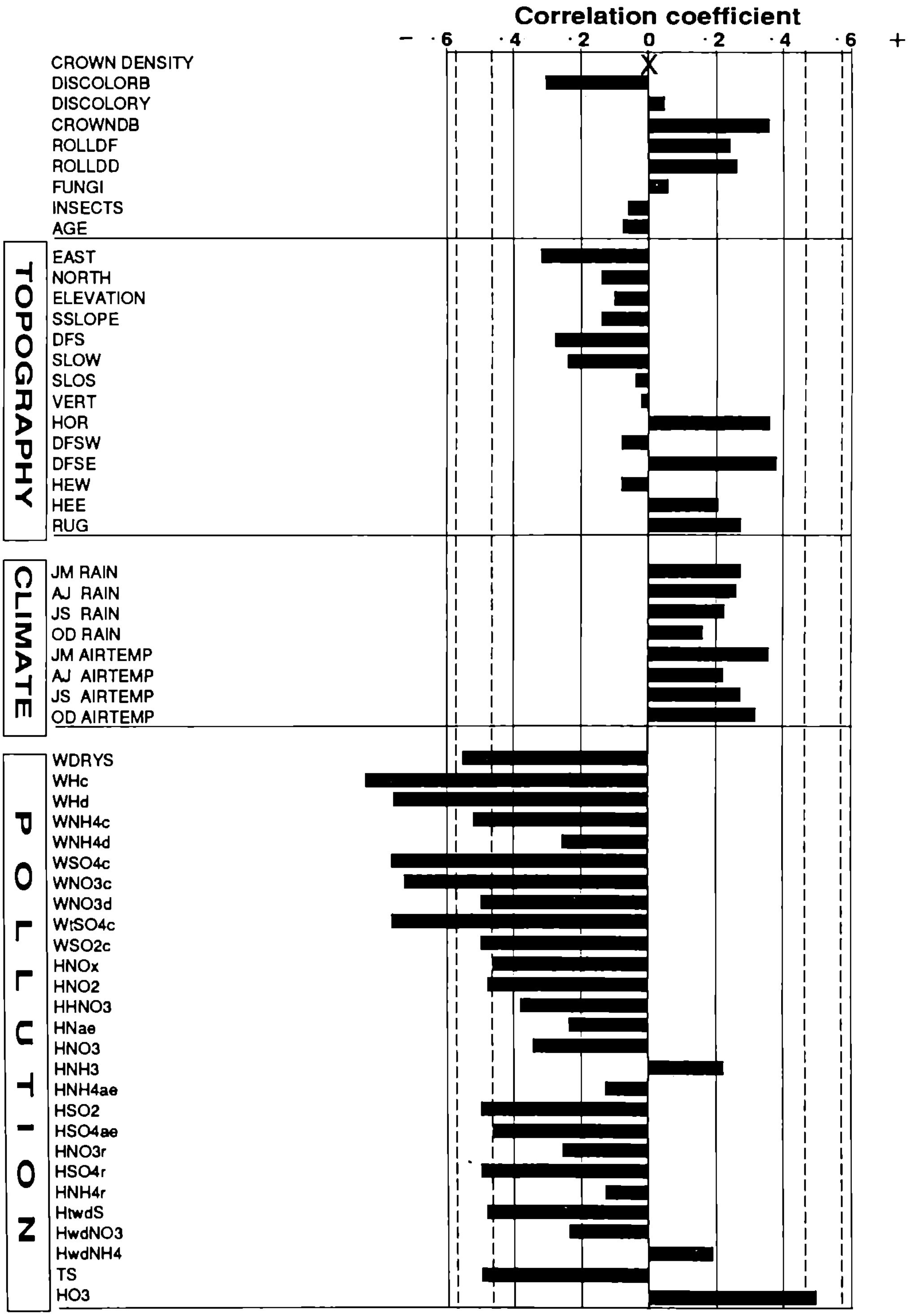


Figure 11a. Beech – crown density

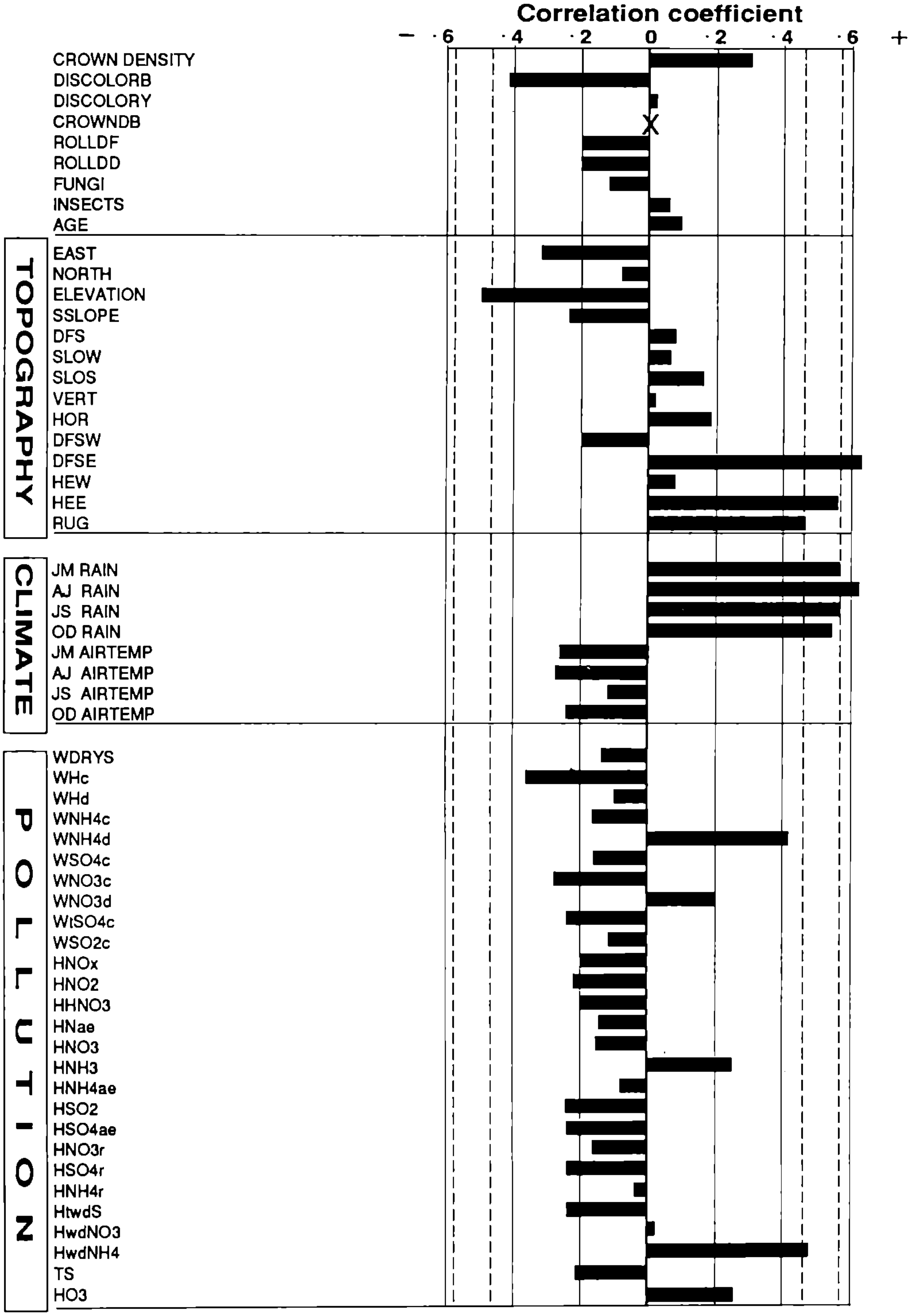


Figure 11b. Beech – crown dieback

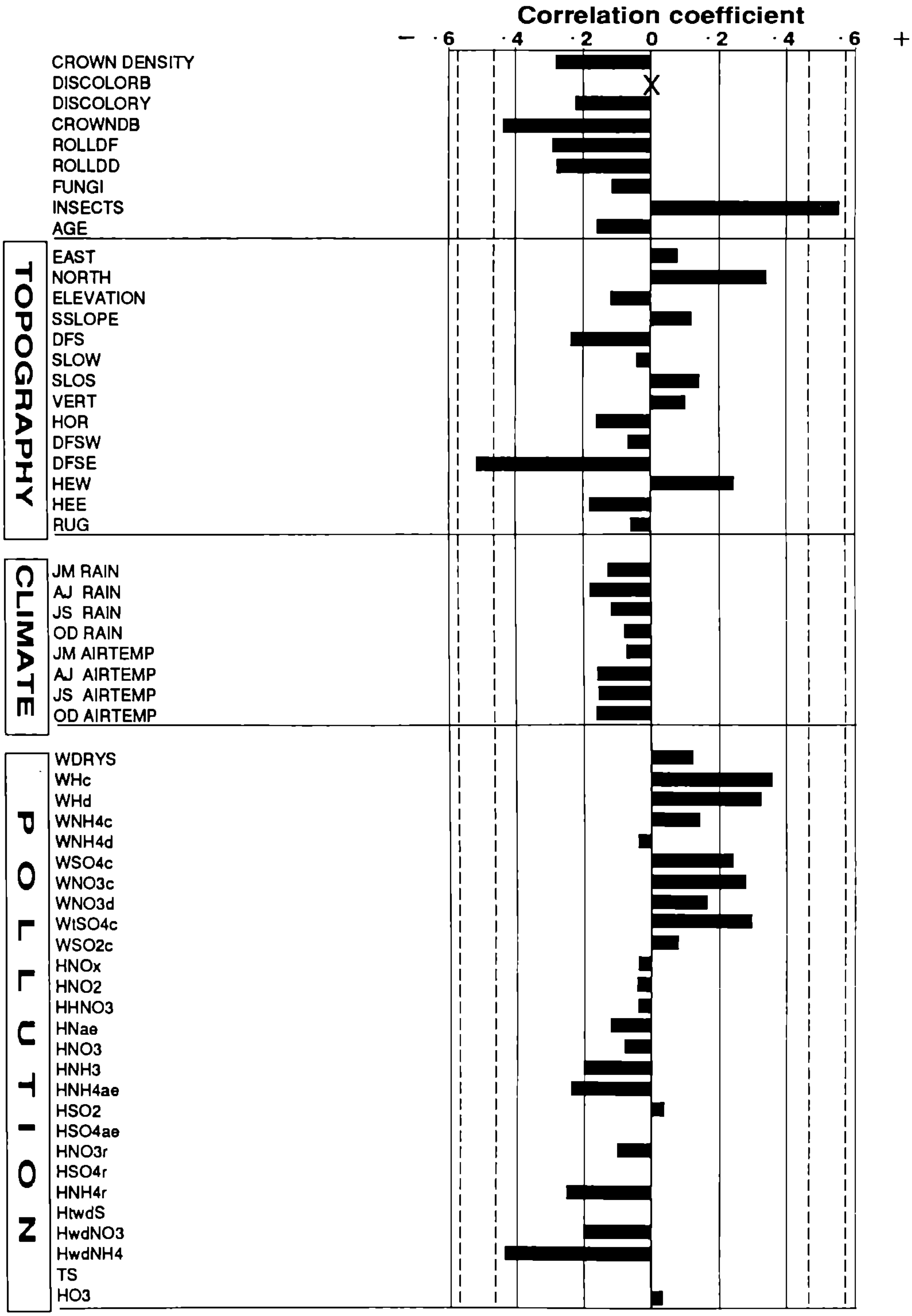


Figure 11c. Beech – browning

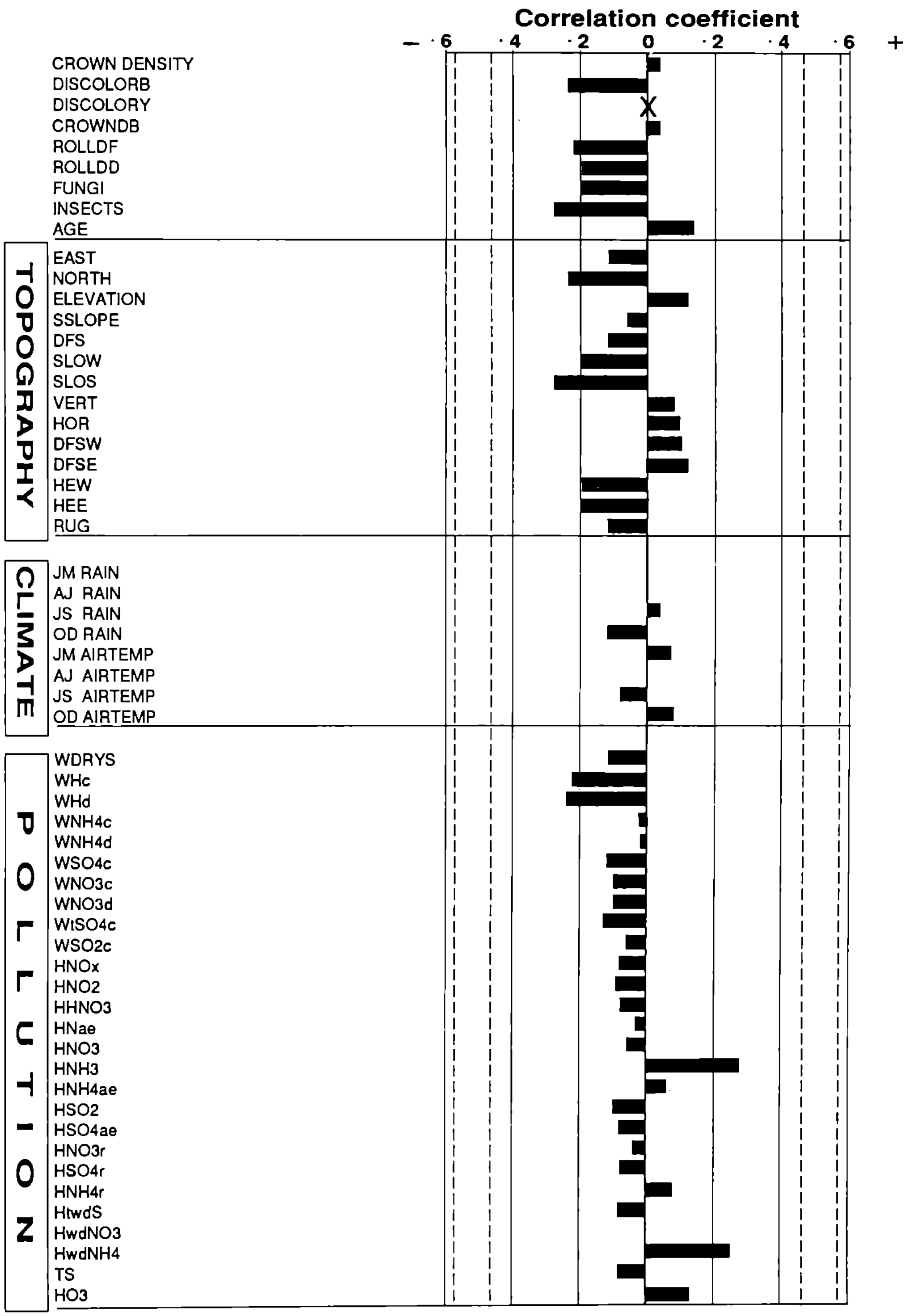


Figure 11d. Beech – yellowing

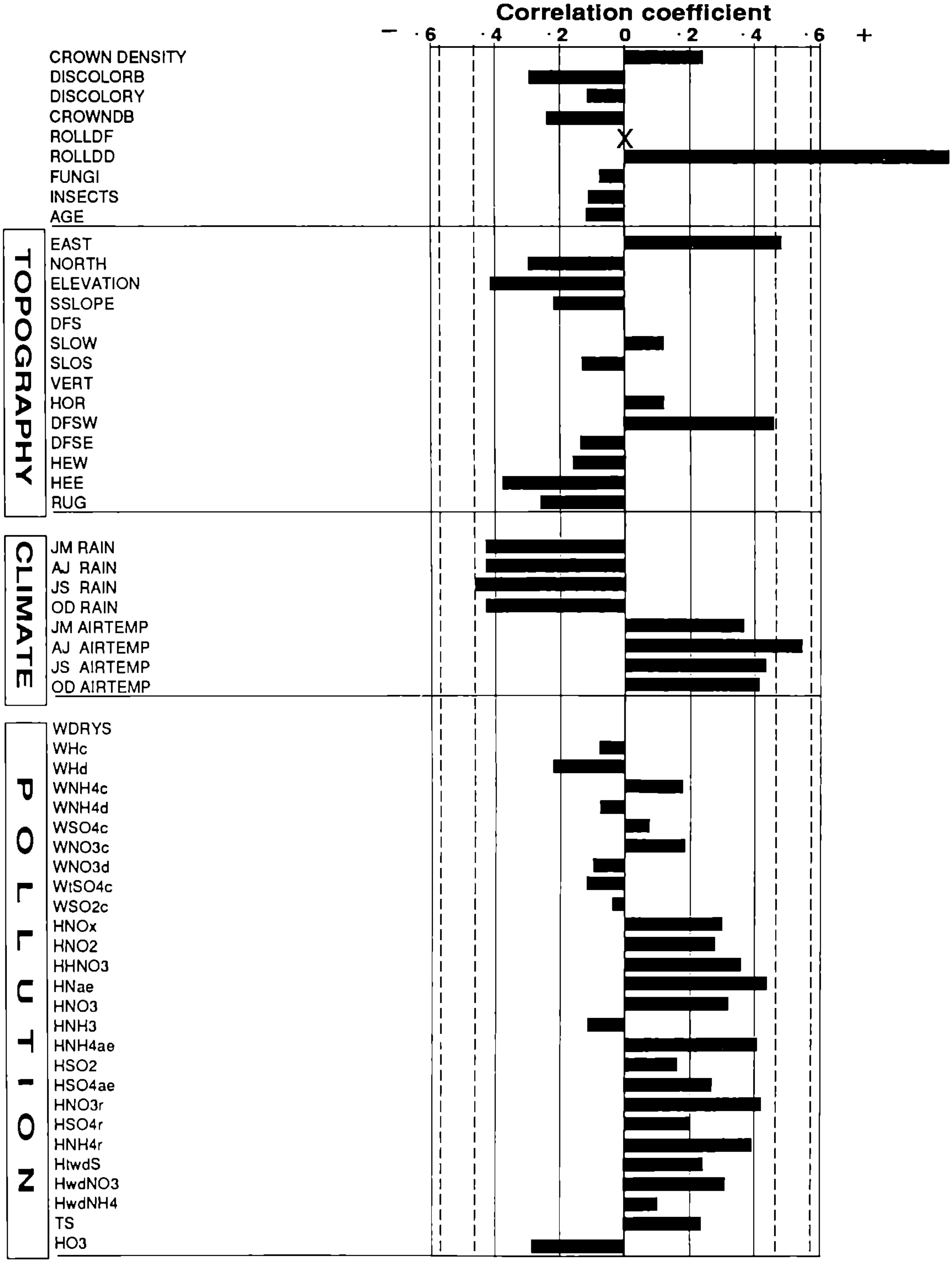


Figure 11e. Beech – frequency of rolled leaves

General

Examples of some of the relationships between crown density and other variables are given in Figures 12 to 15. Four variables, long-term ozone concentrations, measured hydrogen ion deposition, measured nitrate deposition and mean air temperature (April–June, °C) have been selected to show the range of relationships that are possible.

The simple correlations reveal a complex pattern of co-variation which is difficult to sort out. However, an attempt was made to do so using multiple regression analysis. For each species data set, a step-wise regression was run. The results are presented in Table 3. For each step-wise regression, only those variables that explained a significant amount of variation in the target index have been included (i.e. the step-wise process

Table 3. Multiple regression equations for crown condition parameters

Sitka spruce	*Variance accounted for*
Crown density	
0.91 + 0.5465 AGE + 0.664 SLOS	43%
Yellowing of current needles	
−5.34 + 0.0636 VERT + 0.00252 HEW − 3.7 HNH3	41%
Yellowing of older needles	
2.62 + 0.1708 WHc − 12.7 WNO3d + 12.02 JMrain	34%
Browning of current needles	
2.86 + 0.01359 HOR	9%
Browning of older needles	
−6.95 + 0.00492 HEW + 0.0598 VERT	18%
