Forestry Commission

Bulletin 88

Monitoring of Forest Condition in the United Kingdom 1988

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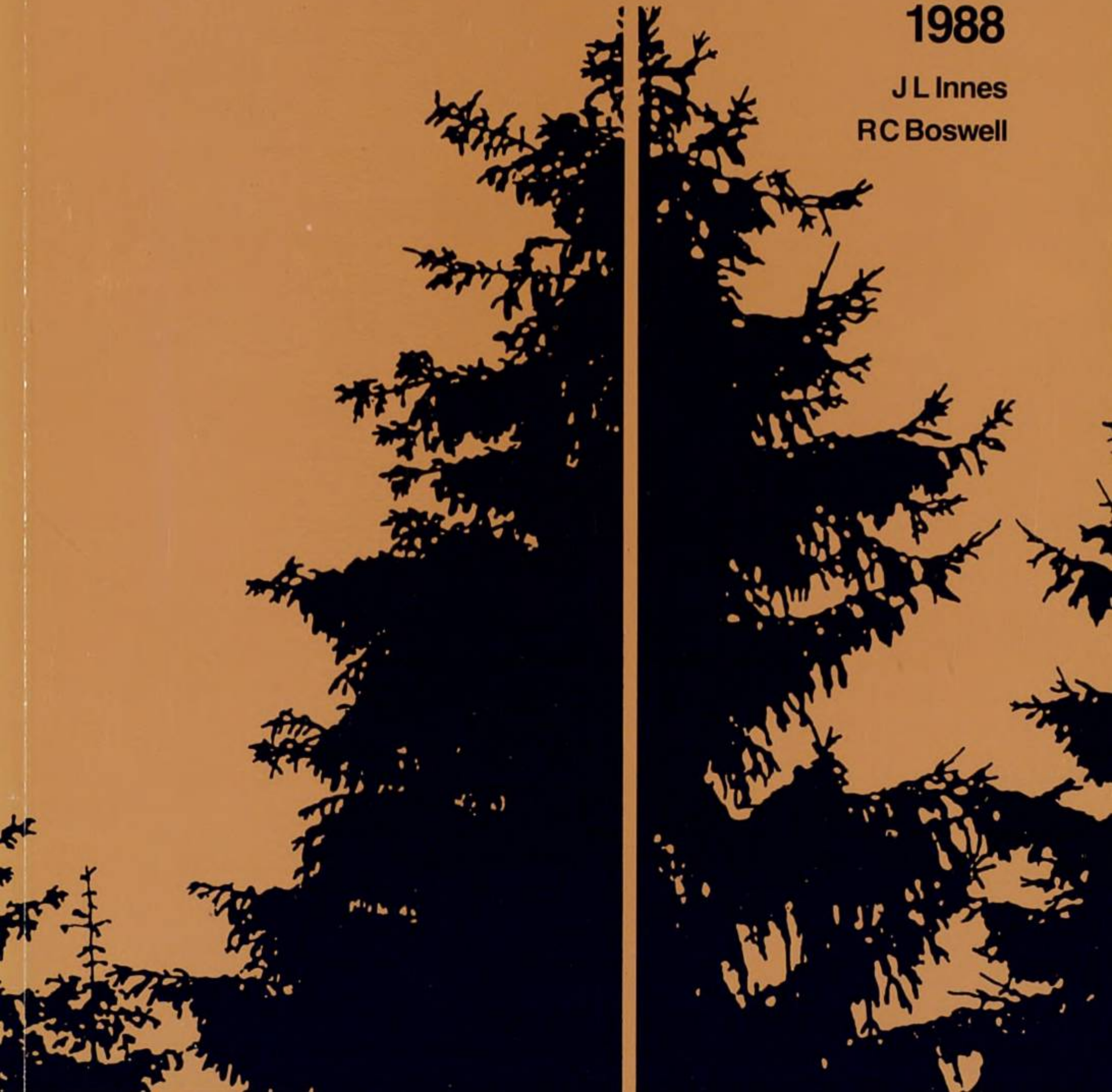

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J.L. Innes and R.C. Boswell
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The projects described in this report were partially funded by grants from the European Community.

LONDON: HER MAJESTY'S STATIONERY OFFICE

First published 1989

ISBN 0 11 710277 6
ODC 425.1 : 423.1 : 181.45 : 524.6 : (410)

KEYWORDS: Tree health, Pollution, Forestry

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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

Monitoring of Forest Condition in the United Kingdom – 1988

Summary

Two programmes dealing with the monitoring of forest condition are currently underway in Britain. One deals exclusively with Sitka spruce, Norway spruce, Scots pine, oak and beech whereas the other includes all species. Both are aimed at identifying any national or regional decline in tree health that might be attributable to air pollution.

In general there was little change between 1987 and 1988. The crowns of Sitka spruce and Scots pine have become thinner whereas the crowns of Norway spruce have remained the same. No clear trend is apparent in oak as a reduction in the proportion of trees with dense crowns has been matched by a reduction in the number of trees with very thin crowns. Beech has shown some improvement over the year.

There are likely to be a number of factors contributing to the condition of tree crowns including the influence of climate and pest organisms. There is some indication of both positive and negative interactions between the condition of a tree and air pollution.

Analysis of a number of indices of crown condition indicates that these may be unrelated. For example, discoloration in most species does not appear to be related to loss of foliage. It is therefore important to look at as many different indices as possible.

Distinct spatial patterns exist amongst some of the different indices. Sitka spruce is extremely variable, with only discoloration and needle retention showing marked patterns. Neither of these appears to be related to any form of pollution. Norway spruce, Scots pine, oak and beech all have higher crown densities in areas with higher levels of pollution. Other indices of condition are more variable and both positive and negative correlations with various forms of air pollution have been identified. The analysis emphasises the presence of a complex set of interacting factors affecting the condition of trees in Britain and it may take many years before these are unravelled.

Monitoring de la Condition des Forêts dans Le Royaume-Uni – 1988

Sommaire

Deux programmes sur le monitoring de la condition des forêts sont en cours dans Le Royaume-Uni. L'un traite exclusivement de l'épicéa Sitka, l'épicéa commun, le pin sylvestre, le chêne et l'hêtre; l'autre traite de toutes les espèces. Les deux programmes ont pour but l'identification d'un éventuel déclin national ou regional dans la santé des arbres, qui soit imputable à la pollution atmosphérique.

En général il n'y a pas beaucoup d'évolution entre 1987 et 1988. Les couronnes de l'épicéa Sitka et du pin sylvestre sont devenues plus claires, mais les couronnes de l'épicéa commun sont restées les mêmes. On ne voit pas une tendance évidente dans le chêne, parce que la réduction dans la proportion des arbres avec couronnes épaisses correspond à la réduction dans le nombre des arbres avec couronnes très claires. L'hêtre a montré une certaine amélioration pendant l'année.

Il est probable que plusieurs facteurs contribuent à l'état des couronnes, y compris l'influence du climat et des nuisibles. Il y a apparemment des interactions positives et negatives entre la condition d'un arbre et la pollution atmosphérique.

L'analyse de plusieurs indices de la condition des couronnes montre qu'ils sont sans corrélation. Par exemple, dans la plupart des espèces la décoloration ne semble pas avoir de relation avec la perte du feuillage. Donc est-il important d'examiner le plus d'indices possible.

Des distributions spatiales distinctes existent parmi les différents indices. L'épicéa Sitka est très variable, et seulement la décoloration et la rétention des aiguilles montrent des distributions distinctes. Ni l'une ni l'autre ne semble avoir de corrélation avec une quelconque forme de pollution. L'épicéa commun, le pin sylvestre, le chêne et l'hêtre ont des couronnes plus denses dans les régions de forte pollution. Les autres indices de la condition des arbres sont plus variables, et on a constaté des corrélations positives et negatives avec les diverses formes de la pollution atmosphérique. L'analyse souligne la présence d'un ensemble complexe de facteurs à actions reciproques, qui touchent la condition des arbres dans Le Royaume-Uni, et il faudra peut-être de nombreuses années avant qu'ils soient compris.

Monitoring des Waldzustandes in Grossbritannien – 1988

Zusammenfassung

Zwei Programm, für die Erfassung des Waldzustandes in Grossbritannien sind jetzt in Kraft. Das eine befasst sich ausschliesslich mit Sitkafichte, Fichte, Kiefer, Eiche und Buche, das andere umfasst alle Baumarten. Zweck der beiden Programm ist, irgendwelcher nationaler oder regionaler Rückgang in Baumgesundheit zu identifizieren, der auf Luftverunreinigung zurückführbar sei.

In allgemeinen wurde wenig Veränderung zwischen 1987 und 1988 bemerkt. Die Kronen der Sitkafichte und der Kiefer sind dünner geworden, während die Kronen der Fichte in dem selben Zustand geblieben sind. Bei der Eiche sieht man keine klare Tendenz, da eine Verminderung im Anteil der Bäumen mit dichten Kronen durch eine Verminderung in der Zahl der Bäumen mit sehr dünnen Kronen geglichen worden ist. Die Buche hat eine Verbesserung während des Jahres gezeigt.

Wahrscheinlich tragen mehrere Faktoren, einschliesslich klimatischer Einflüsse und Schädlinge, zum Zustand der Baumkronen bei. Sowohl positive als auch negative Zusammen-wirkungen zwischen Baumzustand und Luftverunreinigung werden hingedeutet.

Die Analyse von verschiedenen Kennziffern des Kronenzustandes deutet darauf hin, dass sie nicht verwandt sing. Zum Beispiel, bei den meisten Baumarten scheint Verfärbung nicht in Beziehung zu Blatt- oder Nadelverlust zu sein. Daher ist es wichtig, möglichst viele verschiedene Kennziffern zu betrachten.

Deutliche räumliche Verbreitungsbilder sind bei einigen der verschiedenen Kennziffern vorhanden. Die Sitkafichte ist höchst variabel, und nor Verfärbung und Nadelbehaltung zeigen deutliche Verbreitungsbilder. Keine der beiden scheint aber in Beziehung zu irgendeiner Verunreinigungsform zu stehen. Fichte, Kiefer, Eiche und Buche haben alle dichtere Kronen in denjenigen Gegenden, wo die Luftverunreinigungsniveaus grösser sind. Andere Kennziffer des Zustandes sind mehr variabel, und sowohl positive als auch negative Wechselbeziehungen mit verschiedenen Luftverunreinigungsformen festgestellt worden sind. Die Analyse zeigt, dass ein komplizierter Satz zusammen-wirkender Faktoren vorhanden ist, die den Zustand von Baümen in Grossbritannien beeinflüssen, und dass vielleicht viele Jahre nötig werden, sie zu lösen.

Monitoring of Forest Condition in the United Kingdom – 1988

J. L. Innes and R. C. Boswell, *Forestry Commission*

Introduction

The condition of forests in the United Kingdom is monitored through two projects undertaken by the Forestry Commission. The first, referred to throughout this publication as the long-term monitoring project, was started in 1984. It was developed in response to a growing concern that air pollution might be affecting the condition of trees in Britain. Since 1984, this project has been gradually extended and the techniques used to assess individual trees have been improved. Unfortunately, this has created problems as the results obtained between 1984 and 1986 are not comparable with the results obtained in 1987 and 1988.

The second project, referred to as the European Community (EC) forest health inventory, was started in 1987 as a direct result of European Community legislation (Commission Regulation (EEC) No. 1696/87). It is much less detailed than the long-term monitoring project, and incorporates fewer sites. However, the results are theoretically directly comparable with the results from inventories undertaken in some other European countries.

In the two projects, a total of 385 stands, each consisting of 24 trees, are assessed. Although this number of stands is relatively small in comparison with the number assessed in countries such as the Federal Republic of Germany and the Netherlands, Britain's total forested area is also low. When the density of assessment sites in the different European countries is compared (Table 1), it is clear that the United Kingdom is above average. This reflects the importance that the Forestry Commission attaches to the issues of forest decline and forest monitoring.

To avoid possible confusion, the results of the two projects are presented separately below. The majority of the report is concerned with the long-term monitoring project; results from the EC forest health inventory are summarised towards the end of the report. Some analyses are still underway and the results will be submitted for publication elsewhere in the near future.

In the past, we have referred to the two projects as forest health surveys. This has caused confusion as neither are primarily concerned with forest health *per se.* A number of indices, which are believed to reflect the general condition of the trees, are recorded annually. The most important of these is crown density, which is widely accepted as reflecting the sum of stresses operating on a tree. However, crown density can be affected by other factors. For

Table 1. Details of national surveys of forest condition undertaken within the European Community in 1988. (All figures are approximate.)

	Forest area (thousand ha)	*Number of plots*	*Plots per 10 000 ha*
Belgium	617	46	0.75
Denmark	460	21	0.46
Eire	335	22	0.66
Federal Republic of Germany	7388	4117	5.57
France	13 845	228	0.16
Greece	2512	84	0.33
Italy	8675	218	0.25
Luxembourg	84	210	25.00
Netherlands	330	3400	103.03
Portugal	2527	154	0.61
Spain	11 921	387	0.32
United Kingdom*	2112	385	1.82

*Includes both 'Level 1' and 'Level 2' sites.

example, a tree that is growing fast may have a thin crown as a result of the lack of side branches. The possibility of using various measures of crown architecture is currently being examined and these may enable factors such as the rate of growth to be either excluded from the assessments or accounted for.

Emphasis has been placed on the monitoring role of the projects. The term survey suggests a single unrepeated assessment. Both of the projects described in this report deal with the repeated assessment of individual marked trees. They are therefore monitoring exercises and not surveys.