Total discoloration	
4.861 + 0.02189 DFSW	11%

Norway spruce	*Variance accounted for*
Crown density	
2.2 + 0.4172 AGE − 0.2228 DFS + 0.2982 SSLOPE + 0.0317 HOR	51%
Yellowing of current needles	
5.2 + 0.1457 WHc − 0.0982 WNO3c − 41.1 WHd	30%
Yellowing of older needles	
4.272 + 0.1066 WHC + 1.639 WdryS − 0.0802 WNO3c − 0.187 WSO2c	48%
Browning of current needles	
0.52 + 0.428 AJairt + 0.0311 SSLOPE	15%
Browning of older needles	
5.879 − 4.38 WNO3d + 0.01873 AGE	17%
Total discoloration	
8.13 + 0.02955 AGE + 0.0576 WHc − 6.16 WNO3d − 0.329 AJairt	28%

Scots pine	*Variance accounted for*
Crown density	
76.2 − 5.09 AJairt + 0.268 SSLOPE	35%
Yellowing of current needles	
10.73 − 1.066 JMairt − 0.002299 HEW	18%
Yellowing of older needles	
5.596 + 0.0825 SSLOPE	13%
Browning of current needles	
−1.52 + 0.0362 VERT − 0.0512 SLOW + 0.357 HNO3	21%
Browning of older needles	
5.004 + 0.00335 ELEV	5%
Total discoloration	
5.204 + 0.00811 ELEV	8%

Oak	*Variance accounted for*
Crown density	
28.89 + 0.02759 HEW − 0.4509 WHc	60%
Browning of leaves	
4.83 + 0.02237 WHc − 0.1279 WdryS − 0.00388 DFS	60%
Yellowing of leaves	
16.74 − 0.0636 VERT + 0.01715 DFS − 0.000552 RUG − 0.243 WdryS	55%
Crown dieback	
−41.71 + 112.3 JSrain + 0.1017 AGE + 0.028 DFSW	47%

Beech	*Variance accounted for*
Crown density	
42.47 − 0.3653 WHc − 0.0248 ELEV	71%
Browning of leaves	
12.64 − 0.02707 DFSE	25%
Yellowing of leaves	
Not significant	
Crown dieback	
40.9 + 0.02637 DFSE + 0.00923 HEE + 10.33 WNH4d + 0.1891 VERT	63%
Extent of leaf-rolling	
−1.949 + 0.1986 AJairt	28%
Degree of leaf-rolling	
−1.939 + 0.1975 AJairt	27%