The two projects have rather different aims. The long-term monitoring project is concerned with identifying any anomalous pattern in forest condition that might be attributable to one or more forms of air pollution. To do this, it is necessary to examine other biotic and abiotic factors, as these also affect crown condition. The EC forest health inventory is undertaken to satisfy European Community regulations on forest monitoring. The information gathered is not considered to be of sufficient value to analyse in detail, although its value may be considerable when data gathered over the rest of the Community are analysed together. The results of the European analyses will be published by the Commission for the European Community in due course.

The long-term monitoring project

Distribution of plots

Considerable changes have been made to the distribution of plots used in this project between 1987 and 1988. As a result of the October 1987 storm, felling operations and a certain amount of rationalisation, 22 of the plots used in 1987 were abandoned. These were replaced by 69 new plots, giving a total of 309 plots. A deliberate attempt was made to locate new plots in areas where the existing density of plots was low.

The selection of new plots was undertaken according to the criteria specified in previous years (Binns *et al.*, 1985, 1987; Innes *et al.*, 1987; Innes and Boswell, 1988). Plots were only located in stands larger than of a 0.5 hectare. Stands with appreciable windthrow were avoided, as were those with particularly exposed margins. Where possible, only those stands that consisted of at least 60 per cent of the target species were selected. Between 1984 and 1986, two further criteria were used; stands that had a history of past problems were avoided and only stands with good growth (minimum yield classes of 10 for Norway spruce (*Picea abies* (L.) Karst.), 12 for Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and 8 for Scots pine (*Pinus sylvestris* L.)) were included. Neither of these criteria was used in 1987 and 1988.

A total of 7411 trees was assessed between late July and early September, 1988. There is unequal coverage between the five species; in 1988 there were 65 Sitka spruce plots, 79 Norway spruce plots, 80 Scots pine plots, 50 oak (*Quercus petraea* (Mattuschka) Lieblein, *Q. robur* L. and hybrids between the two) plots and 35 beech (*Fagus sylvatica* L.) plots. A relatively small number of beech plots was assessed as the area covered by this species is small and beech has also been the subject of a separate investigation*. The distributions of stands used in the project are shown in Figure 1.

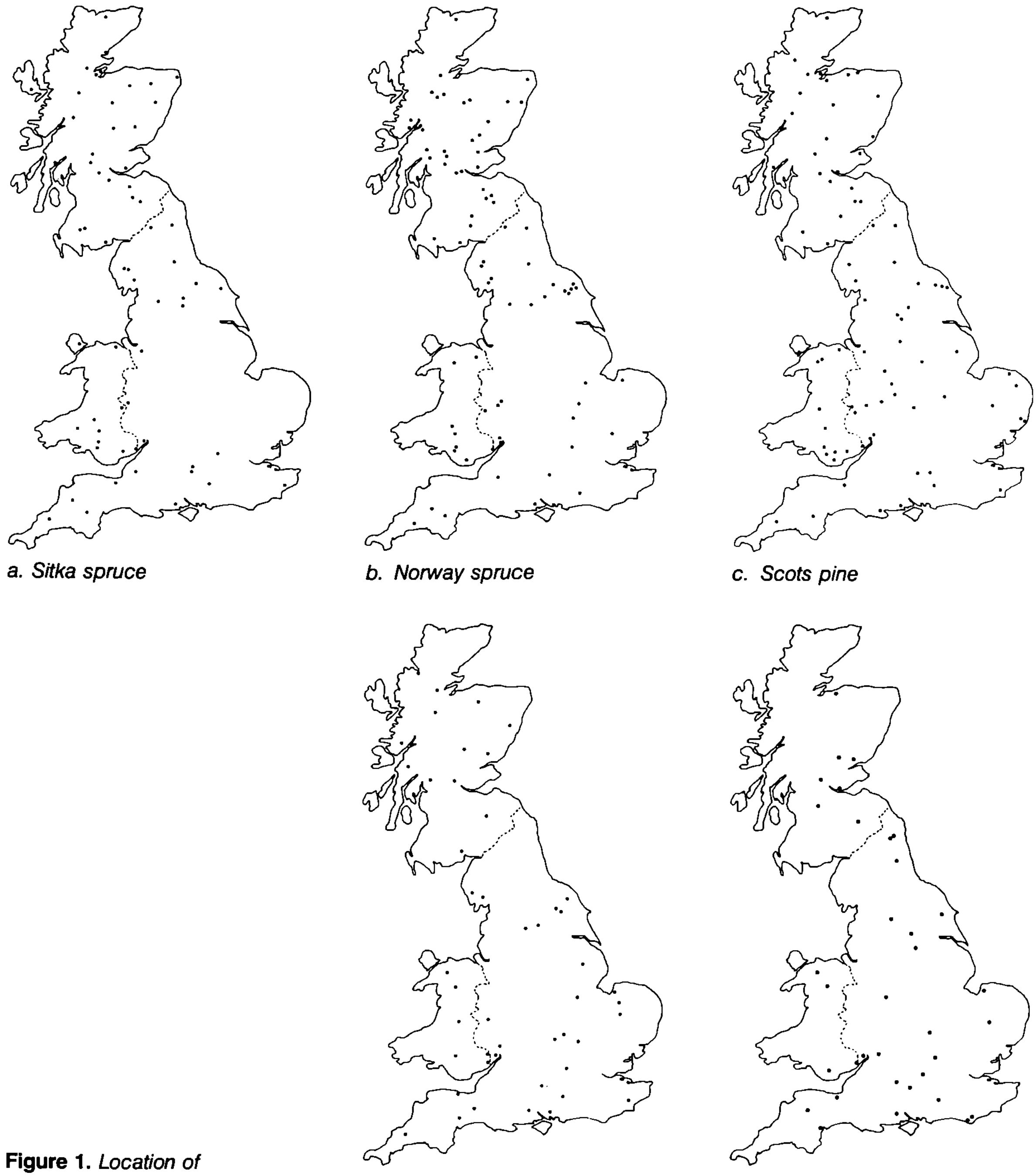
Assessment procedures

The methods used in both projects were the same as in 1987 and have been detailed in Innes *et al.* (1986) and Innes and Boswell (1987). At each site, the condition of 24 trees was examined using visual techniques. The indices assessed are described below. In addition, the diameter at breast height and total height of the majority of trees were measured. The procedures follow the recommendations laid down for 'Level 2' sites in the European manual for the assessment of forest condition (ECE, 1988).

Reliability of observations

The reliability of the observations has been one of the biggest problems associated with the

*Undertaken by Imperial College, London and jointly financed by the Forestry Commission and the Nature Conservancy Council.



a. *Sitka spruce* b. *Norway spruce* c. *Scots pine* d. *Oak* e. *Beech*

Figure 1. *Location of sample stands in 1988*

projects. This has now been largely resolved through the intensive training of observers. A week-long training course, based on the one developed at Freiburg in the Federal Republic of Germany (Schöpfer, 1985), was held. In 1988, eight teams of observers were involved in the projects, with a further 'control' team being used to ensure standardisation between teams. With one exception, the observers were the same as in 1987, ensuring compatibility between the two

Table 2. Data completeness. All tree indices refer to the percentage of trees assessed. The figures for soil analyses refer to the percentage of sites sampled.

	Species				
	Sitka spruce	*Norway spruce*	*Scots pine*	*Oak*	*Beech*
Tree indices					
Crown density	100	100	100	100	100
Browning	100	100	99	98	100
Yellowing	100	100	99	98	100
Needle retention	100	100	99	—	—
Shoot death	92	98	96	—	—
Crown dieback	—	—	—	98	97
Epicormics	—	—	—	100	—
Presence of fungi	—	—	—	95	96
Presence of insect damage	—	—	—	97	99
Premature leaf loss	—	—	—	—	91
Site data — climate	100	100	100	100	100
Site data — Harwell	100	100	100	100	100
Site data — Warren Spring	100	100	100	100	100
Site data — soils	83	90	84	78	83

years. All the observers were trained foresters specialising in survey work.

In all, 13 per cent of the stands were assessed by the control team, a lower proportion than last year because the total number of stands assessed has increased while the number examined by the control team has remained constant. The estimates of crown density obtained by the field crews were on average within 0.4 per cent of the control team. The majority of observations (95 per cent) fell within ±14 per cent of those made by the control team, a 1 per cent improvement on the result obtained in 1987. As in 1987, there were small variations in the consistency of observations between different species. The estimates obtained in 1988 can be ranked in decreasing order of consistency for each species: Scots pine, oak, beech, Norway spruce and Sitka spruce. In 1987, the estimates of Scots pine were the least consistent whereas in 1988 they were the best. This reflects the emphasis placed on Scots pine during the 1988 training period. In 1989, emphasis will be placed on the two spruce species.

Data completeness

Within a study such as this, the completeness of the data set is important. Table 2 shows that data for most of the characteristics assessed were more or less complete but data on soils are available only for plots established prior to 1988.

Results

Crown density (Table 3)

Crown density is the most ubiquitous of the indices of crown condition used in the assessment of forest damage. However, crown density does not necessarily reflect the health of a tree, nor does a reduced crown density always indicate damage. Crown density was assessed in 10 per cent classes relative to a fully-foliaged tree, from class 0 (0-10 per cent reduction in foliage) to 9 (> 90 per cent reduction).

In most cases, the percentage of trees in class 0 (0-10 per cent reduction in crown density) is fairly low. Only young Norway spruce have more than 25 per cent of the trees in this category. Conversely, there are relatively few trees with more than 60 per cent reduction in foliage. The majority of trees have between 10 and 50 per cent reduction in foliage with the modal class in most cases being 2 (21-30 per cent reduction in density). The crown densities of older Sitka and Norway spruce are clearly lower than those of younger trees, confirming earlier findings (Innes and Boswell, 1988). As the distribution of crown densities that would occur under pollution-free conditions is unknown, no further observations can be drawn from the data presented in Table 3.

Discoloration (Tables 4 and 5)

In conifers, discoloration has been separated by colour and by the age-class of affected needles. In addition, the overall discoloration in the crowns of conifers was assessed. All estimates are made using binoculars, which may lead to serious underestimation of symptoms such as chlorotic flecking (Muir and Armentano, 1988).

High levels of discoloration were generally very rare. Discoloration of older needles was more frequent than discoloration of younger needles, as might be expected. Browning of older

Table 3. Percentage distribution of trees by 10 per cent crown density classes, 1988; all plots. A density class of 0 represents a reduction of 0–10%, 1 represents a reduction of 11–20%, and so on.

		Crown density class									
	n	*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Sitka spruce (< 50 years old)	1032	12	27	27	19	11	3	1	0	0	0
Sitka spruce (≥ 50 years old)	528	2	14	26	30	16	10	2	0	0	0
Sitka spruce (all trees)	1560	9	23	27	22	13	5	1	0	0	0
Norway spruce (< 50 years old)	1104	29	32	24	11	3	1	0	0	0	0
Norway spruce (≥ 50 years old)	791	9	20	25	24	13	6	2	1	0	0
Norway spruce (all trees)	1895	21	27	24	17	7	3	1	0	0	0
Scots pine (< 50 years old)	956	9	24	30	22	11	4	1	1	0	0
Scots pine (≥ 50 years old)	960	8	24	35	19	8	2	1	1	1	1
Scots pine (all trees)	1916	8	23	32	21	9	3	1	1	1	1
Oak (80–180 years old)	1200	4	16	28	29	13	6	2	1	1	0
Beech (60–120 years old)	840	9	24	33	23	9	2	0	0	0	0

foliage was more frequent than yellowing and, with the two spruce species, was more frequent on younger trees. The levels of discoloration in Sitka spruce and Norway spruce were very similar. Overall levels of discoloration indicated that approximately 10 to 15 per cent of trees were affected.

Discoloration was much more frequent in beech than in oak. Many beech showed both browning and yellowing, and over half of the beech assessed had evidence of yellowing. Neither the significance nor the cause of the yellowing was identified in this study although lime-induced chlorosis, drought and beech bark disease are all known to be contributary.

Needle retention (Table 6)

The number of years over which needles are retained was recorded. In the two spruce species, it is frequently very difficult to count back more than 7 years and consequently, trees with more than 7 years' needle-retention were aggregated into a single category. While this results in some loss of data, it also reduces the chance of needle retention being underestimated. Average needle retention of the two spruce species cannot be derived from these data; the figures for average needle retention of spruce given in previous reports are invalid and should not be cited.

In both spruce species, needle retention was higher in younger trees. No clear distinction was evident for Scots pine. More than half of the spruce assessed had less than 8 years' needle retention, although the majority had 6 or more years. In Scots pine, more than 90 per cent of the trees assessed had either 2 or 3 years' needle retention. No pines with more than 4 years' needle retention were identified.

The proportion of sample trees with a given

Table 4. Percentages of coniferous trees in each needle-browning class, 1988.

	Current				*Old*			
	0	*1*	*2*	*3*	*0*	*1*	*2*	*3*
	0–10%	*11–25%*	*26–60%*	*>60%*	*0–10%*	*11–25%*	*26–60%*	*>60%*
Sitka spruce (<50)	99	1	0	0	85	10	5	0
Sitka spruce (⩾50)	100	0	0	0	97	3	0	0
Sitka spruce (all)	99	1	0	0	89	8	3	0
Norway spruce (<50)	99	1	0	0	85	9	6	0
Norway spruce (⩾50)	99	1	0	0	92	7	1	0
Norway spruce (all)	99	1	0	0	88	8	4	0
Scots pine (<50)	96	4	0	0	95	4	1	0
Scots pine (⩾50)	96	4	0	0	91	8	1	0
Scots pine (all)	96	4	0	0	93	6	1	0
Percentages of coniferous trees in each needle-yellowing class, 1988.								
Sitka spruce (<50)	96	4	0	0	95	4	1	0
Sitka spruce (⩾50)	96	4	0	0	90	8	2	0
Sitka spruce (all)	96	4	0	0	93	5	2	0
Norway spruce (<50)	99	1	0	0	98	2	0	0
Norway spruce (⩾50)	94	5	1	0	95	4	1	0
Norway spruce (all)	97	3	0	0	97	3	0	0
Scots pine (<50)	98	2	0	0	92	7	1	0
Scots pine (⩾50)	96	4	0	0	95	4	1	0
Scots pine (all)	97	3	0	0	94	5	1	0

Percentage of coniferous trees in each overall discoloration class, 1988.