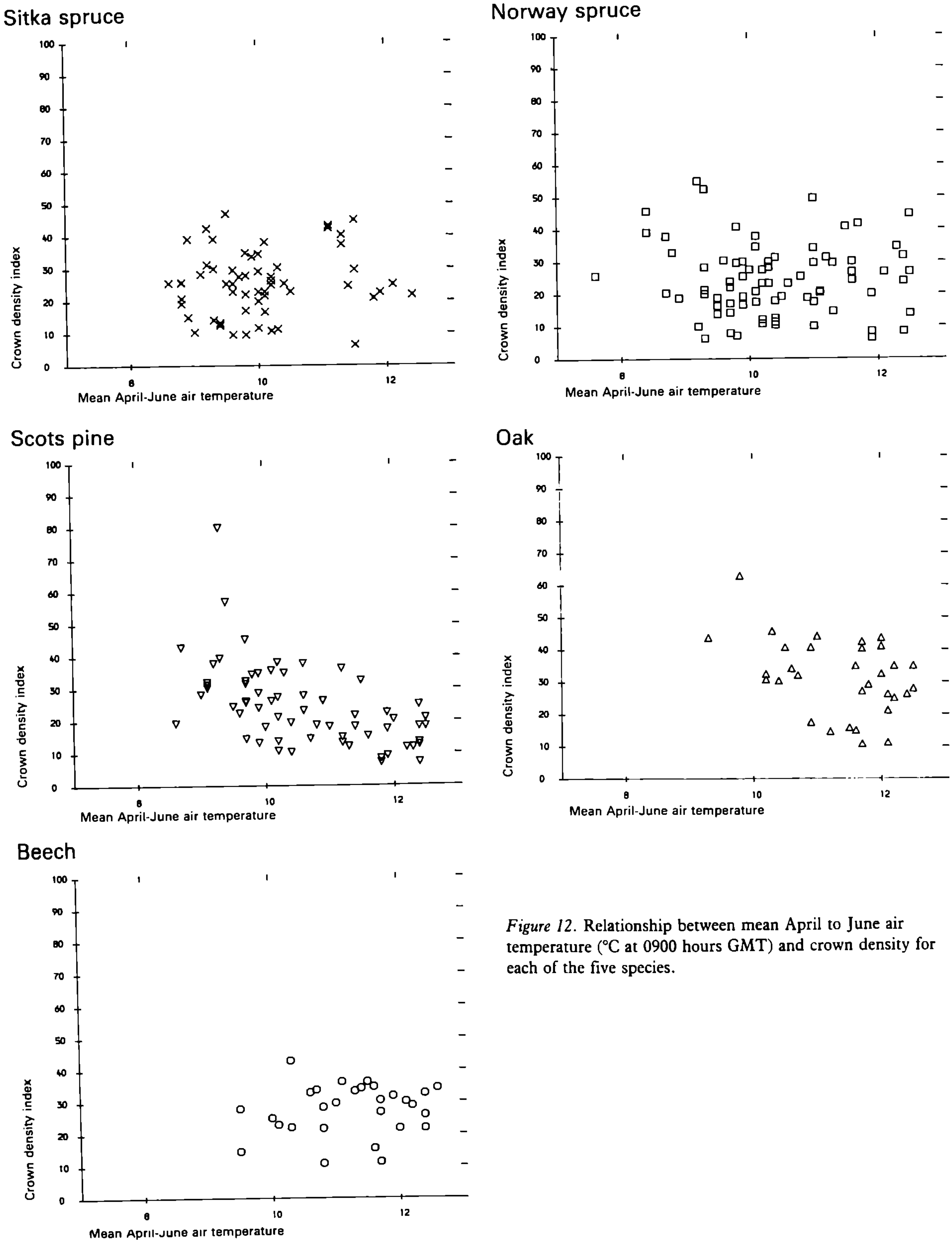
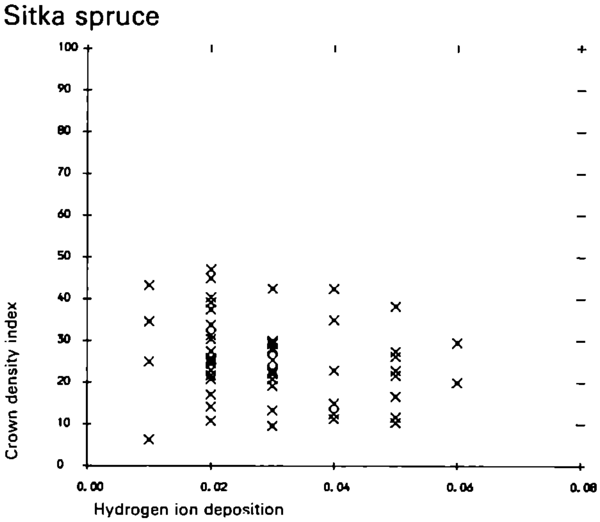
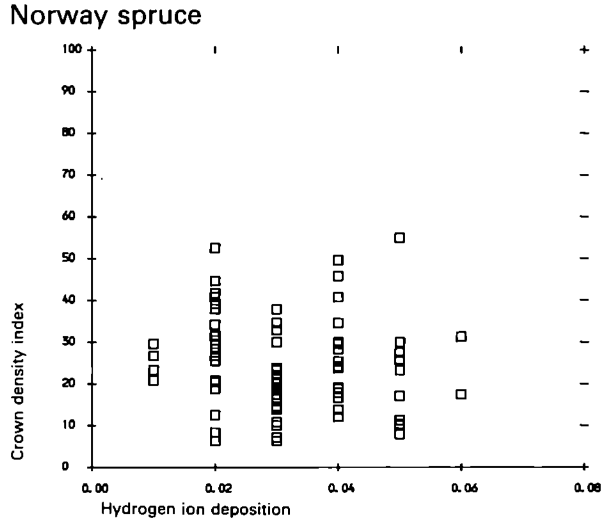
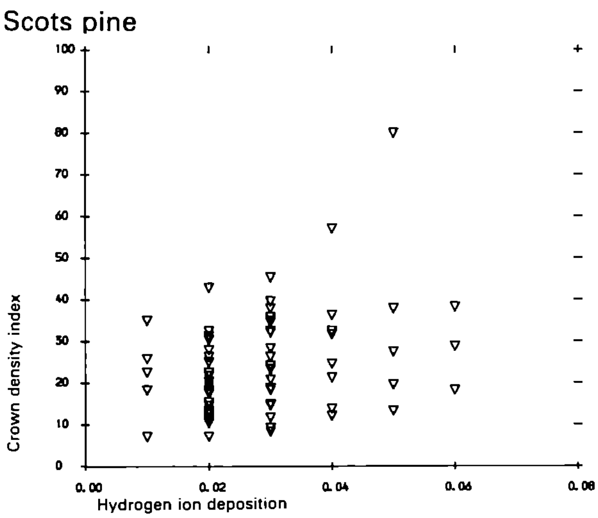
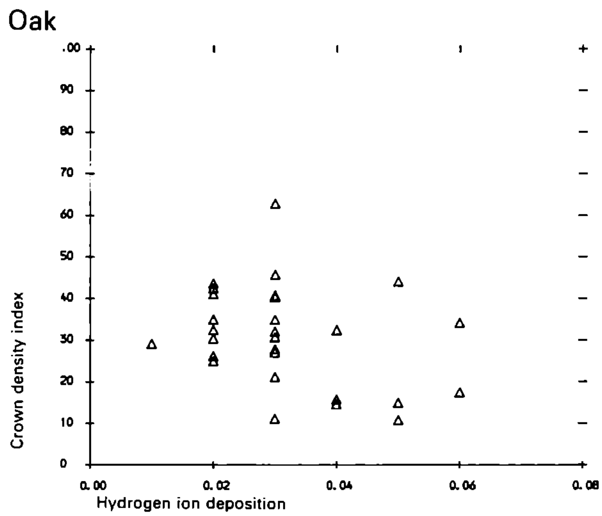


Figure 12. Relationship between mean April to June air temperature (°C at 0900 hours GMT) and crown density for each of the five species.









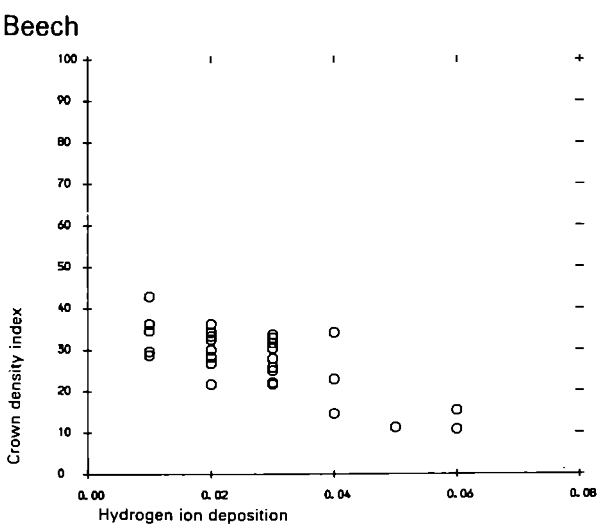
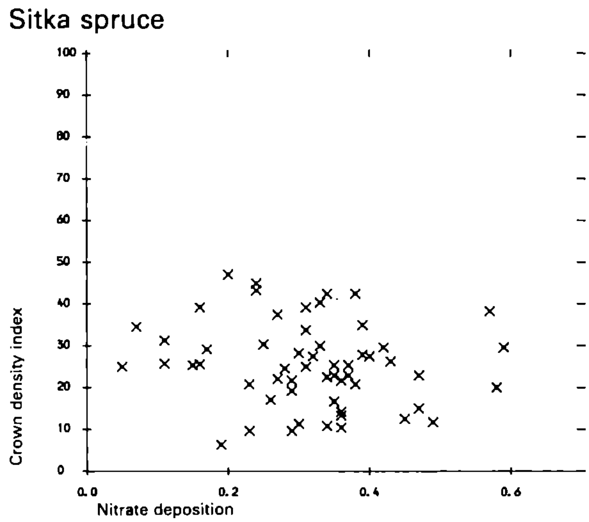
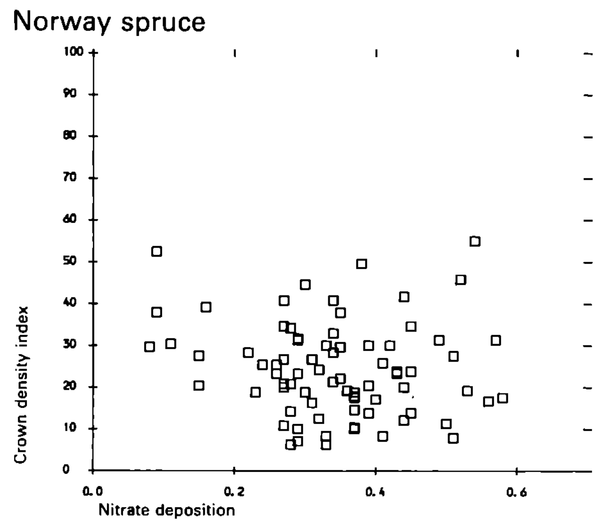
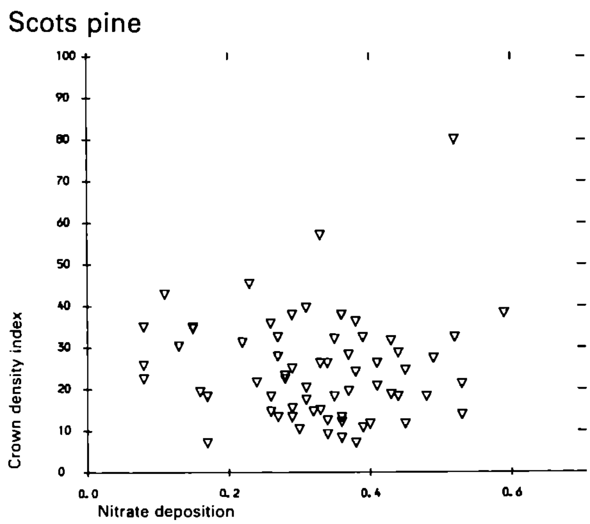
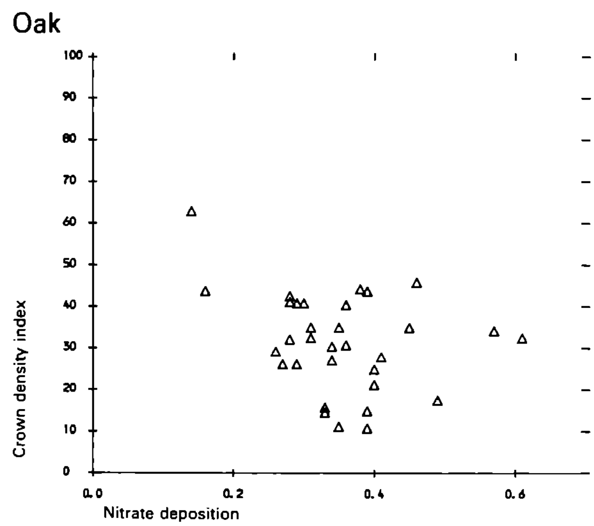


Figure 13. Relationship between bulk deposition of hydrogen ions (g m^{-2} per annum) (Warren Spring data) and crown density for each of the five species.









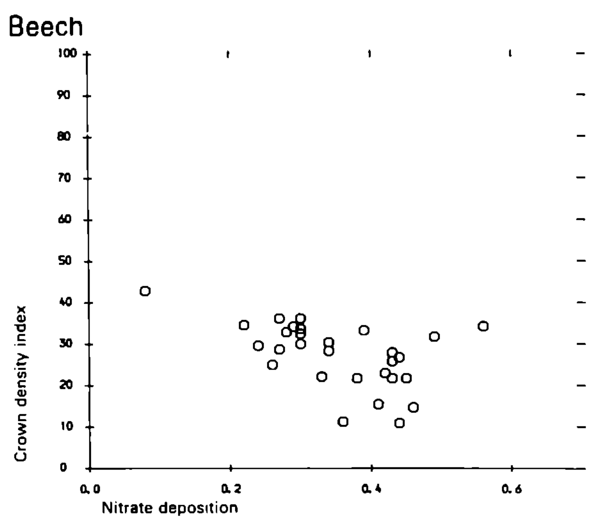
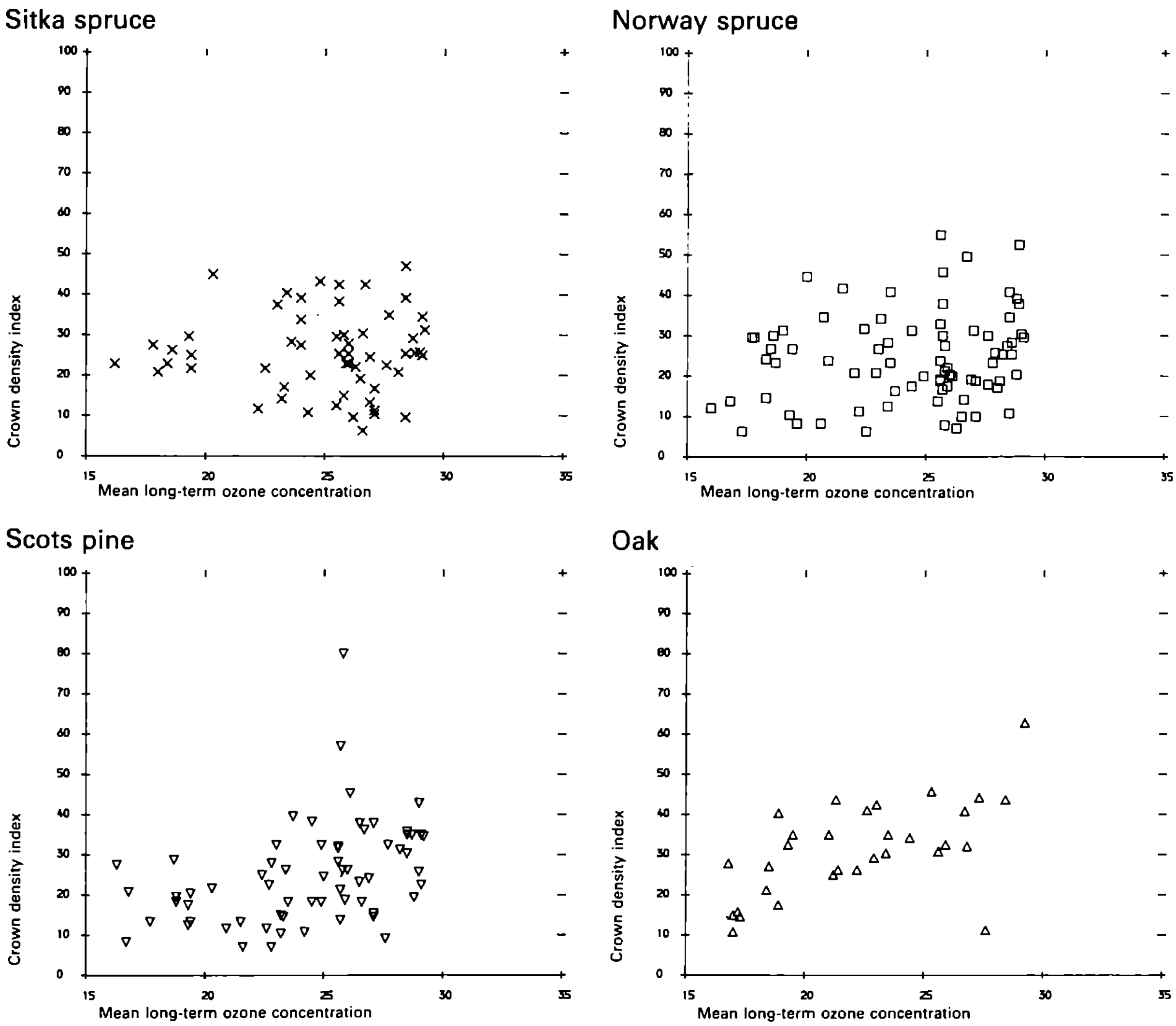


Figure 14. Relationship between bulk deposition of nitrate (g m^{-2} per annum) (Warren Spring data) and crown density for each of the five species.



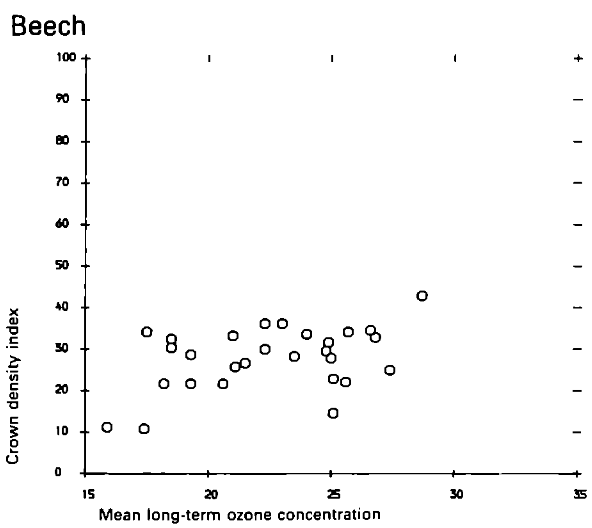


Figure 15. Relationship between long-term ozone concentrations (ppb) (Harwell model) and crown density for each of the five species.

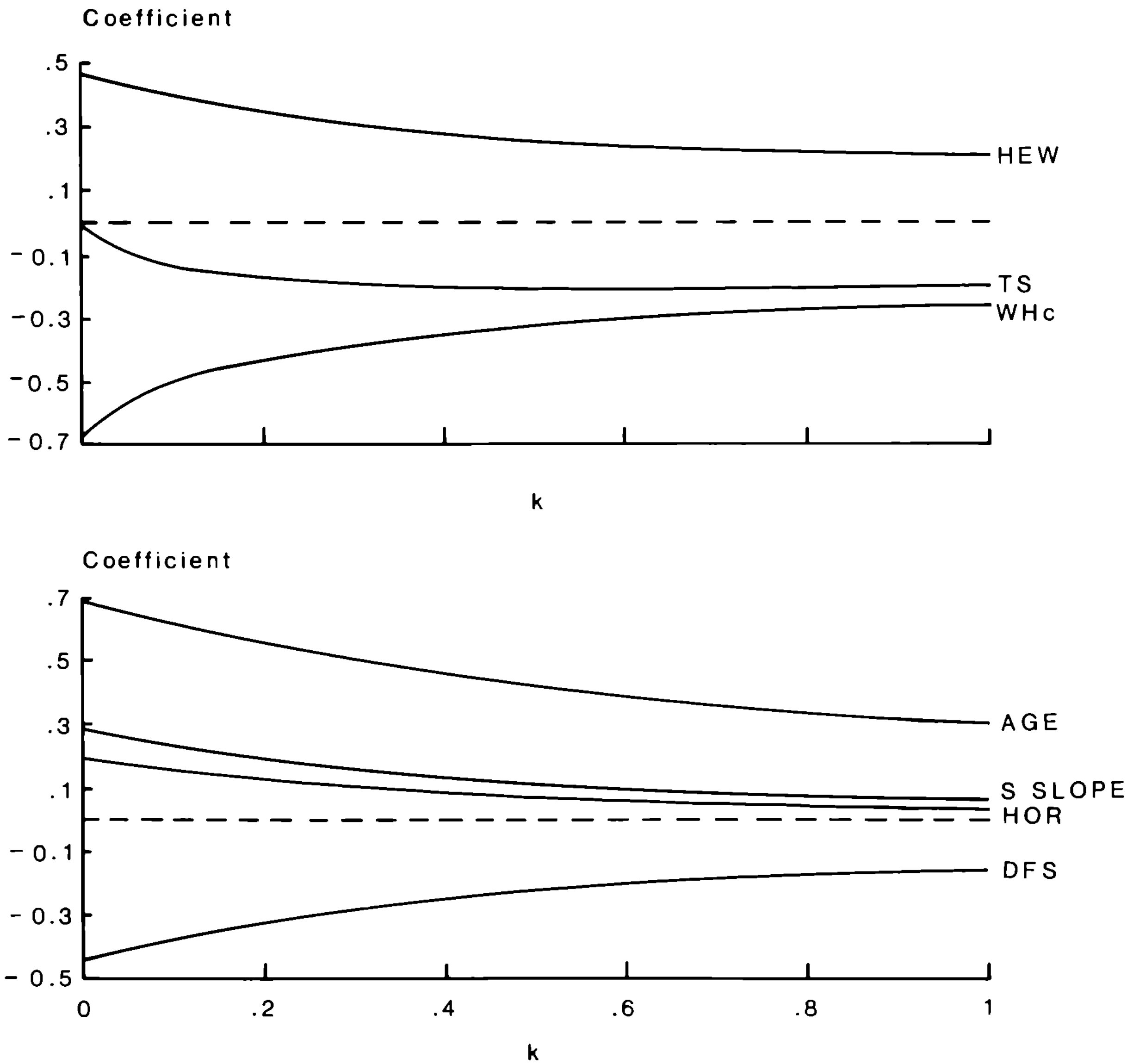


Figure 16. Ridge regression plots for the factors affecting crown density of beech (upper plot) and Norway spruce (lower plot).

was stopped when the F-ratios ceased to be significant).

Very little can be said about the regressions because of the problem of multicollinearity in the data. Suppose for example that a given pollutant is highly correlated with some environmental factor such as temperature, and both affect crown density. If only temperature is included in the regression, its importance will be overestimated and a steep regression slope will be derived. If only the pollutant is included in the regression, its effect will be overestimated. If both are included, their slopes will be reduced, implying that they both have weak effects. In such situations, it is impossible to say, without other experimental evidence, whether the effect on crown density is due entirely to temperature, entirely to the pollutant or partly to both.