	Overall discoloration			
	0	*1*	*2*	*3*
Sitka spruce (<50)	84	11	4	1
Sitka spruce (⩾50)	90	7	3	0
Sitka spruce (all)	86	10	4	0
Norway spruce (<50)	85	9	6	0
Norway spruce (⩾50)	88	9	3	0
Norway spruce (all)	86	9	5	0
Scots pine (<50)	90	8	2	0
Scots pine (⩾50)	91	8	1	0
Scots pine (all)	90	8	2	0

Table 5. Percentages of oak and beech showing leaf discoloration in different classes, 1988.

	Browning				*Yellowing*			
	0	*1*	*2*	*3*	*0*	*1*	*2*	*3*
	0–10%	*11–25%*	*26–60%*	*>60%*	*0–10%*	*11–25%*	*26–60%*	*>60%*
Oak	95	5	0	0	92	7	1	0
Beech	72	24	4	0	47	35	16	2

Table 6. Percentage of trees with needle life (needle retention) for a given number of years, 1988.

	Number of years 0	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*>7*
Sitka spruce (<50)	0	0	0	1	4	14	15	19	47
Sitka spruce (≥50)	0	0	0	2	6	15	19	17	41
Sitka spruce (all)	0	0	0	1	5	15	16	18	45
Norway spruce (<50)	0	0	0	0	1	7	20	26	46
Norway spruce (≥50)	0	0	0	2	7	17	20	22	32
Norway spruce (all)	0	0	0	1	3	11	20	24	41
Scots pine (<50)	0	1	57	39	3	0	0	0	0
Scots pine (≥50)	0	3	61	35	1	0	0	0	0
Scots pine (all)	0	2	59	37	2	0	0	0	0

Table 7. Percentage of sites with a given number of trees having less than 7 years' needle retention.

	Number of trees per site 0	*1–4*	*5–8*	*9–12*	*13–16*	*17–20*	*21–24*
Sitka spruce	34	20	7	6	5	6	22
Norway spruce	30	29	10	6	8	6	11

number of needle-years in each stand can also be examined for the two spruce species (Table 7). The number of trees with less than 7 years of needle retention has been used as a threshold. As there is no difficulty in counting back 6 years, the figures should be reliable. Studies in central Europe suggest that less than 5 to 6 years of needle retention indicate that the trees are under stress (e.g. Heinsdorf *et al.*, 1988), providing a further reason for adopting this threshold.

The distributions are bimodal with peaks at the minimum and maximum values. In both species, over half of the plots had fewer than four sample trees with less than 7 years' needle retention. However, 22 per cent of the Sitka spruce and 11 per cent of the Norway spruce plots had between 21 and 24 of the sample trees within a plot with less than 7 years' needle retention.

There is some evidence of a relationship between needle retention and crown density. The relationship is most apparent in the data for Scots pine (Table 8), although it is also present for both Sitka spruce (Table 9) and Norway spruce (Table 10). However, the relationship is not universal and some individual trees show an inverse relationship.

An accurate estimate of needle retention can be obtained by a 'hands-on' count. However, without resorting to destructive sampling, this is only feasible for branches accessible from the ground. Such branches are subject to shading and may also be preferentially defoliated by insects such as *Elatobium abietinum* (Walker); Hemiptera. Comparisons of the counts obtained using the two methods are given in Tables 11 and 12. In Sitka spruce, hands-on counts in the lower crowns tend to underestimate severely the binocular estimations of retention in the upper crown. With Norway spruce, hands-on counts in the lower crowns also underestimate the retention in the upper crown, but the results suggest that foliage may either be retained longer in the lower crown or binocular counts underestimate the needle retention more than previously supposed. This is indicated by the relatively large numbers of values falling above the 1:1 line in Table 12.

Table 8. Relationship between needle retention and crown density in Scots pine, 1988. The number of trees in each category is shown. No trees with more than 4 years of needle retention were recorded in 1988.

Crown density	*Needle retention (years)* 0	1	2	3	4
0	0	0	33	119	6
1	0	0	202	223	19
2	0	1	380	219	10
3	0	4	296	95	5
4	0	1	137	38	1
5	0	4	47	11	0
6	0	4	15	2	0
7	0	7	11	0	0
8	0	4	6	2	0
9	3	5	0	0	0

Table 9. Relationship between needle retention and crown density score for Sitka spruce, 1988. The number of trees in each category is given.

Crown density	*Needle retention (years)* 0	1	2	3	4	5	6	7	>7
0	0	0	0	0	0	10	16	25	83
1	0	0	0	0	2	28	50	57	214
2	0	0	0	0	11	45	73	97	188
3	0	0	0	4	15	66	59	62	140
4	0	0	0	7	24	50	41	32	49
5	0	0	1	4	17	25	12	7	16
6	0	0	0	3	4	4	2	2	2
7	0	0	0	1	1	1	0	1	0

Table 10. Relationship between needle retention and crown density in Norway spruce, 1988. The number of trees in each category is given.

Crown density	*Needle retention (years)* 0	1	2	3	4	5	6	7	>7
0	0	0	0	0	5	21	66	94	201
1	0	0	0	0	7	31	105	116	253
2	0	0	0	0	10	32	105	124	185
3	0	0	2	4	20	59	55	74	97
4	0	0	0	5	9	40	27	28	25
5	0	0	0	1	6	16	20	17	3
6	0	0	0	0	4	8	1	3	2
7	0	0	0	0	2	1	0	1	0
8	0	0	0	1	3	0	0	0	0

Flowering in Scots pine (Table 13)

The extent of male flowering in the crowns of Scots pine is assessed on the proportion of shoots on which flowering occurred in the current and previous year (1987, 1988) or both. Four categories were used: 0–10 per cent, 11–25 per cent, 26–60 per cent, >60 per cent. Flowering was recorded in approximately half of the trees, being more frequent in older trees than younger ones. Heavy flowering was present in fewer than 3 per cent of the trees.

Dead branches in the live crowns of conifers (Table 14)

The presence of dead branches in the live crowns of conifers was noted. The results have been compiled on a stand-by-stand basis as this gives a more accurate reflection of the nature of this phenomenon. Trees with dead branches were present in 70–90 per cent of the stands. They were most frequent in Scots pine stands. With the two spruce species, dead branches were present in fewer than half of the trees at the majority of sites.

Crown dieback in broadleaves (Table 15)

Four categories of crown dieback in broadleaves were assessed (none, 1–10 per cent, 11–30 per cent, >30 per cent); the results are presented in Table 15. Dieback was present in two-thirds of the trees and the figures were similar for both oak and beech. Only 10 per cent of the trees were recorded as having more than 10 per cent dieback.

Leaf-rolling in beech (Table 16)

Although the significance of leaf-rolling in beech is still unknown, its presence was noted on a number of occasions. Approximately 20 per cent of the trees were affected.

Premature leaf loss in beech

Premature leaf loss was assessed on the basis of the frequency of green leaves on the ground under the trees. Small numbers of leaves were recorded as being present under approximately

Table 11. Relationship between binocular counts of needle retention in upper crown of Sitka spruce and hands-on count of retention on branches within 2 m of the ground. Each category is the number of needle-years retained. Each value in the table refers to the number of trees in each category.

Upper crown	*Lower crown* 0	1	2	3	4	5	6	7	8	9	10	11	12
3	0	0	1	5	0	0	0	0	0	0	0	0	0
4	0	0	1	6	6	1	0	0	0	0	0	0	0
5	1	3	1	1	6	25	9	11	0	0	0	0	0
6	9	4	2	5	3	9	19	12	7	0	0	0	0
7	15	2	7	3	7	10	13	27	24	2	4	0	0
8	27	5	1	5	4	5	17	19	22	12	5	0	0
9	25	0	1	3	1	7	13	16	18	11	7	7	2
10	10	0	0	0	2	3	10	12	11	7	5	3	1
11	2	0	0	0	2	1	2	2	4	4	2	1	1
12	5	0	0	0	0	0	1	1	2	3	2	1	1

Table 12. Relationship between binocular counts of needle retention in upper crown of Norway spruce and hands-on count of retention on branches within 2 m of the ground.

Upper crown	*Lower crown* 0	1	2	3	4	5	6	7	8	9	10	11	12
3	0	0	0	0	0	1	0	0	0	0	0	0	0
4	0	0	0	0	0	10	1	0	0	0	0	0	0
5	14	0	0	1	0	10	7	2	3	2	0	1	0
6	16	0	0	1	3	13	19	14	17	8	4	2	4
7	15	0	0	0	4	11	18	32	42	20	12	3	1
8	4	0	0	1	2	4	14	29	26	13	10	5	2
9	8	0	0	1	4	4	8	22	20	24	11	2	5
10	0	1	0	1	3	4	6	12	11	11	10	8	5
11	0	0	0	0	0	1	5	7	7	4	8	2	6
12	0	0	0	0	1	0	0	1	2	2	0	2	1

Table 13. Percentage of pine in each flowering class, 1988.

	n	*0–10% None*	*11–25% Light*	*26–60% Medium*	*>60% Heavy*
Scots pine (<50)	939	53	32	13	2
Scots pine (≥50)	960	43	33	22	3
Scots pine (all years)	1899	48	33	17	2

Table 14. Percentage of sites with a given number of trees with dead branches in the live crown.

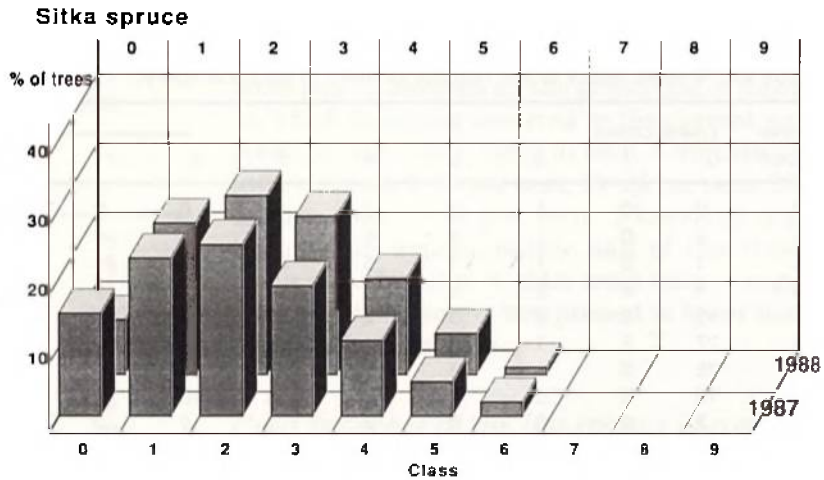
	Number of trees 0	*1–4*	*5–8*	*9–12*	*13–16*	*17–20*	*21–24*
Sitka spruce	25	32	14	12	12	2	3
Norway spruce	28	27	18	8	8	6	5
Scots pine	10	25	16	18	9	14	8

Table 15. Percentages of beech and oak in each crown dieback class, 1988.

	n	*Extent of crown dieback* None	*1–10%*	*11–30%*	*>30%*
Oak	1176	63	26	8	3
Beech	816	62	27	10	1

Table 16. Percentages of beech with leaf-rolling in crown ($n = 767$).

Extent	*Degree* Nil	*Light*	*Moderate*	*Severe*
Absent	79	0	0	0
Rare	0	7	4	0
Common	0	4	6	0



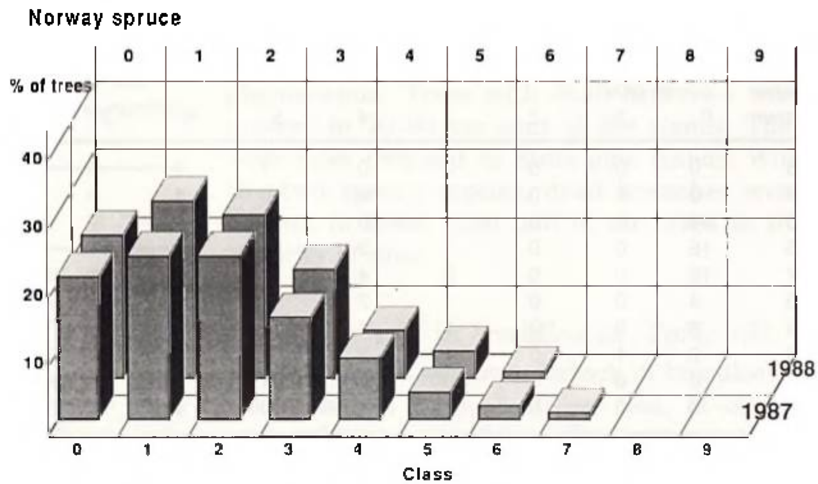


Figure 2. *Changes in crown density classes between 1987 and 1988. Only stands assessed in both years have been included.*

25 per cent of the trees and larger numbers were recorded under 2 per cent of the trees. The cause of the leaf loss was not established.

Presence of insects and fungi on broadleaves

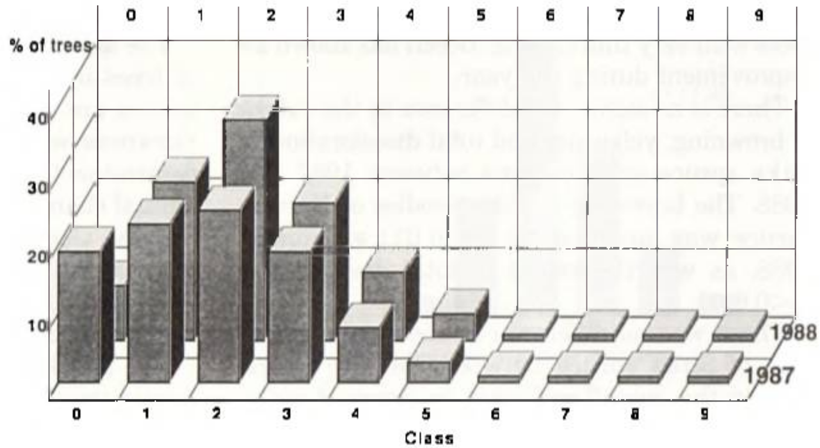
Insects were recorded as having had a significant effect in 59 per cent of the beech crowns and 57 per cent of oak crowns. Significant effects of fungi were recorded in 14 per cent of beech and 2 per cent of oak.

Comparison between 1987 and 1988

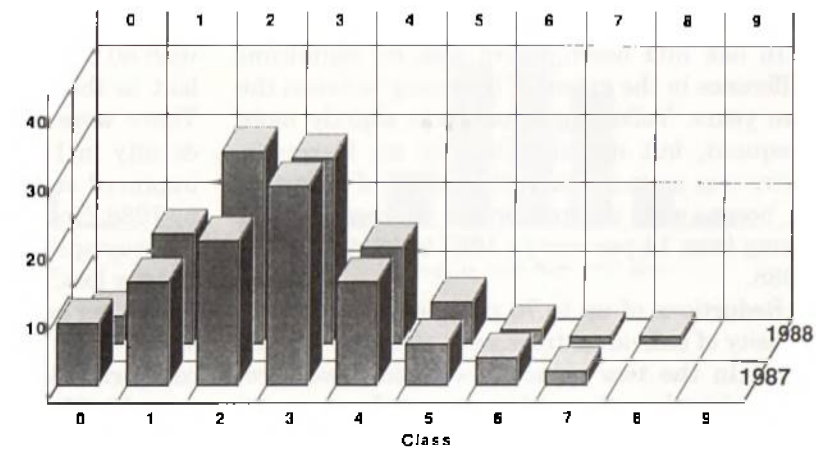
The techniques used to assess tree crowns were the same in 1987 and 1988 and changes between the two years can therefore be examined. Data from stands examined in both years have been used. Comparisons of this nature can take two forms. Firstly, overall changes in the data between 1987 and 1988 can be examined. A second approach involves changes in the indices related to individual trees. Both techniques have been adopted here.

In Figure 2, the overall changes between 1987 and 1988 are shown. These figures illustrate that, in general, there was little change between the two years, with only small variations in the percentages of trees in each category. The crowns of Sitka spruce and Scots pine have become thinner whereas the crowns of Norway spruce have remained approximately the same. No clear trend is apparent in oak as a reduction

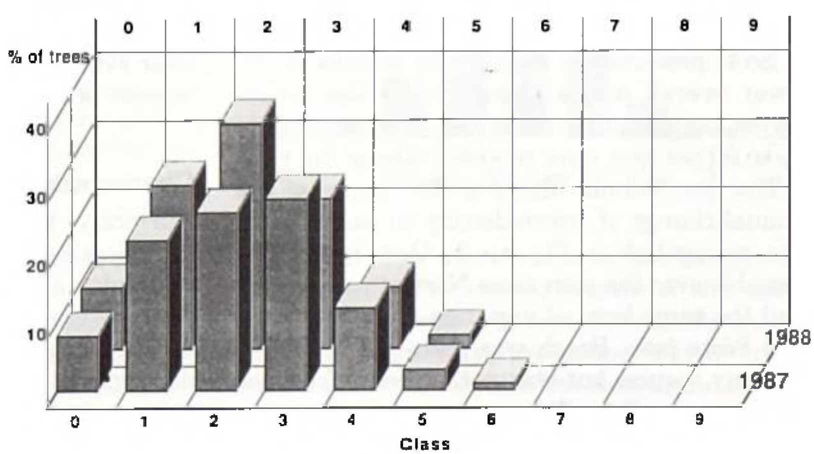
Scots pine



Oak



Beech



in the proportion of trees with dense crowns has been matched by a reduction in the proportion of trees with very thin crowns. Beech has shown an improvement during the year.

There is no significant difference in the extent of browning, yellowing and total discoloration in Sitka spruce or Scots pine between 1987 and 1988. The browning in older needles of Norway spruce was significantly ($p<0.01$) greater in 1988, as was the extent of total discoloration ($p<0.001$).

There was no difference in the needle retention of Sitka spruce between the two years, despite the overall reduction in crown density. The needle retention in Norway spruce was significantly ($p<0.001$) longer in 1988 in Norway spruce but significantly shorter in Scots pine. These results are consistent with the changes in crown density.

In oak and beech, there was no significant difference in the extent of browning between the two years. Yellowing in oak was slightly more frequent, but not significantly so. However, there was an increase in the extent of yellowing in beech, with the proportion of trees affected rising from 14 per cent in 1987 to 53 per cent in 1988.

Reductions of up to 70 per cent in the crown density of individual trees were recorded in Scots pine. In the two spruces, reductions were restricted to less than 50 per cent. Increases in density of up to 40 per cent were recorded on individual trees in all three species and the only tenable explanation is that the nature of the current year foliage exerts an undue influence on crown density. This may be more important in Scots pine than in the spruces because of the lower overall needle retention. In the broadleaves, both improvements and deteriorations of up to 50 per cent were recorded during the year.

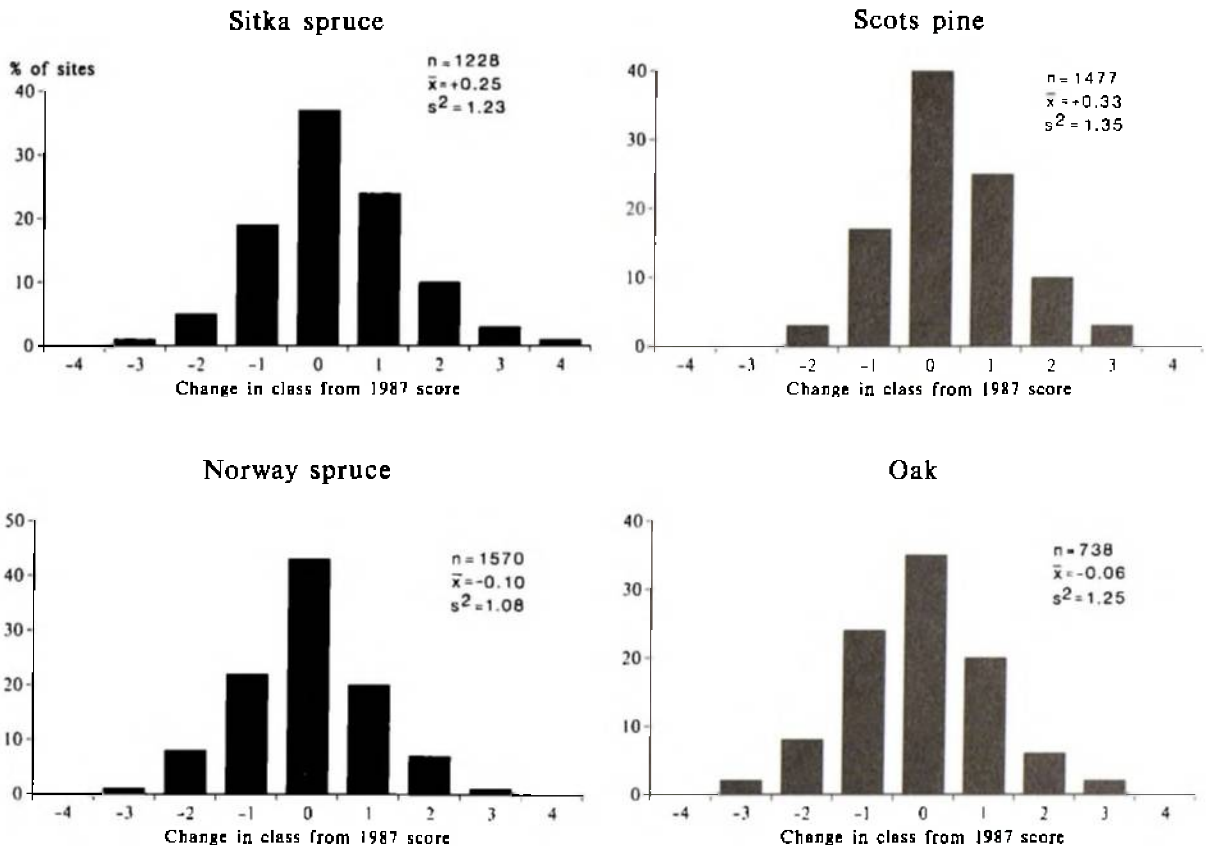
The distributions showing the nature of the annual change of crown density in each species are presented in Figure 3. Oak was more variable over the year than Norway spruce, but had the same level of variation as Sitka spruce and Scots pine. Beech was more variable than Norway spruce, but was not different from the other two conifers. Sitka spruce was more variable than Norway spruce but did not differ from the two broadleaves. Scots pine was more variable than either of the two spruce species.

The above results suggest that the proportions of trees improving and worsening within each species are similar. However, the extent of any skewness within the distributions appears to determine the extent and significance of any annual change in the overall statistics for crown density. Generalisations about annual changes are clearly misleading; the results indicate that the summary statistics conceal an extremely complex situation.

The majority of changes occurred among the denser trees and it is these trees that determine the overall statistics. Trees with low crown densities generally showed little change between 1987 and 1988. Any changes of these trees were generally towards a denser crown. This can be illustrated by examining the movements of trees with 60 per cent or more loss of density (equivalent to the German 'severe damage' category). There were 26 Sitka spruce with this level of density in 1987, of which 21 (81 per cent) had improved one or more crown density categories by 1988. None of the trees deteriorated. Of the 43 Norway spruce with 60 per cent or more crown density loss, 2 (5 per cent) deteriorated one class, 17 (40 per cent) remained in the same category and 24 (55 per cent) improved one or more categories. With the 52 Scots pine, the figures were 13 (25 per cent), 23 (44 per cent) and 16 (31 per cent), respectively. With the 44 oak, 3 (7 per cent) deteriorated and 7 (16 per cent) remained constant, whereas all four beech trees with 60 per cent or more reduction in crown density improved over the year. These figures provide clear evidence that 'severely damaged' trees are capable of recovery at least in the short-term.

Characterisation of stand condition

Currently, there are two principal methods of aggregating data from particular stands or particular areas. One method uses the percentage of trees below a given level of crown density. For example, the reports on forest damage in the Federal Republic of Germany refer to the percentages of trees with either >10 per cent or >25 per cent defoliation (Anon.,



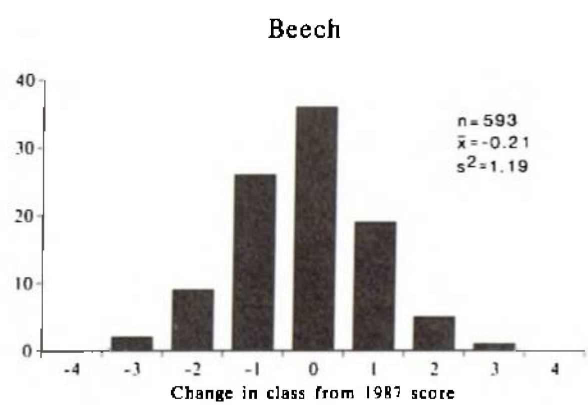


Figure 3. *Percentages of trees with a given change in crown density score between 1987 and 1988. A positive change indicates that the score increased, representing a decrease in crown density.*

1988). An alternative method is to calculate a mean value for a stand.

The usefulness of either method depends on the nature of the data being collected. In the Federal Republic of Germany, individual trees are placed into one of five categories (0–10 per cent, 11–25 per cent, 26–60 per cent, 61–99 per cent, dead). The uneven sizes of the categories, together with the skewed nature of the data, mean that averages cannot be reliably calculated. Consequently, the proportion of trees above a given threshold is the most useful means of presenting the data. In Britain, crown density is assessed in 10 per cent classes, and therefore stand averages, which are more sensitive than the percentage of trees above a given defoliation level, can be calculated.

To maintain consistency with the crown density figures, averages for discoloration have been calculated. In each case, the midpoint of the class has been used. As the data are highly skewed, the stand indices for discoloration overestimate the actual extent of discoloration within the trees.

One problem encountered with stand means is the considerable variation within each stand. In particular, substantial differences may exist between the four sub-samples within a stand. This has been formally tested using the following model:

$$u_{ijk} = u + S_i + E_{j(i)} + T_{k(ij)} \quad (1)$$

where

u_{ijk} : the crown density score for an individual tree

u : the mean crown density score for the entire sample

S_i : variation attributable to stand i

$E_{j(i)}$: variation attributable to edge j at stand i

$T_{k(ij)}$: variation attributable to tree k on edge j at stand i

This model assumes that the trees are randomly placed on edges randomly selected within randomly distributed stands. These assumptions are not strictly valid but violations are unlikely to invalidate the model. For example, although the edges are roughly placed on north, south, east and west axes, variations in the orientation of the edges of sub-compartments combined with marked variations in the environmental conditions experienced by each edge are likely to result in effectively randomly-distributed values.