The multicollinearity resulted in the coefficients being highly unstable, as is typical of such data. Ridge regression provides a means of looking at data of this nature (Belsey *et al.*, 1980; Freund and Minton, 1979). The multicollinearity in the data set results in inflated variances of the regression coefficients. The degree of inflation can be reduced by introducing bias, the underlying principle of ridge regression. The amount of bias that has been introduced into an equation is represented by the value k on the horizontal axis of the ridge plot. Examples of these plots, using k values from 0 to 1 in steps of 0.05 are given in Figure 16. The coefficients are standardised and therefore the coefficients for $k = 0$ are different from those given in Table 3. In the upper plot of Figure 16, the symmetry between total sulphur deposition (TS) and measured hydrogen ion concentration (WHc) indicates a high correlation (actually 0.609, $p < 0.001$) and the two coefficients compensate for each other. This suggests that only one should be used in any regression model. In the lower plot, the coefficients are more stable relative to each other and they are therefore more reliable. As a result of the instability of the regression coefficients, the models should not be used to predict the likely effects of any changes in pollutant levels.

Principal Components Analysis

In cases where the regression coefficients are highly unstable, a commonly used approach is to reduce the number of explanatory variables using principal components analysis. The main components are then used as variables in a multiple regression analysis.

This approach was tried with the forest health data set, but yielded no useful results. Two main problems arose. Firstly, with most of the principal components, it was impossible to single out any particular explanatory variable that was influencing it. In those components where the important variables could be identified, the component explained a negligible amount of the variation in the data set. Secondly, the multiple regression equations that were developed did not explain significantly more variation in crown density than the regressions using the original explanatory variables (Table 4). Consequently, this particular approach was not taken any further.

Table 4. Results of principal components analysis and regression using the crown parameters and grouping the variables

Sitka spruce

Component	1	2	3	4	5	6
Percentage variance	45	13	11	6	4	3

Multiple regression analysis of the components on crown density indicated that PC6 accounted for 25% of the variance in crown density. Using the main data set, 43% of the variation was accounted for.

Norway spruce

Component	1	2	3	4	5	6
Percentage variance	52	9	9	6	4	3

PC6 accounted for 6% of the variation in crown density. Using the main data set, 51% of the variation was accounted for.

Scots pine

Component	1	2	3	4	5	6
Percentage variance	48	13	9	5	4	3

PC1 and PC2 accounted for 32% of the variation in crown density. Using the main data set, 35% of the variation was accounted for.

Oak

Component	1	2	3	4	5	6
Percentage variance	52	11	9	6	5	3

PC1, PC2 and PC4 accounted for 50% of the variation in crown density. Using the main data set, 60% of the variation was accounted for.

Beech

Component	1	2	3	4	5	6
Percentage variance	46	13	12	6	5	4

PC1, PC2 and PC4 accounted for 66% of the variation in crown density. Using the main data set, 71% of the variation was accounted for.

A Composite Index of Forest Condition

Principal components analysis was no help in grouping explanatory variables such as climatic factors or pollutants which might influence tree health. Nevertheless, principal components analysis might still be useful in grouping the response variables which characterise tree appearance, thereby producing a composite index of crown appearance at each site. The biological validity of such an approach is unknown: it is likely that at least some of the indices used to assess crown appearance are unrelated. However, others, such as degree of leaf rolling and crown density might be expected to be related, and the approach may help to identify particular regions where there are problems.

For conifers, crown density, degree of yellowing in current needles, degree of yellowing in older needles, degree of browning in current needles, degree of browning in older needles and total discoloration were aggregated. In oak, crown density, degree of yellowing, degree of browning and degree of crown dieback were used. In beech, crown density, degree of yellowing, degree of browning, degree of crown dieback, amount of leaf-rolling and degree of leaf-rolling were used.

The first two components for oak and beech have been mapped on to a 20 by 20 km grid (Figure 17). As they are principal components, they are rather more difficult to interpret than the straightforward maps of individual indices.

In the case of oak, the first component essentially reflects all the crown indices. High scores are associated with low crown densities, low levels of discoloration and high crown dieback indices. The second component is primarily determined by the amount of yellowing in the crown, with browning and dieback also being important. High absolute scores indicate relatively higher amounts of yellowing, browning and dieback. With both these components, high scores are therefore associated with trees in poor condition.

With beech, high absolute scores in the first component indicate low amounts of leaf-rolling, high crown densities and higher levels of browning. High absolute scores in the second component reflect low amounts of crown dieback, high crown densities and higher levels of browning. Essentially this means that the trees in areas with high scores for component two are in better condition than in areas with low scores.

For each species, the components were regressed against the variables used in the step-wise regressions described above. With the conifers, the amount of variation accounted for by the significant variables in the step-wise regressions was relatively small (Sitka spruce 29 per cent, Norway spruce 37 per cent and Scots pine 17 per cent). With oak, 81 per cent of the variation was accounted for in the first component and 63 per cent in the second. With beech, the figures are 41 and 73 per cent, respectively (Table 5). These figures are remarkably high, suggesting that the explanatory variables used in the analysis (or other factors that are highly correlated with these variables) are responsible for most of the variation seen in the composite indices. However, the regressions suffer from the same problem as before: multicollinearity. This means that the coefficients are again unstable, severely limiting any potential for interpretation or prediction.

Discussion

The results presented above provide an indication of the complexity of the problem of establishing whether pollution affects those parameters commonly used to characterise tree health. Statistical associations have been demonstrated between a number of variables and these parameters. Any interpretation of these associations must necessarily be subjective, although the viability of some of the relationships may be indicated by independent experimental work.

There are two elements to the data. The first consists of the variation that occurs from year-to-year and is caused by short-term factors such as insect and fungal attacks, extreme climatic conditions and high pollution episodes. These may be particularly important for parameters such as crown discoloration. The second element is the long-term condition of trees, determined by factors operating over longer time-scales, such as soil fertility, including long-term soil acidification, exposure to wind and persistent insect or fungal problems. In the literature on pollution, effects are often separated into acute (caused by short-term factors) and chronic (caused by long-term factors) and this provides a useful distinction in the present context.

Short-term elements may have effects that last for a long time: defoliation of a spruce in one year will be evident for a number of successive years. This means that in some cases, crown thinness today may be the result of short-term effects acting at some time in the past.

Short-term factors

The Forestry Commission is actively involved in forest protection and its pathology and entomology advisory services spend a considerable amount of time inspecting damaged trees. From these observations, it is possible to draw up a general picture of what has

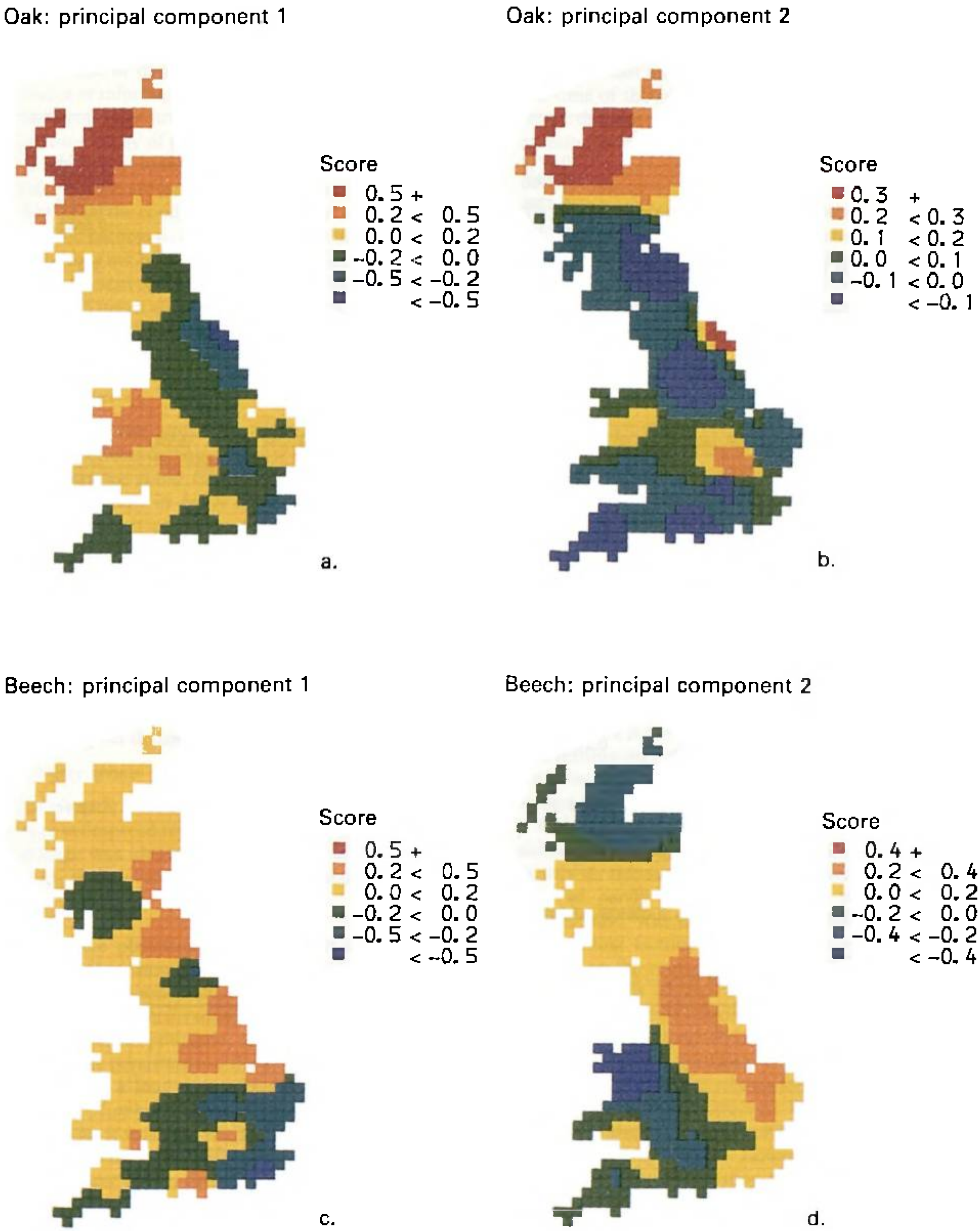


Figure 17. Distribution of principal component scores for oak and beech. Only the first two components have been shown.

Table 5. Principal components analysis of oak and beech crown indices

Oak

	Component			
	1	2	3	4
Crown density	0.5770	0.3798	−0.0501	0.7214
Browning	−0.3960	0.6261	−0.6691	−0.0594
Yellowing	−0.4706	0.4848	0.7171	0.1710
Crown dieback	0.5374	0.4782	0.1888	−0.6685
Variance accounted for	51.4	28.0	13.3	7.3

Multiple regression analysis for first two components

First component:
0.458 − 0.00908 WHc + 0.003887 AGE − 0.1037 ODairt − 0.00553 SSLOPE + 0.0000999 RUG (81%)

Second component:
3.178 − 0.01452 VERT − 0.1234 JMairt − 0.008 SSLOPE − 0.0434 WdryS − 0.01136 SLOW (63%)

Beech

	Component					
	1	2	3	4	5	6
Crown density	−0.3164	−0.3845	0.2775	0.7946	0.2086	−0.0160
Yellowing	0.0432	−0.2933	−0.8739	0.2560	−0.2877	−0.0069
Browning	0.3453	0.4999	0.1866	0.4733	−0.6093	−0.0055
Crown dieback	0.0147	−0.6491	0.3460	−0.2654	−0.6232	0.0027
Frequency of leaf rolling	−0.6228	0.2209	−0.0434	−0.0774	−0.2389	−0.7059
Degree of leaf rolling	−0.6250	0.2151	−0.0453	−0.0521	−0.2387	0.7080
Variance accounted for	37.9	27.66	17.03	11.45	5.56	0.4

Multiple regression analysis for first two components

First component:
1.53 − 0.1398 AJairt + 0.00612 WHc − 0.000939 DFSW (41%)

Second component:
1.908 − 0.001652 DFSE + 0.01024 WHc − 0.01012 VERT − 8.66 WHd (73%)

happened in any given year. In addition, the surveyors involved in the crown assessments were asked to note any cause of damage that they observed. This latter source of information is less reliable than the first as the surveyors (who are trained in forest surveys rather than in entomology of pathology) may fail to either observe or identify a particular condition. The two sources of information are separated below. It should be noted that while the condition of a tree may be explained by a specific pathogen, the reason for the attack in the first place may not be known. This is particularly important in the present context as interactions between pollution and both insect attacks and fungal infections are known to occur. Unfortunately, the precise nature of these interactions remains uncertain.