The results of the analysis of variance are presented in Table 17. In all species, there is a significant amount of between-tree variation. Above this, there is a significant amount of variation between edges within stands, although this source of variation is much smaller than that attributable to between-stand variation. In relation to the overall mean, the components of variance suggest that the precision with which the crown density of the trees within the country as a whole has been estimated could be improved by increasing the number of trees sampled on each edge and by increasing the number of stands. The results indicate that an increase in the number of stands is needed most for Scots pine.

Table 17. Results of the analysis-of-variance tests carried out on the plot data.

	Degrees of freedom	*Mean square*	*F-ratio*	*Component of variance*
Sitka spruce				
Between site	64	17.24	6.35	0.61
Between edge	195	2.71	2.55	0.28
Between tree	1300	1.06		1.06
Norway spruce				
Between site	78	23.1	9.68	0.86
Between edge	237	2.39	2.34	0.23
Between tree	1580	1.02		1.02
Scots pine				
Between site	79	28.52	16.39	1.12
Between edge	240	1.74	1.5	0.1
Between tree	1600	1.16		1.16
Oak				
Between site	49	16.9	14.74	0.61
Between edge	150	2.17	1.58	0.13
Between tree	999	1.38		1.38
Beech				
Between site	30	12.83	6.29	0.45
Between edge	93	2.04	2.09	0.18
Between tree	620	0.98		0.98

Although the original data are categorical and collected on an ordinal scale, mean indices of crown condition are continuous and lie on the interval scale. This means that different statistical techniques need to be used to investigate the raw data (e.g. Burk, 1988; Dees, 1988) and the mean stand indices. In this report, emphasis has been placed on the stand indices, as these are believed to characterise the condition of the trees in each stand and it is the nature of between-stand variation that is of greatest relevance to the aims of the project.

A composite index of crown condition

The value of a single index of crown condition may be limited and in 1987, an attempt was made to derive a composite index using principal compon-

Table 18a. Principal components analyses of indices of crown condition in Sitka spruce. Only those components accounting for more than 10 per cent of the variance have been included.

	Component				
	1	*2*	*3*	*4*	*5*
Crown density	−0.117	0.581	−0.150	−0.332	0.125
Current needle browning	0.232	0.198	0.293	0.453	0.783
Old needle browning	0.609	0.081	−0.311	−0.231	0.000
Current needle yellowing	0.107	0.301	−0.176	0.764	−0.493
Old needle yellowing	0.131	0.162	0.740	−0.127	−0.289
Total discoloration	0.643	0.186	−0.087	−0.126	−0.075
Trees with < 7 years' needle retention	−0.317	0.382	−0.375	0.014	0.148
Trees with dead shoots	−0.141	0.565	0.260	−0.122	−0.132
Variance accounted for	26.6%	21.3%	15.2%	12.0%	10.5%

Table 18b. Results of principal components analysis for Norway spruce.

	1	*2*	*3*	*4*
Crown density	−0.440	−0.154	−0.214	−0.183
Current needle browning	−0.054	−0.017	0.395	−0.849
Old needle browning	−0.164	0.670	−0.219	−0.085
Current needle yellowing	−0.488	−0.086	0.297	0.289
Old needle yellowing	−0.465	−0.042	0.434	0.286
Total discoloration	−0.296	0.618	−0.097	−0.035
Trees with < 7 years' needle retention	−0.202	−0.276	−0.659	−0.028
Trees with dead shoots	−0.439	−0.244	−0.172	−0.267
Variance accounted for	34.5%	23.8%	13.3%	13.1%

Table 18c. Results of principal components analysis for Scots pine.

	1	*2*	*3*	*4*
Crown density	−0.221	0.565	−0.061	0.114
Current needle browning	−0.334	0.053	−0.338	−0.464
Old needle browning	−0.411	−0.171	0.059	0.657
Current needle yellowing	−0.347	0.075	−0.213	0.056
Old needle yellowing	−0.366	−0.284	0.346	−0.396
Total discoloration	−0.612	−0.158	0.055	0.085
Flowering	0.099	−0.198	−0.706	0.270
Trees with dead shoots	−0.181	0.417	−0.330	−0.235
Mean needle age	0.013	−0.570	−0.322	−0.213
Variance accounted for	25.9%	20.5%	14.3%	10.5%

Table 18d. Principal components analyses of indices of crown condition in oak.

	1	*2*	*3*	*4*
Crown density	−0.625	−0.139	−0.002	0.253
Browning	−0.282	0.641	−0.418	−0.574
Yellowing	−0.189	0.668	0.575	0.397
Number of epicormics	−0.416	−0.314	0.576	−0.594
Crown dieback	−0.567	−0.159	−0.404	0.310
Variance accounted for	41.8%	23.3%	18.5%	11.7%

Table 18e. Results of principal components analysis of beech.

	1	*2*	*3*
Crown density	0.156	−0.554	−0.497
Browning	0.307	−0.265	0.445
Yellowing	−0.401	−0.372	0.145
Crown dieback	0.277	−0.641	0.022
Premature leaf loss	−0.093	−0.147	0.726
Frequency of leaf rolling	−0.562	−0.177	−0.061
Degree of leaf rolling	−0.565	−0.147	−0.046
Variance accounted for	39.5%	20.2%	17.8%

ents analysis (Innes and Boswell, 1988). The results were inconclusive although some pattern was evident in oak and beech. The same analysis was undertaken with the 1988 data, with the advantage of having rather more stands and indices to work with. The results of the analyses are given in Table 18.

Principal components analysis is based on a linear response model which takes into account all the correlations between the response variables and the environmental factors. As such, it is an extension of least-squares regression. Each component shown in Table 18 accounts for a proportion of the total variance within the data set. The components are expressed as orthogonal axes and take the form of theoretical variables that explain the response variable data best. The first component is the theoretical variable that accounts for the greatest amount of variation in the response variables. The second and further axes account for successively less variance, subject to the constraint that they must not be correlated with previous axes.

The contribution of each response variable is also given in Table 18. The theoretical range for each score lies between 1 and −1. A high absolute (either positive or negative) score indicates that that variable is contributing to the component. If the score is positive, then it is high values of the variable that are important. If the score is negative, then low values, of the variable are important. The exception is with crown density. High crown density scores are associated with low density and, therefore, negative values in Table 18 indicate that the component is associated with increasing levels of thinness in the stand.

With Sitka spruce, the first component reflects the extent of browning in older needles and the total discoloration. The second component reflects crown density and the frequency of trees with dead shoots in the crown. The third component reflects the yellowing of older needles. The conclusion that can be drawn from the scores is that crown density and discoloration are relatively independent, indicating that they should be analysed separately.

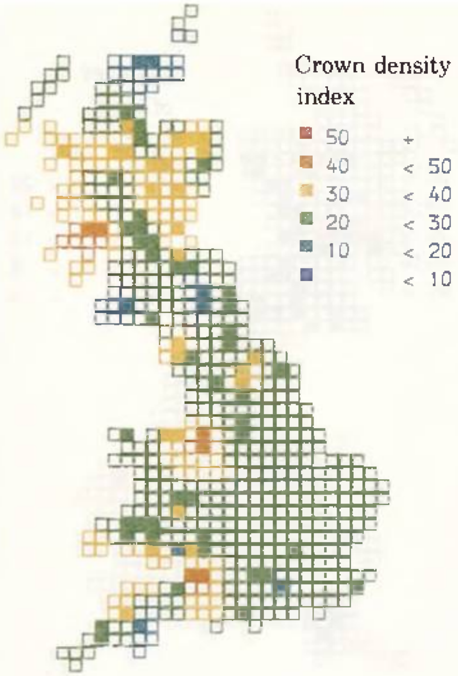
With Norway spruce, there is a greater amount of interaction between the different indices. The first principal component primarily reflects crown density, yellowing of both current and older needles and the frequency of trees with shoot death in the crown. Browning of older needles and total discoloration is reflected in the second component and needle retention in the third.

Scots pine again has a different pattern. Total discoloration and browning of older needles is reflected in the first component. The second appears to be most influenced by crown density, the number of trees with dead shoots in the live crown and needle retention and the third by the extent of flowering.

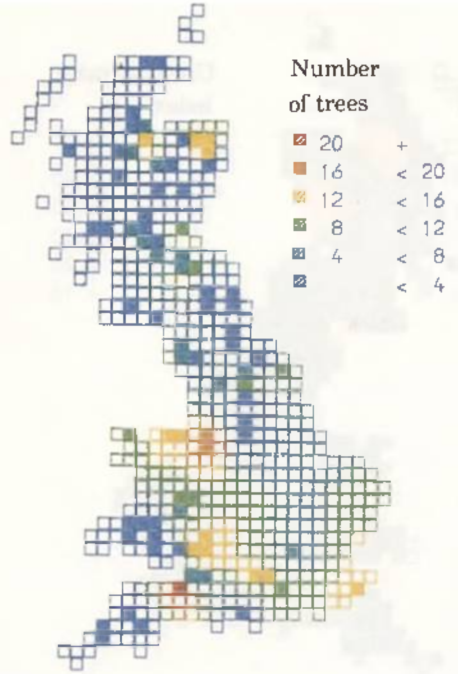
In oak, the first component reflects the influence of crown density and crown dieback. The second component is determined by discoloration and the third by the amount of yellowing and number of epicormic shoots on branches within the crown.

In beech, the first component is determined by the degree and frequency of leaf-rolling within the crown, whereas the second reflects crown density and crown dieback. The third component is primarily affected by premature leaf loss.

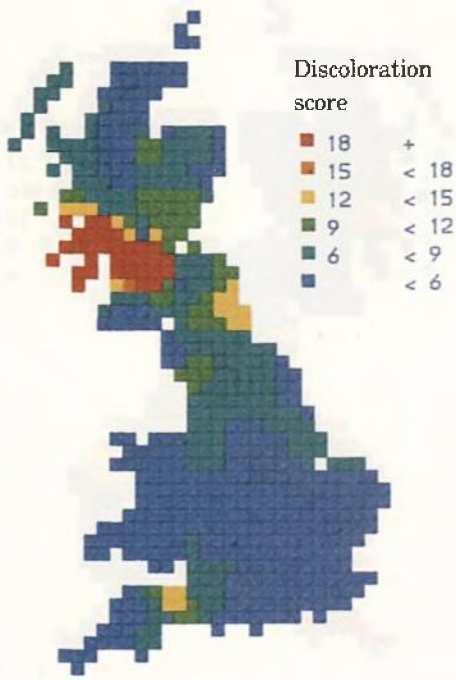
These results confirm that it is not possible to produce an integrated measure of forest condition from these data using principal components



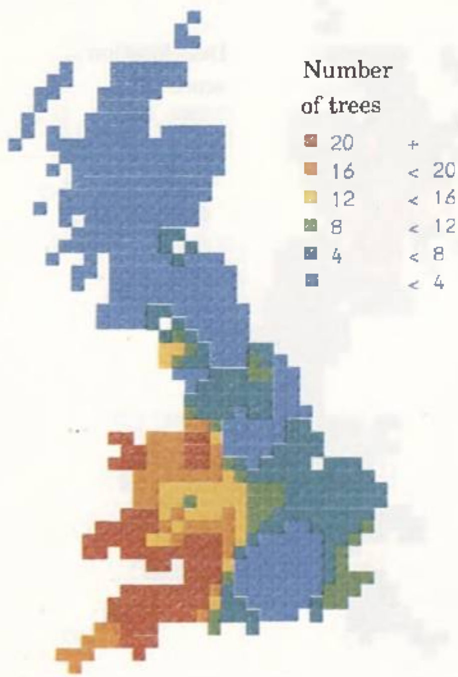
a. Crown density, after taking age into account (N.B. high scores indicate thin crowns)



c. Number of trees at each site with dead shoots in the live crown

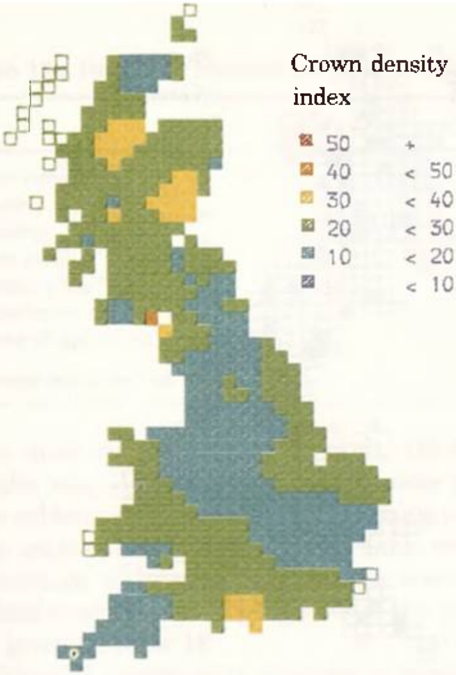


b. Overall discoloration

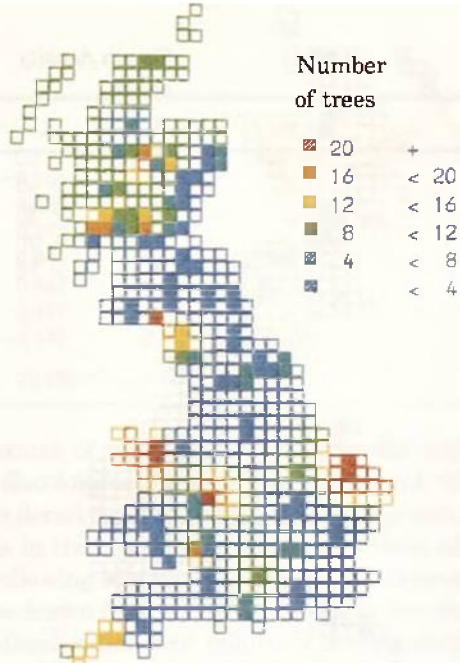


d. Number of trees at each site with less than 7 years' needle retention.

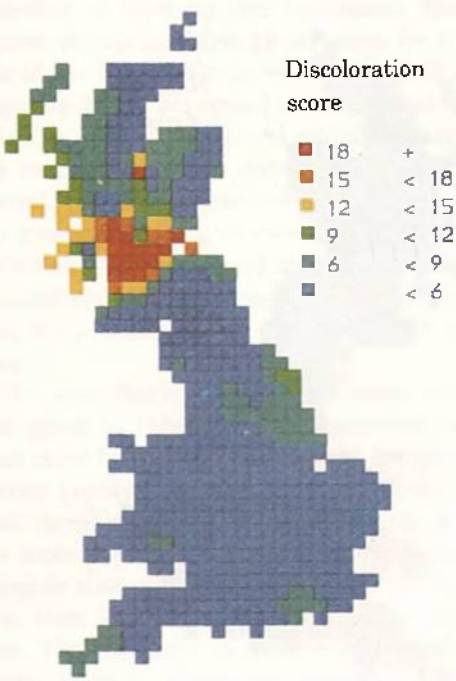
Figure 4. *Patterns of crown indices in Sitka spruce in 1988.*



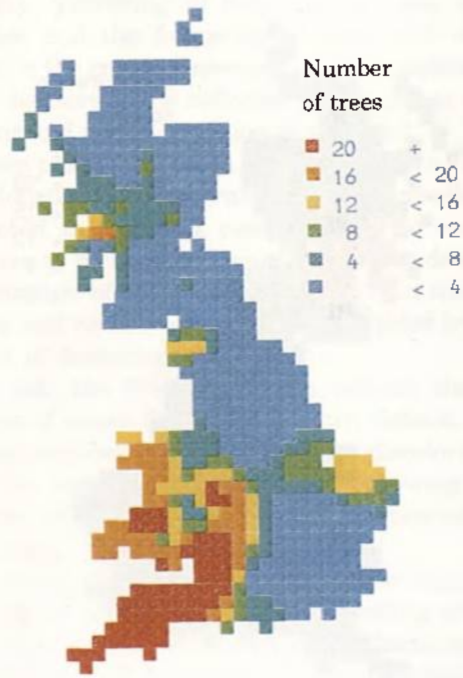
a. Crown density, after taking age into account (N.B. high scores indicate thin crowns)



c. Number of trees at each site with dead shoots in the live crown

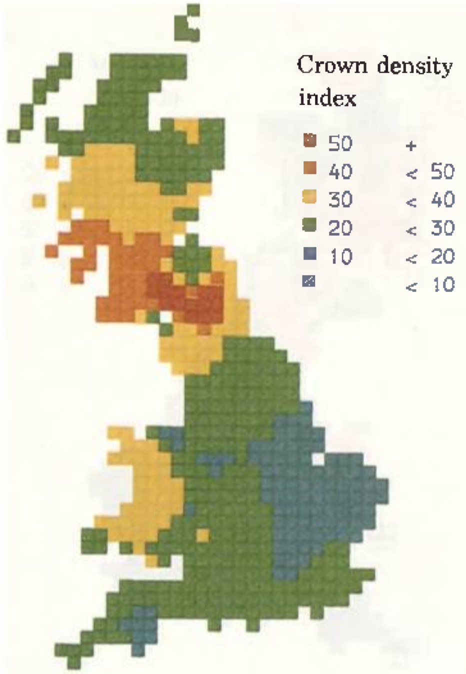


b. Overall discoloration

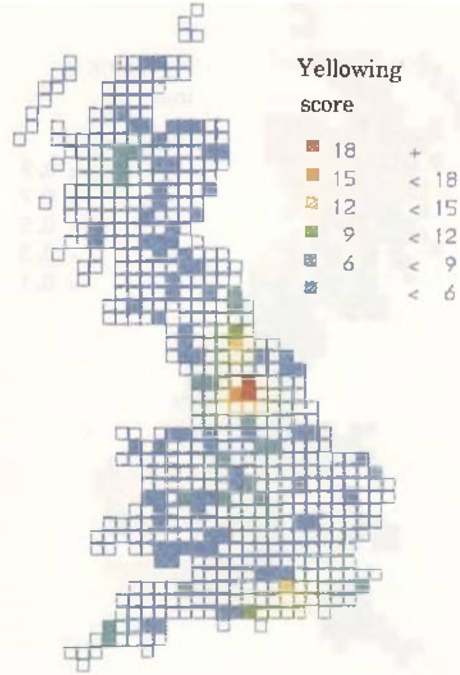


d. Number of trees at each site with less than 7 years' needle retention.

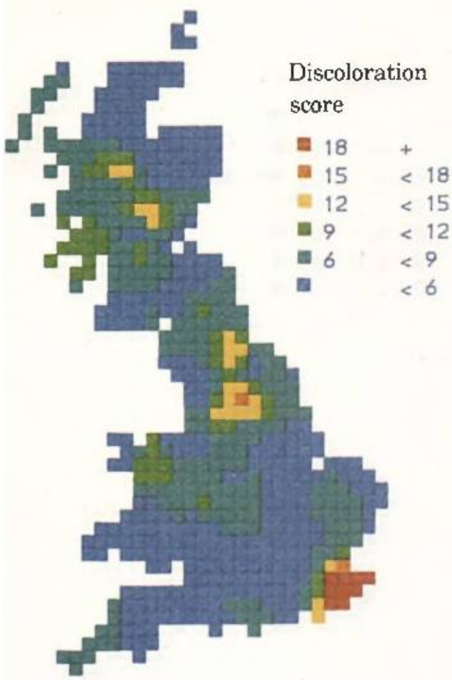
Figure 5. *Patterns of crown indices in Norway spruce in 1988.*



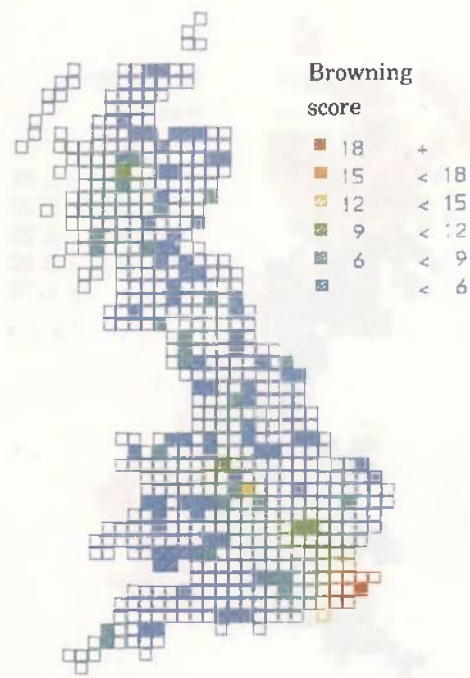
a. Crown density (N.B. high scores indicate thin crowns)



c. Yellowing of older needles

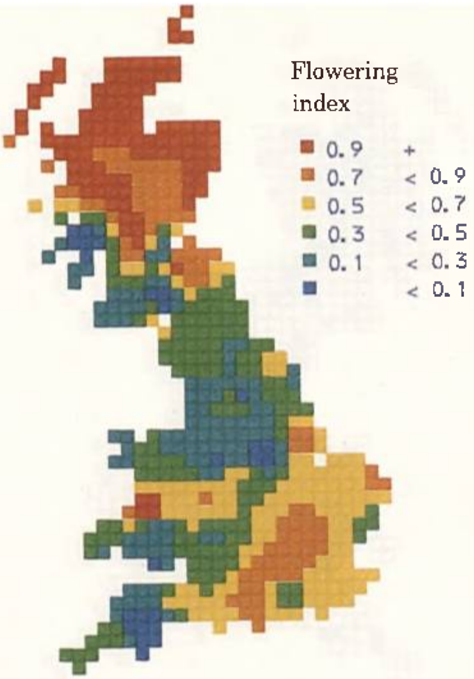


b. Overall discoloration

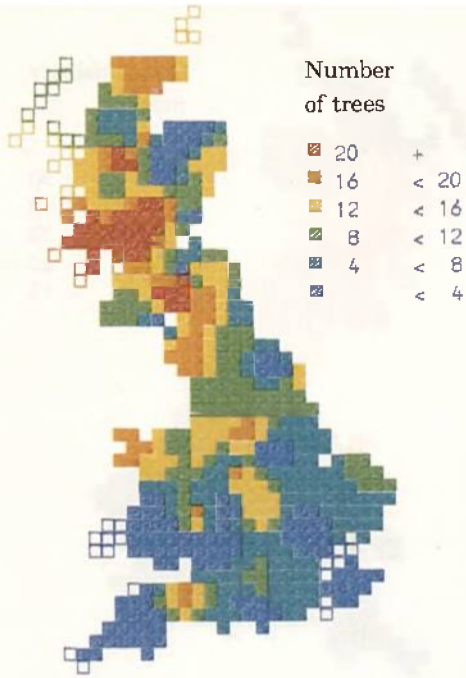


d. Browning of older needles

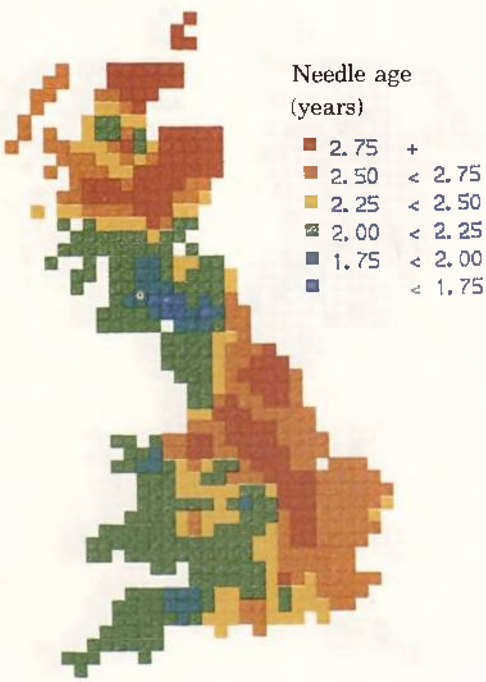
Figure 6. *Patterns of crown indices in Scots pine in 1988.*



e. Male flowering

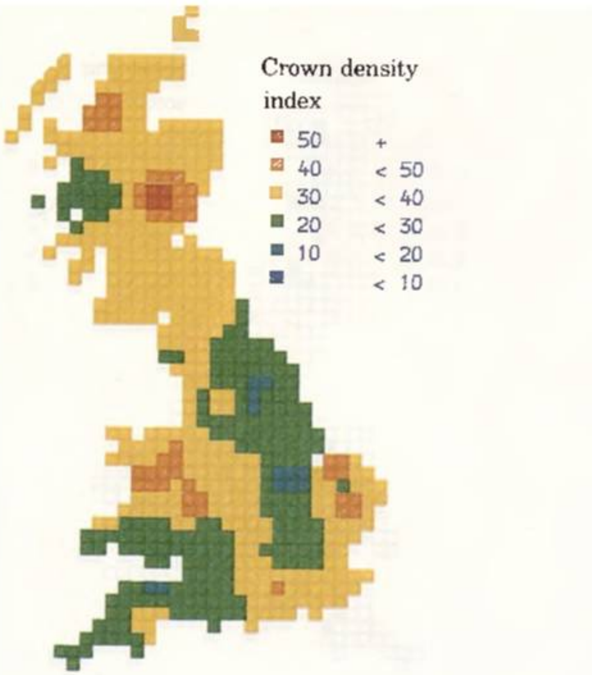


g. Number of trees at each site with shoot death in the live crown

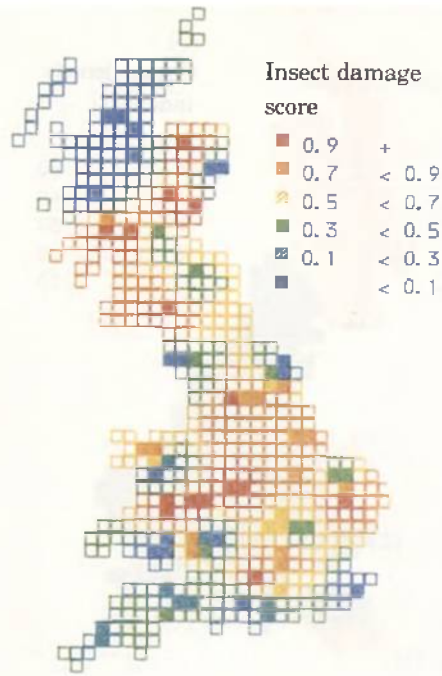


f. Needle retention

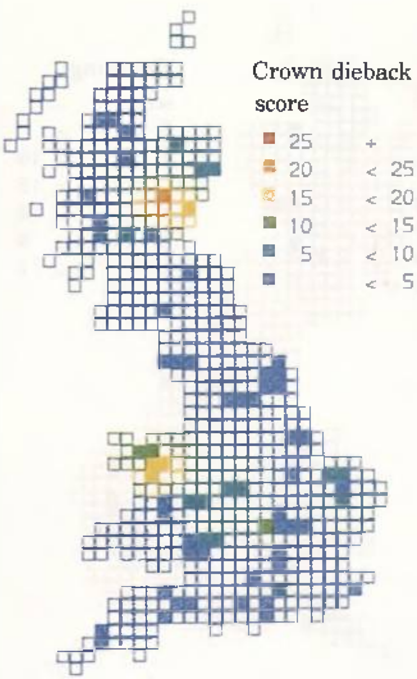
Figure 6 *(continued).*



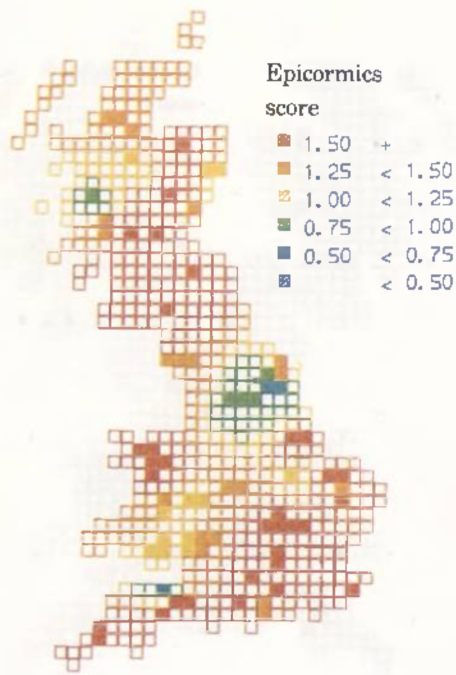
a. Crown density (N.B. high scores indicate thin crowns)