Sitka spruce

Generally, the advisory services noted no adverse climatic effects on large trees (> 5 m) during 1987. The green spruce aphid *Elatobium abietinum* was particularly abundant in many areas and, in Scotland, the damage that it caused to Sitka spruce was the worst since the mid-1970s. Damage by *Elatobium* was identified in 12 of the 57 Sitka spruce survey plots although this is probably an underestimate of its actual frequency. The effects that the insect attack had on the crowns is unknown, but it may have been severe in some individual cases. Damage by the pineapple gall woolly aphid *Adelges abietis* was identified at nine sites, but this insect was unlikely to have markedly influenced crown density.

Norway spruce

No climatic effects were noted during 1987 but there were widespread reports of damage by *Elatobium*. Such damage was identified in three out of the 80 survey plots, with severe damage being noted in one.

Scots pine

Scots pine plantations above 250 m above sea level continued to show the effects of attacks by the fungus *Brunchorstia pinea* (a cause of shoot dieback), the needle cast fungus *Lophodermium seditiosum* and the pine shoot beetle *Tomicus piniperda*, acting singly or in combination. The persistence of these attacks means that they are having a long-term effect on Scots pine at high altitudes. *Lophodermium seditiosum* was less common in 1987 than it was in 1986, but the effects of the needle cast induced by the 1986 attacks are still evident in the form of low crown densities in affected trees.

Oak

No widespread disease or problems of climatic origin were noted in oak. However, serious defoliation by caterpillars of the green oak tortrix moth *Tortrix viridana* early in the season was noted particularly in the south-east and some trees had failed to recover by the time of the survey in August. As noted in *Part 1*, insect damage was recorded in 59 per cent of the trees assessed in the survey.

Beech

Throughout most of Britain, there were severe attacks by the beech leaf miner *Rhynchaenus fagi* which resulted in extensive browning of leaves. Additional discoloration was caused by an above average incidence of the fungus *Gloeosporium fagicolum*. The survey indicated insect damage in 54 per cent of the beech crowns.

Long-term factors

The majority of the climatic and pollution variables used in the analysis can be taken as representative of long-term factors that might affect tree condition. Of course, individual episodes of pollution act in the short term but, for a number of reasons, it is not yet possible to assess the effects of such events on the trees used in this survey. In Scots pine, the analysis reveals a broad pattern of decreasing crown densities towards the north and west of Britain. This is consistent with our existing knowledge of this species (White, 1982). Although it is difficult to say whether it is temperature or rainfall that is the controlling variable, results from the Swedish surveys of forest health suggest that temperature is the major control on Scots pine vitality. Site fertility may also be important, but as there are no data available on the soil conditions at the sites, this cannot be assessed.

Oak and beech show a similar pattern to Scots pine, although the pattern of correlations with climatic factors do not suggest a direct climatic control. This may be partly attributable to the relatively small sample size, which will increase the effect of any confounding factors. The natural range of beech is centred on the south and east (Godwin, 1975) and its appearance, as judged by the data presented here, steadily deteriorates outside these areas. Oak occurs naturally throughout Britain, and the gradients in appearance are rather more difficult to interpret.

As stated above, the pattern for Norway spruce and Sitka spruce is rather different. The crown densities of these two species seem primarily to be determined by tree age and topographic factors. When age is taken into account, the distribution of crown density in Sitka spruce is very irregular. Discoloration increases with increasing distance from the west coast: an unsurprising finding in view of the maritime origin of the species.

In the case of Norway spruce, crowns are thinnest in north Scotland and the Lake District when age is taken into account. There is also an area with thinner crowns along the south coast of England. The regressions indicate that trees on steeper slopes or in more exposed situations have thinner crowns. Crown densities improve with increasing distance from the sea, consistent with the continental origin of the species. Discoloration is generally low across the whole of the country.

Observer bias

It must be borne in mind that the use of observers operating regionally may have resulted in some regional bias. The available information suggests that this factor was insignificant in 1987, but the importance of maintaining field checks on the observers is clear.

The role of pollution

Several correlations between indices of crown condition and pollutant loadings have been identified. With some species, these have indicated that the crown density is higher in areas with high levels of pollution. There are several reasons why this could be the case. Firstly, high levels of pollution occur in those parts of the country where the climate is thought to be most suitable for tree growth and it is possible that any effects of pollution are insignificant in relation to the effects of climate. Secondly, it is possible that the deposition of sulphate, nitrate and ammonia is having a fertilising effect on the trees, thereby stimulating growth. Acidic deposition has been seen to have a fertilising effect in a number of Scandinavian studies (Abrahamsen *et al.*, 1976; Ogner and Teigen, 1980; Tamm and Wiklander, 1980; Tveite and Abrahamsen, 1980). In West Germany, tree growth in many areas is considerably above that predicted from growth models developed in the 1940s (Eichkorn, 1986; Spelsburg, 1987) and this has been tentatively attributed to increased levels of nitrate deposition. Most of these studies have suggested that, in the long term, the benefits of increased growth may be more than offset by the adverse effects of soil acidification and a reduction in the trees' resistance to frost.

The correlations with ozone are equally difficult to interpret, not least because the predicted values at present lack detailed verification. Long-term mean ozone concentrations (i.e. background levels) are believed to be greatest in the more remote parts of Britain (Anon., 1987). This means that there is a possible difficulty in separating climatic effects from any effects attributable to background ozone in species that favour the south and east. The maximum background level predicted at any of the sites was 29 ppb (parts per billion). This concentration is below the minimum that is thought to cause damage to the tree species used in this study. However, the existing knowledge of threshold concentrations is based on short-term fumigation studies, and it is possible that background concentration levels, which are believed to be increasing (Anon., 1987), have had some effect on sensitive plant species. As this has not been tested, no further comment can be made.

Much more is known about the effects of high short-term concentrations of ozone (see Guderian (1985) for a full review). The spatial distribution of such events in the United Kingdom remains very uncertain because of the lack of measurements and existing maps are considered to be too crude for the type of analysis used in this study. The available evidence suggests that there are regional variations in the timing, frequency, duration and intensity of ozone episodes, but that these cannot as yet be quantified (Anon., 1987). Sites in northern Britain are thought to receive shorter episodes, and the intensity of the episodes may be lower. A good indication of the inter-annual variation in the effect of ozone on an indicator species (Bel-3 tobacco) has been provided by Ashmore *et al.* (1978) and Anon. (1987), who showed that in 1977, damage was greatest in north Wales and central Scotland whereas in 1978, it was greatest in the south of England. Information on the short-term concentrations in Britain in 1987 will be available later in 1988 and will be used to assess possible effects on the trees examined in this study.

Future Work

It is proposed to continue the two surveys in 1988 (both the survey described in this publication and the survey carried out as part of the EEC-wide investigation of forest health). Plots lost through storm damage or felling will be replaced using the existing sampling criteria and any obvious gaps in the distribution of the plots will be filled.

An increasing amount of pollution data is likely to become available in 1988 including more information on ozone levels. This will clearly increase the ability to clarify any association between tree condition and pollution levels. At the same time the use of additional methods of assessing tree health is currently being considered. Crown density is a useful general measure of tree health but it would clearly be an advantage if other, more specific, assessments, including ones of a biochemical or physiological nature, could be made.

Conclusions

This study has demonstrated that statistical associations exist between the patterns of various crown indices and various independent factors, ranging from climatic conditions to levels of individual pollutants. Unfortunately, interpretation of these relationships is extremely difficult because of the inter-correlations between the independent variables.

Some broad patterns in the crown appearance of Scots pine, oak and beech are evident. In all three cases, crown density decreases towards the north and the west. With oak and beech, crown dieback increases towards the north and west. A similar pattern is not present in either Sitka spruce or Norway spruce. It is likely that the observed patterns primarily reflect the influence of climate. However, levels of pollution may also be affecting these patterns and strong correlations have been obtained between the levels of some pollutants and crown density. The correlations suggest that, if anything, the deposition of some atmospheric pollutants is having a fertilising effect on trees, improving the density of their crowns. The exception is with background ozone concentrations, high levels of which are associated with low crown densities. There is no experimental evidence that would validate this finding.

Much of the work presented in this report has been of an exploratory nature and the techniques used to analyse and present the results will be refined. A large amount of data has become available this year, both as a result of doubling the size of the survey and as a result of the much better information on regional pollution levels that is now available. We will be undertaking further analysis of the 1987 data as yet more environmental information becomes available, the results of which will be presented in future survey reports and publications in the scientific press.

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References

ABRAHAMSEN, G., BJOR, K., HORNTVEDT, R. and TVEITE, B. (1976). Effects of acid precipitation on coniferous forest. In, *Impact of acid precipitation on forest and freshwater ecosystems in Norway*, ed. F.H. Braekke, 36–63. SNSF Research Report 6/76, Oslo.

ANON. (1987). *Ozone in the United Kingdom.* United Kingdom Photochemical Oxidants Review Group Interim Report, Harwell Laboratory.

ASHMORE, M.R., BELL, J.N.B. and REILLY, C.L. (1978). A survey of ozone levels in the British Isles using indicator plants. *Nature, London*, **276**, 813–815.

BELSEY, D.A., KUH, E. and WELSCH, R.E. (1980). *Regression diagnostics. Identifying influential data and sources of collinearity.* Wiley Interscience, New York.

CAPE, J.N., PATERSON, I.S., WELLBURN, A.R., WOLFENDEN, J., MEHLHORN, H., FREER-SMITH, P.H. and FINK, S. (1988). *Early diagnosis of forest decline.* Institute of Terrestrial Ecology, Grange-over-Sands.

DENTON, S.R. and BARNES, B.V. (1987). Spatial distribution of ecologically applicable climatic statistics in Michigan. *Canadian Journal of Forest Research* **17**, 598–612.

DERWENT, R.G., DOLLARD, G.J. and METCALFE, S.E. (1987). *On the nitrogen budget for the United Kingdom and North-west Europe.* United Kingdom Atomic Energy Authority, Harwell, AERE R 12616.

DEVENISH, M. (1986). *The United Kingdom precipitation composition monitoring networks.* Warren Spring Laboratory Report LR 584 (AP)M.

DIXON, M. and GRACE, J. (1984). Effect of wind on the transpiration of young trees. *Annals of Botany* **53**, 811–819.

DOLLARD, G.J., UNSWORTH, M.H. and HARVEY, M.J. (1983). Pollution transfer in upland regions by occult precipitation. *Nature, London*, **302**, 241–243.

EICHKORN, T. (1986). Wachstumanalysen an Fichten in Südwest-deutschland. *Allgemeine Forst- und Jagdzeitung* **157**, 125–139.

FEILER, S. (1985). Influence of sulphur dioxide on membrane permeability and consequences on frost-sensitivity of spruce (*Picea abies* (L.) Karst.). *Flora* **177**, 217–226.

FLÜCKIGER, W., BRAUN, S., LEONARDI, S., ASCHE, N. and FLÜCKIGER-KELLER, H. (1986). Factors contributing to forest decline in northwest Switzerland. *Tree Physiology* **1**, 177–184.