c. Insect damage

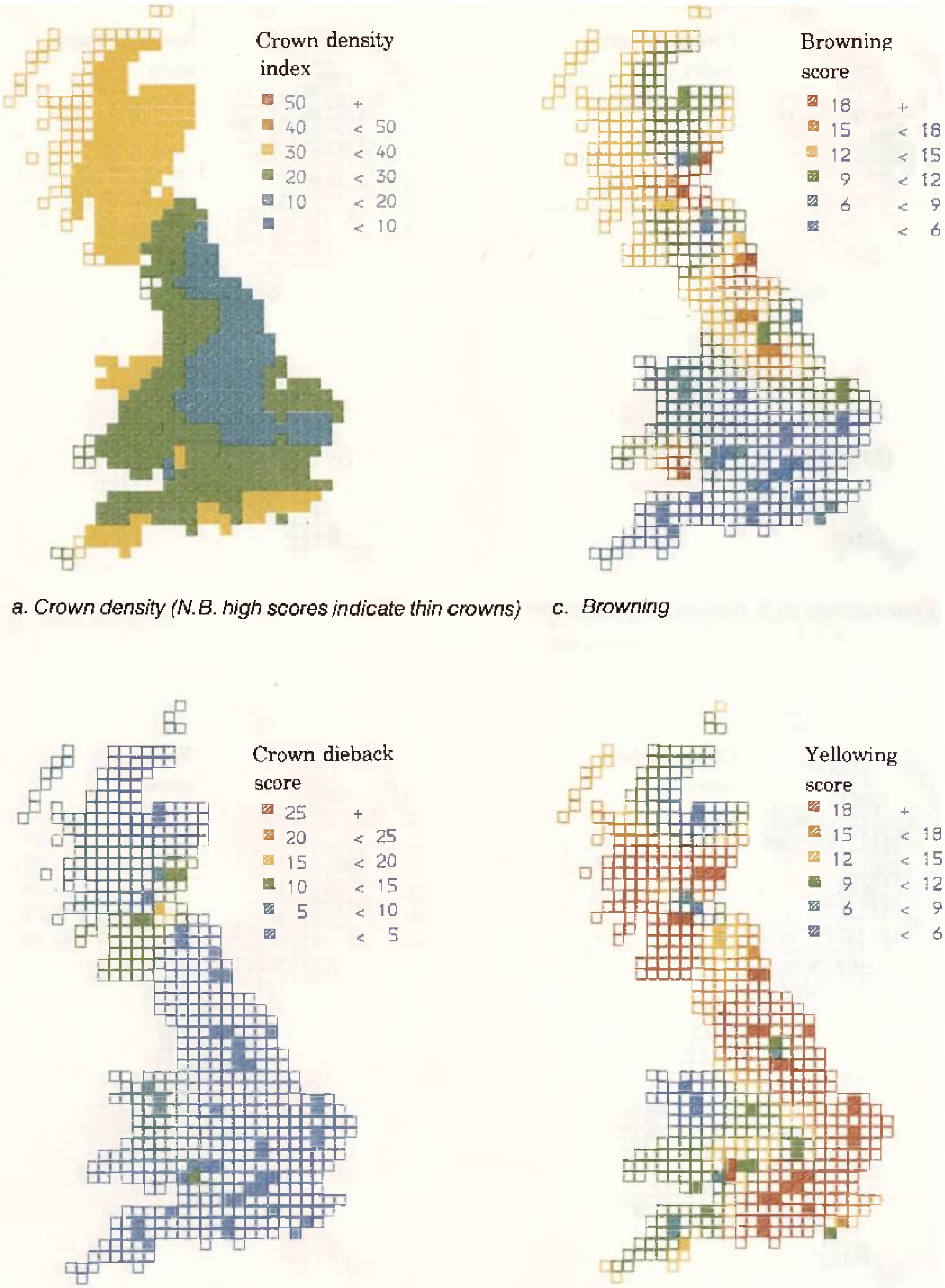


b. Dieback



d. Epicormics on branches

Figure 7. *Patterns of crown indices in oak in 1988.*



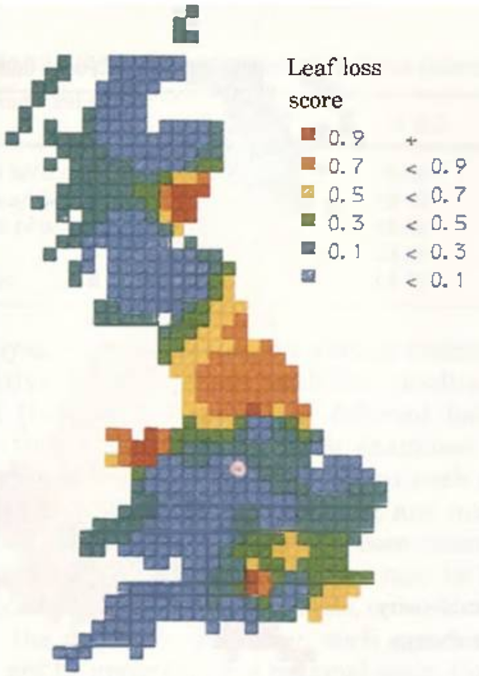
a. Crown density (N.B. high scores indicate thin crowns)

c. Browning

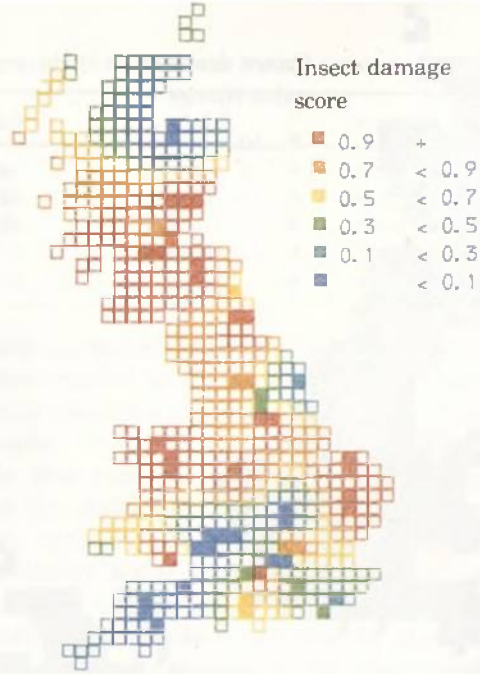
b. Dieback

d. Yellowing

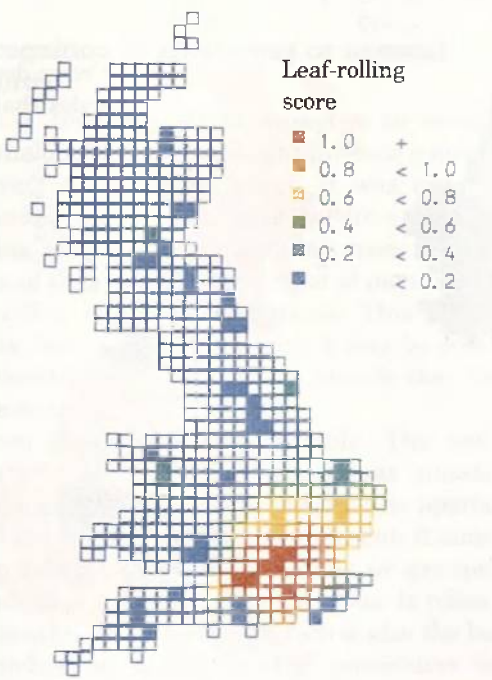
Figure 8. *Pattern of crown indices in beech in 1988.*



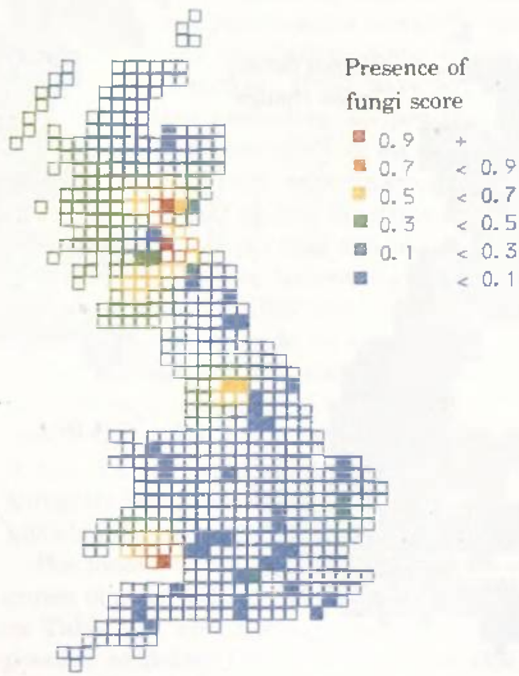
e. *Premature leaf loss*



g. *Insect damage*



f. *Frequency of leaf-rolling*



h. *Presence of fungi*

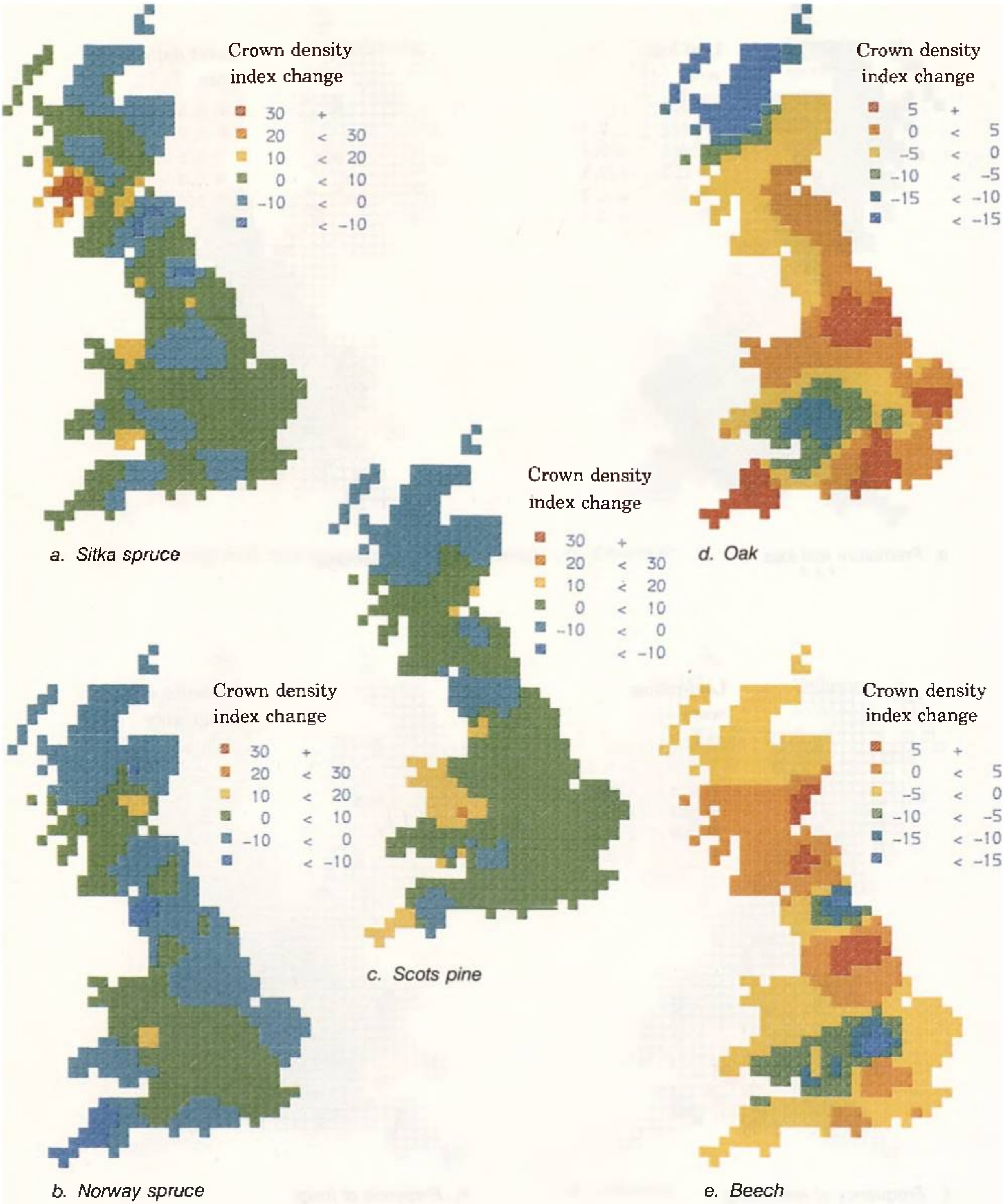


Figure 9. *Regional patterns in the changes in crown density indices between 1987 and 1988. A positive change indicates a reduction in the average crown density in a stand.*

Table 19. Upper and lower confidence limits (standard deviations) about the mean for the site crown density indices.