FREUND, R.J. and MINTON, P.D. (1979). *Regression methods. A tool for data analysis.* Marcel Dekker, New York.

GODWIN, H. (1975). *History of the British flora. A factual basis for phytogeography.* Cambridge University Press, Cambridge.

GUDERIAN, R. (ed). (1985). *Air pollution by photochemical oxidants.* Springer-Verlag, Berlin.

INNES, J.L. (1988). Forest health surveys – a critique. *Environmental Pollution*, in press.

INNES, J.L. and BOSWELL, R.C. (1987). *Forest health surveys 1987. Part 1: results.* Forestry Commission Bulletin 74. HMSO, London.

KELLER, T. (1984). Direct effects of sulphur dioxide on trees. *Philosophical Transactions of the Royal Society of London*, Series B, **305**, 317–326.

MATERNA, J. (1982). Concentration of sulphur dioxide in the air and sulphur content in Norway spruce seedlings (*Picea abies* Karst.). *Communicationes Instituti Forestalis Cechosloveniae* **12**, 136–146.

MILLER, K.F., QUINE, C.P. and HUNT, J. (1987). The assessment of wind exposure for forestry in upland Britain. *Forestry* **60**, 179–192.

OGNER, G. and TEIGEN, O. (1980). *Effects of acid irrigation and liming on two clones of Norway spruce.* SNSF Project, Report FA 55/80, Oslo.

PEARS, N.V. (1967). Wind as a factor in mountain ecology: some data for the Cairngorm mountains. *Scottish Geographical Magazine* **83**, 118–124.

ROELOFS, J.G.M., KEMPERS, A.J., HOUDJIK, A.L.F.M. and JANSEN, J. (1985). The effect of air-borne ammonium sulphate on *Pinus nigra* var. *maritima* in the Netherlands. *Plant and Soil* **84**, 45–56.

SPELSBURG, G. (1987). Zum Problem der Beurteilung des Zuwachses in geschädigten Beständen. *Allgemeine Forst – und Jagdzeitung* **158**, 205–210.

TAMM, C.O. and WIKLANDER, G. (1980). Effects of artificial acidification with sulphuric acid on the growth of Scots pine forest. In, *Ecological impact of acid precipitation*, eds. D. Drabløs and A. Tollan, 188–189. SNSF-Project, Oslo.

TVEITE, B. and ABRAHAMSEN, G. (1980). Effects of artificial acid rain on the growth and nutrient status of trees. In, *Effect of acid precipitation on terrestrial ecosystems*, eds. T.C. Hutchinson and M. Havas, 305–318. Plenum Press, New York.

WARREN SPRING LABORATORY (1986). *United Kingdom acid rain monitoring*. Warren Spring Laboratory, Stevenage.

WHITE, E.J. (1982). Relationship between height growth of Scots pine (*Pinus sylvestris* L.) and site factors in Great Britain. *Forest Ecology and Management* **4**, 225–245.

WHITE, E.J. and SMITH, R.I. (1982). *Climatological maps of Great Britain*. Institute of Terrestrial Ecology, Cambridge.

Appendix 1

Specific Problems Arising from the 1987 Survey

There are substantial differences between the results of the main survey and the results of the grid survey. At least two possible reasons for this can be offered. Firstly, the distribution of sites for particular species in each of the surveys is very different. The main survey deliberately aims to achieve as wide a coverage for each species as possible and therefore includes plots that are suboptimal for a given species. By contrast, the grid survey reflects the distribution of each species within the country and therefore the majority of sites will be in areas where that species grows best.

Secondly, the age distributions of the trees are very different. For Sitka spruce, Norway spruce and Scots pine, all the trees assessed in the grid survey are less than 60 years old, and the majority (84 per cent) are less than 40 years old. In the main survey, only 41 per cent of the trees are less than 40 years old. Given the strong relationship between crown density and age in the two spruces (Figure 6), the grid plots would be expected to have higher crown densities and this is borne out by the data. The broadleaf plots in the grid survey cover a much wider age range than the main survey plots and the differences between the two surveys are probably attributable to the high proportion of grid plots in the south-east.

Appendix 2

Maps Showing Patterns of Pollution in Great Britain

(Warren Spring Laboratory, 1986; S. Coster, personal communication; G. Campbell, personal communication.)

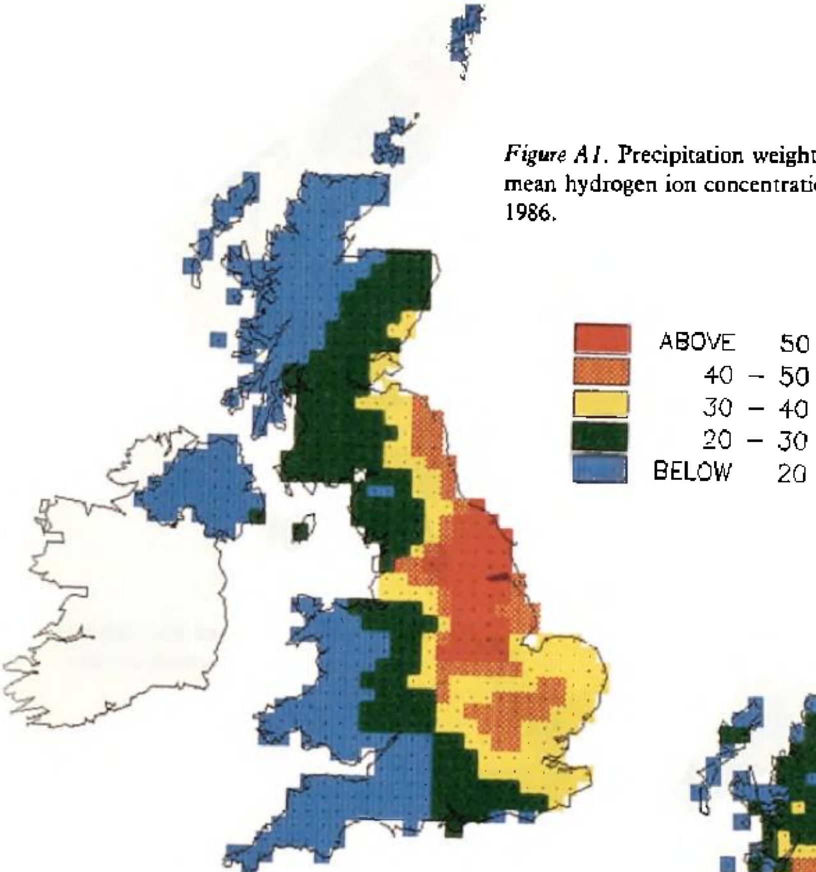

Figure A1. Precipitation weighted annual mean hydrogen ion concentration (μeq l^{-1}), 1986.

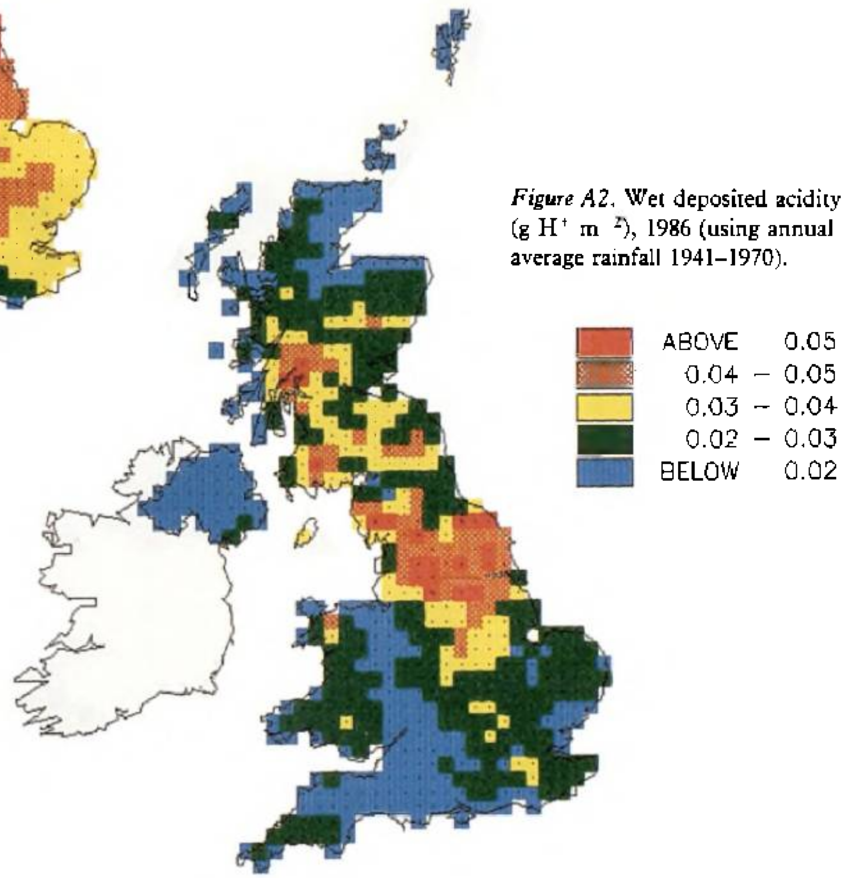

Figure A2. Wet deposited acidity (g H^+ m^{-2}), 1986 (using annual average rainfall 1941–1970).

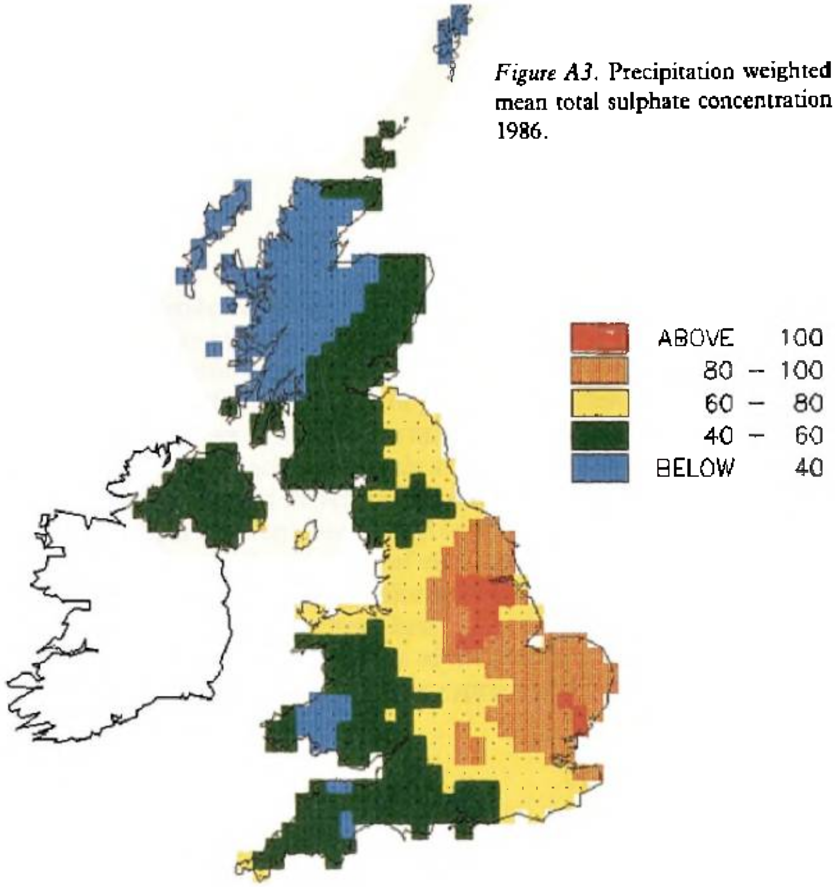

Figure A3. Precipitation weighted annual mean total sulphate concentration ($\mu eq\ l^{-1}$), 1986.

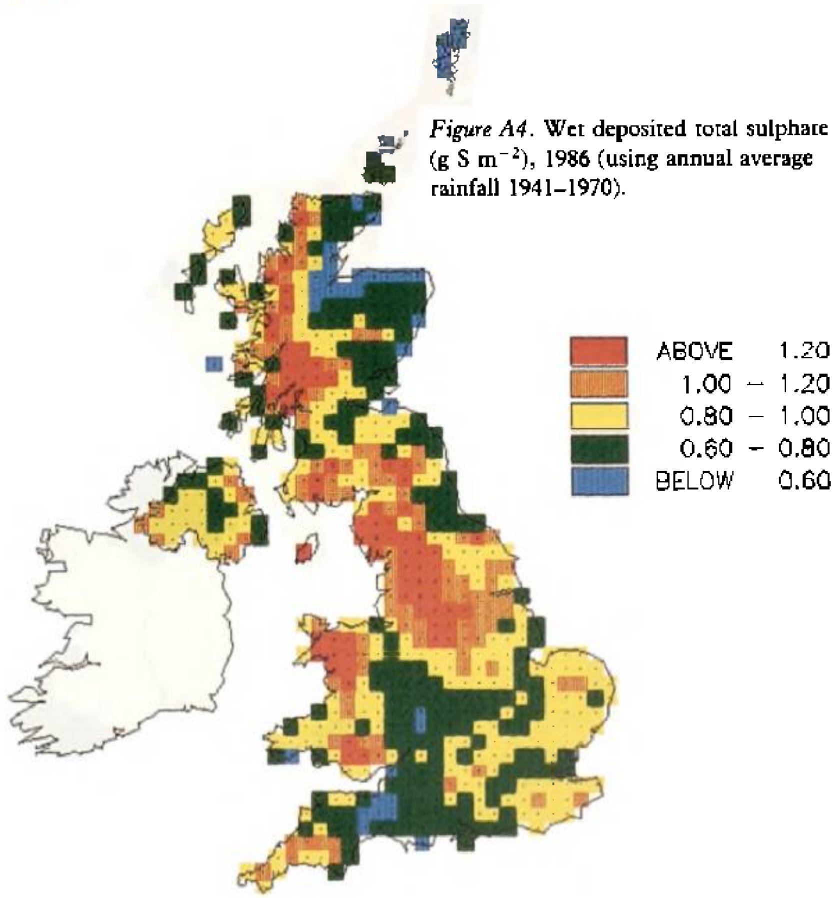

Figure A4. Wet deposited total sulphate ($g\ S\ m^{-2}$), 1986 (using annual average rainfall 1941–1970).

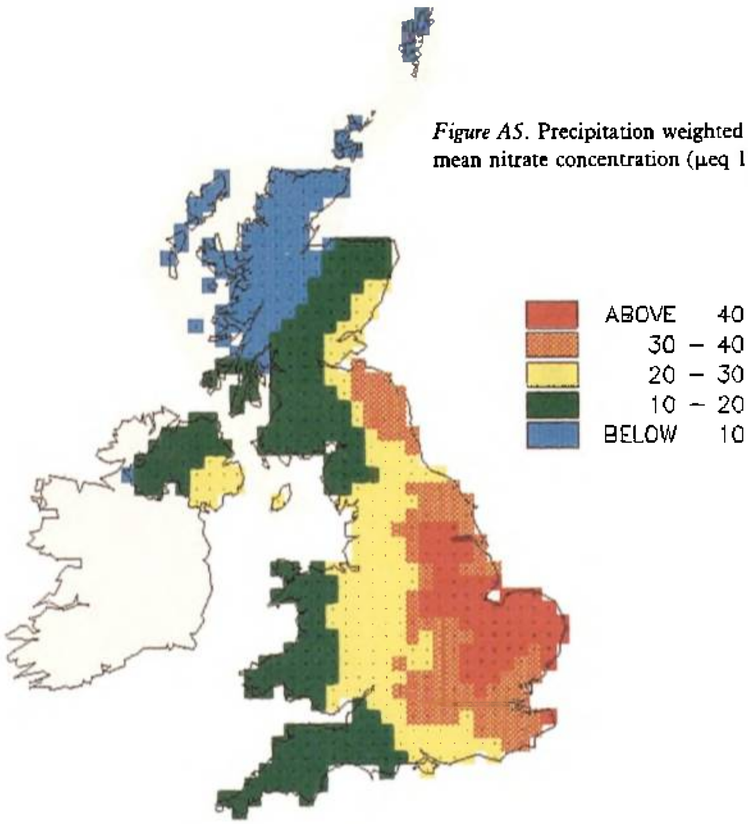

Figure A5. Precipitation weighted annual mean nitrate concentration (μeq l^{-1}), 1986.

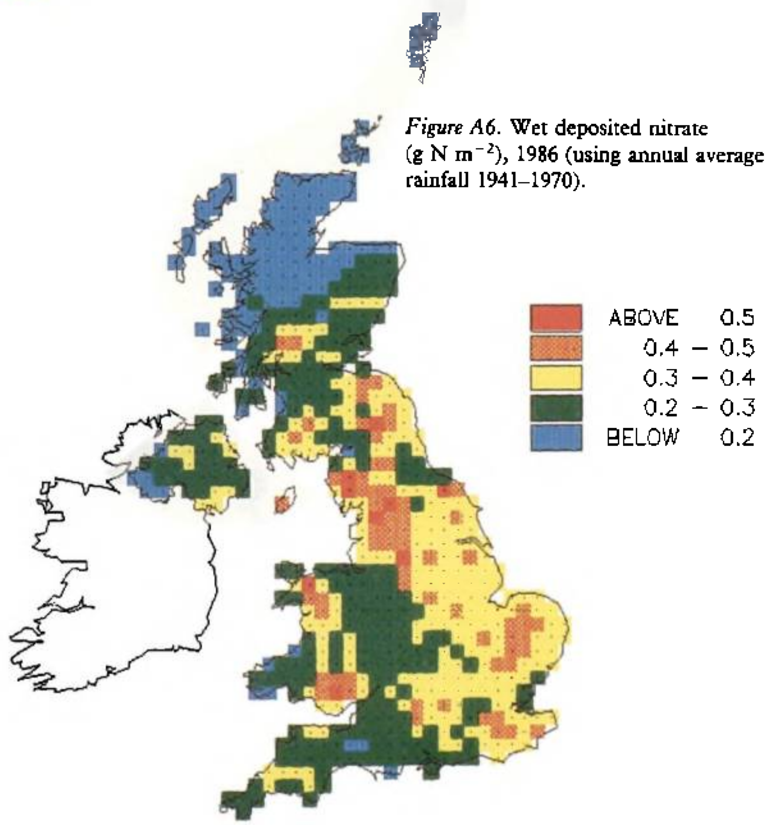

Figure A6. Wet deposited nitrate (g N m^{-2}), 1986 (using annual average rainfall 1941–1970).

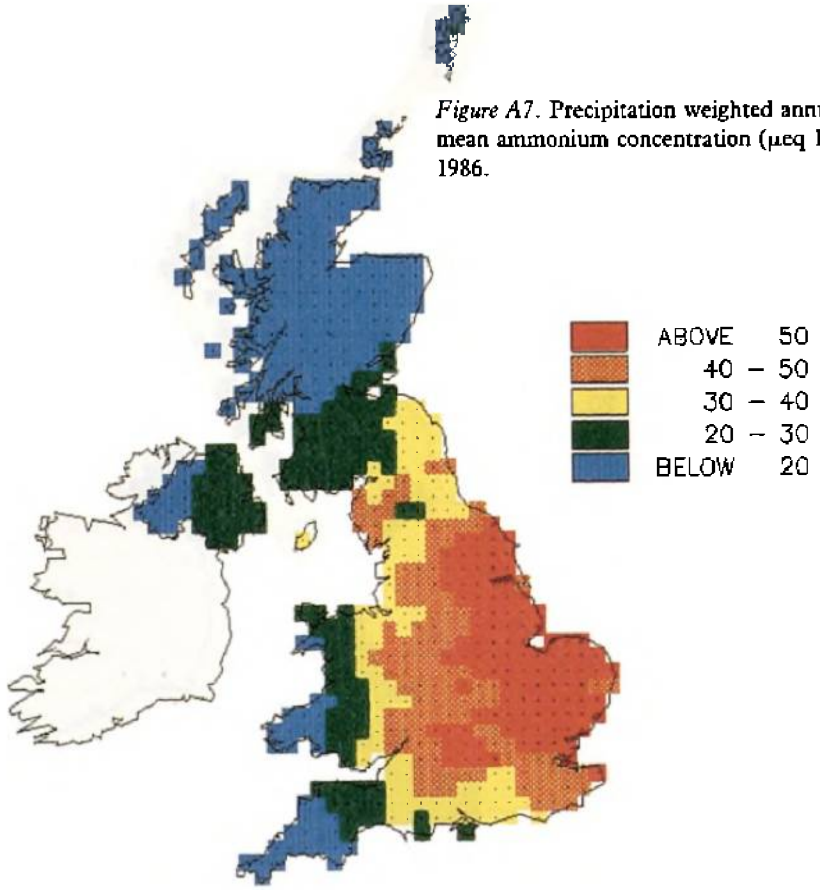

Figure A7. Precipitation weighted annual mean ammonium concentration (μeq l^{-1}), 1986.

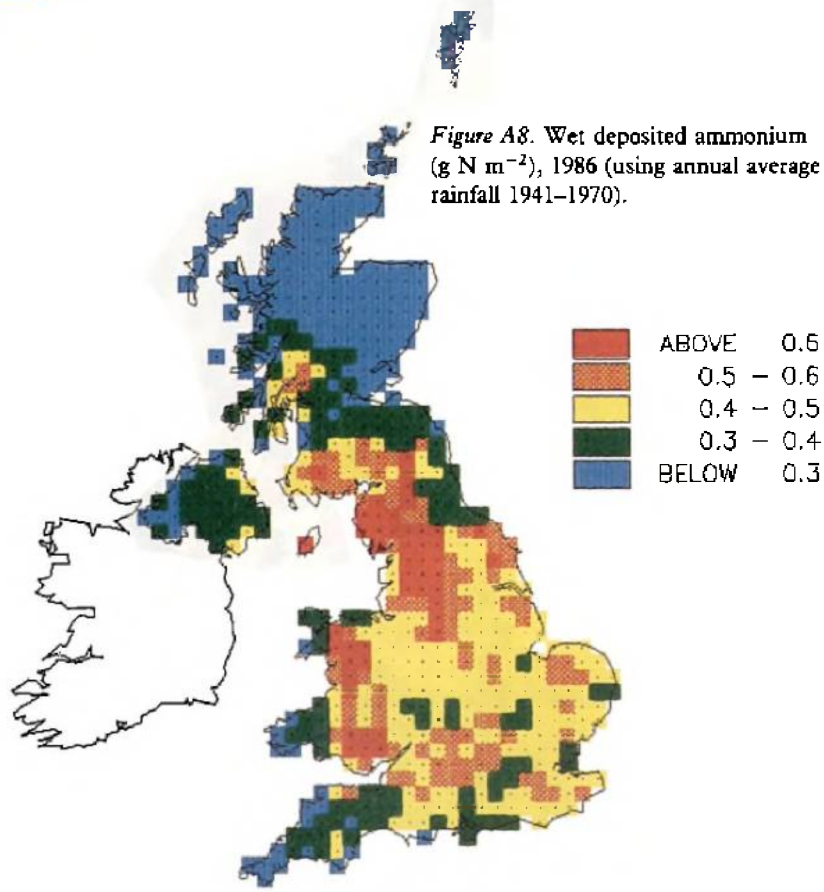

Figure A8. Wet deposited ammonium (g N m^{-2}), 1986 (using annual average rainfall 1941–1970).

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