	−2 S.D.	*−1 S.D.*	*Mean*	*+1 S.D.*	*+2 S.D.*
Sitka spruce	10.94	19.45	27.96	36.47	44.98
Norway spruce	—	13.13	22.86	32.59	42.32
Scots pine	5.69	16.69	27.68	38.67	49.66
Oak	14.63	23.11	31.59	40.08	48.56
Beech	11.66	18.77	25.89	33.01	40.12

analysis. In most species, the various indices are relatively independent, with the implication that they are determined by different factors, and they therefore need to be examined and interpreted separately. This confirms work elsewhere in Europe where the extent and magnitude of particular symptoms have been examined in detail (FBW, 1986). While there may be local associations between, for example, crown density and the degree of yellowing, such associations will not be apparent on a national scale. Consequently, this approach has not been taken any further and the analyses reported in the ensuing sections treat each index separately.

Recognition of anomalous or unusual records

One of the aims of the project is to recognise anomalous stands that might indicate a direct or indirect air pollution effect. It was originally intended that this should be done by establishing whether or not Britain's trees were in a state of decline, with the period of measurement extending over about 10 years. This aim still exists, but in the shorter term it may be possible to identify either regions or stands that have unexpected values.

Two approaches are possible. The use of geostatistics to identify anomalous stands is examined in the following section. The approach used in this section is rather different: it aims at identifying either single stands or groups of stands that appear to be anomalous. It relies on the central limit theorem, which is also the basis for industrial quality control procedures (e.g. Aft, 1986). These procedures are not strictly applicable to the data as they are based on time series and the level of quality is strictly defined. For instance, a suitable control sample is normally compared with further samples. Times series related to crown density data are presently unavailable and there is no 'control' sample.

In this analysis, the working hypothesis is that the distribution of mean stand indices for each variable should be normally distributed. Probability levels for particular indices can be identified on statistical grounds and outliers identified. The outliers can then be examined in detail and an explanation for their condition sought. The approach has two drawbacks. Firstly, the correct mean for the distribution is unknown. A certain amount of crown thinness and discoloration would be expected under natural conditions, just as some mortality would be expected in any population. Some studies (e.g. Nilsson and Duinker, 1987) have argued that any defoliation exceeding 25 per cent is the result of the adverse effect of air pollution, but there are numerous experimental and field investigations that clearly illustrate that foliage loss in excess of 25 per cent can occur as a result of a range of natural factors (e.g. Carter, 1977; Bella and Navratil, 1987; Grier, 1988). Here, no attempt has been made to identify the correct mean. Instead, the statistics are based on the distributions obtained in 1988. Secondly, it is assumed that the relevant model for the indices is the normal distribution. This assumption is currently being examined and the use of other models is being explored.

The means and lower and upper limits of the crown density indices for each species are given in Table 19. For Norway spruce, it was not possible to define the lowest limit as this was below 5.0, the minimum index value for a stand. Eight (2.6 per cent) stands had mean crown density indices falling outside the upper 95 per cent limit. These consisted of one Sitka spruce, three Norway spruce, two Scots pine and two oak stands. All the spruce stands were relatively old and the trees in them could be expected to have lower than average crown densities. Severe defoliation by *Elatobium abietinum* had occurred in the Sitka spruce stand although it is unclear whether this was the only cause of the thin crowns. Of the Norway spruce stands, trees at one of the stands may well have been adversely affected by waterlogging whereas exposure was cited as a possible cause at the other two stands. The two Scots pine stands lie in an area where problems have been noted in the past. The trees show the type of damage that has been associated with a combination of disease or pest damage, mainly *Brunchorstia pinea* (P. Karsten) Höhnel (the pycnidial state of *Ascocalyx abietina* (Lagerberg) Schlaepfer-Bernard), *Lophodermium seditiosum* Minter *et al.* and *Tomicus piniperda* L.; Coleoptera, although again it is not possible to establish whether the damage by these agents is primary or secondary. No explanation for the poor condition of the two oak stands is available.

Spatial analysis of crown condition

Several techniques have recently become available for the analysis of the structural variation within spatially distributed data. Of these, the methods used to analyse spatial autocovariation within data sets seem to be particularly appropriate. Full details of the techniques used in this report are given in the Appendix.

In Sitka spruce, there is no evidence of any spatial dependence amongst the data. This suggests (but does not prove) that there is no factor operating on a regional scale that has significantly affected crown density. This does not preclude the possibility of factors affecting the trees on a local scale, nor does it rule out the possibility that there is a regional-level effect operating outside the area covered by the majority of the sample stands (see Figure 1).

This is not the case for Norway spruce. There is clear evidence of a spatial effect on crown density, which appears to be operating on a scale of about 80 km. Stands separated by distances of less than 80 km are more similar than stands separated by greater distances. The effect is more marked in a north–south direction than it is in an east–west direction.

Scots pine shows a marked degree of spatial dependence which is still present at the maximum sampling interval examined. This suggests that the variance is unstable over the range of sampling intervals used, which, in turn, suggests that there are substantial regional differences in the crown density of Scots pine. Over short distances, north–south variations are important but that over larger distances (*c.* 150 km), variation is greater in an east–west direction. This may indicate the role of more than one factor in determining the regional variation in crown density.

There is also evidence of a regional effect in oak. This occurs over distances separated by more than 200 km and does not appear to be primarily due to variation in either a north–south or east–west direction. Beech shows a similar trend to Scots pine. The effect appears to be largely due to differences in a north–south direction. In both oak and beech, any interpretation has to be made with care because of the small sample size.

Regional factors appear to be operating in the cases of Norway spruce and oak. There are several regions with similar levels of crown density separated by distances of more than 80 km in the case of Norway spruce and 200 km in the case of oak. Scots pine and beech behave differently, and regions with similar levels of crown density cannot be identified. The variation between Sitka spruce stands is structureless. These results suggest that in four of the five species, regionally-distributed factors may be affecting crown density. However, these factors are operating on different scales for each of the species, indicating that further, species-by-species, analysis is required before the relevant factor(s) can be identified.

The above analysis has dealt with the indices of crown density. For the construction of the maps presented in the following section, semi-variograms were constructed and models fitted for each of the other indices (see the Appendix for a full explanation of the construction and use of semi-variograms). In many cases, the semi-variograms showed no structure. This was particularly apparent in beech and oak, where none of the variables produced semi-variograms with a range or sill (see Figure A1). In those cases where some evidence of a trend was apparent, the spherical model was used to calculate the sill and range. The summary statistics and omnidirectional semi-variograms are presented in the Appendix. Considerable difficulty was experienced in interpreting these as the variance accounted for by many of the models is negligible. Consequently, they have only been used to calculate the range over which interpolation is feasible.

Patterns of crown condition

As last year, maps of the various indices of crown condition have been prepared (Figures 4 to 8). For each stand, the mean of a particular index is calculated. The means then form the basis for an interpolation procedure which calculates values for each 20 × 20 km square in Great Britain. The maps are for the same indices as last year although some new maps have been added. The omission of any particular index generally indicates that it is highly correlated with another index (see below) or that it shows very little variation across the country.

The reliability of these maps has been a major concern. By using an interpolation/extrapolation procedure, models have been generated that allocate values to each 20 by 20 km cell, regardless of whether-or-not there is a sample stand within the square. The aim is to provide a purely visual impression of spatial trends in particular indices; the modelled values have not been used in any of the subsequent analyses. The ranges calculated from the semi-variogram modelling have been used to identify those areas where the interpolations were invalid and these are shown on the maps as blank squares. The outline of each blank square has been drawn in the colour the square would have been had a full interpolation been undertaken.

The differences between the crown density indices derived for each stand in 1987 and in 1988 have also been mapped (Figure 9). These maps are intended to give a visual impression of the pattern of change only, and the data have not been subject to any form of geostatistical analysis. In Sitka spruce, a large change in one of the stands has resulted in an area of marked change in the south-west of Scotland. The combination of a reduction in crown density and increase in discoloration (caused exclusively by an increase in the extent of browning of older needles) suggested a severe attack by *E. abietinum* and this was confirmed at the time of assessment. Severe attacks by this insect were also noted further east and are probably responsible for the increase in discoloration in other stands in central Scotland. Elsewhere, the change in crown condition appears to be fairly uniformly distributed.

With Norway spruce, the majority of changes are less than ± 10 per cent and there appears to be no obvious spatial pattern, although decreases in crown density occur mainly in an area extending from Kent to north Wales and in mid-Scotland. A general reduction in overall discoloration occurred over much of England, with the exception of the south and south-west. Increases were noted in north Wales, the Lake District and over the whole of Scotland with the exception of the north-east. Increases in the extent of discoloration were most marked in the central valley of Scotland. As with Sitka spruce, the discoloration was mainly in the form of browning of older needles, suggesting attacks by *E. abietinum*.

With Scots pine, crown density improved in northern Scotland and northern England. Substantial reductions in density are primarily restricted to north and central Wales and one or two isolated stands elsewhere. A small reduction in crown density is apparent over much of the remainder of the country. Changes in total discoloration have mostly been fairly small.

In the two broadleaved species, total discoloration is not assessed and only the changes in crown density have been shown here. The crown density of oak appears to have improved in south Wales and the Forest of Dean and over much of Scotland. Thinning has occurred in the south and east of England. In beech, there has been a general improvement over much of the country, the exceptions being Yorkshire, south Scotland and mid-Scotland.

Environmental analysis

In 1987, a number of topographic and climatic variables, together with a variety of measures of pollution, were derived for each site. In 1988, considerably more data became available. These are described below.

Topographic data and derived climatic data

The topographic data used in 1987 were again used to derive estimates of quarterly climatic variables, using the model of White and Smith (1982). Full details of this procedure are given in Innes and Boswell (1988). The estimates give an approximate indication of the climatic conditions at each site, but do not take into account any recent anomalies or trends. A full list of the variables used in the analysis is given on the inside back-cover of this report.

Pollution data

Pollutant concentrations in rainfall were supplied by the Warren Spring Laboratory. Gaseous and airborne particulate concentrations, together with pollutant concentrations in rainfall, were obtained from the trajectory model developed by Dr R.G. Derwent and colleagues at the United Kingdom Atomic Energy Authority research establishment at Harwell (Derwent and Curtis, 1988; Derwent *et al.*, 1988; Metcalfe *et al.*, 1988).

Two years of rainfall concentration data are available from Warren Spring, covering the period January 1986 to December 1987. There is some evidence that the precipitation-weighted annual mean concentrations of the various pollutants vary from year to year. However, this variation appears to be either less than or equal to the variation attributable to other factors such as measurement and modelling. For this study, the precipitation-weighted mean annual concentrations for 1987 have been used.

Total deposition of particular ions is more difficult to estimate. The figures used in the analysis of the 1987 data (Innes and Boswell, 1988) were based on the 1986 concentration multiplied by the 1941–1970 mean annual rainfall. The biological significance of the total deposition in an individual year is probably less

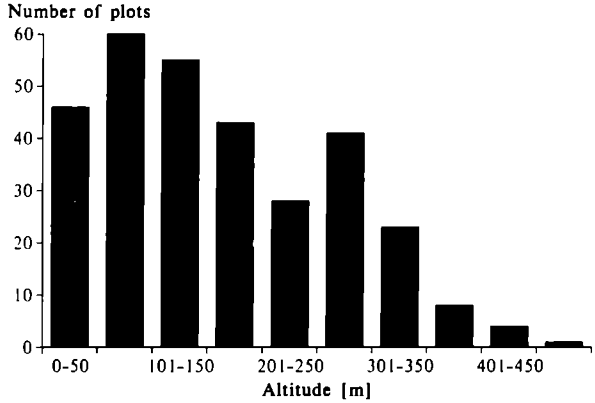


Figure 10. *Altitudinal distribution of plots used in the assessment programme.*

than the total deposition averaged over a number of years. The pattern of pollutant emissions has changed over the last decade, with the result that any long-term estimates of pollutant deposition based on 1986–87 concentrations multiplied by long-term rainfall figures are also likely to be inaccurate. In the absence of other information, the 1987 deposition data have been used as an indication of the long-term deposition values for each site. The pollution indices used in the analysis are listed on the inside back cover of this report.

There has been concern over the underestimation of the pollutant load at higher altitudes (Rodda *et al.*, 1985; Rodda and Smith, 1986). Pollutant concentrations in rainfall increase with altitude (Fowler *et al.*, 1988) although this phenomenon is by no means ubiquitous, with lower concentrations being recorded at higher altitudes in some areas (Duncan *et al.*, 1986; Puxbaum *et al.*, 1988). These discrepancies are probably the result of local factors. Occult deposition, involving the impaction of cloud particles on surfaces such as conifer needles, may add a further, highly significant, contribution to the total pollutant load (Lovett *et al.*, 1982). Both these processes have been recognised, but there is insufficient information on them to permit the weighting of the Warren Spring concentration data by altitude.

Some indication of the potential bias in the accuracy of the deposition estimates can be gained from examining the altitudinal distribution of stands (Figure 10). All stands lie below

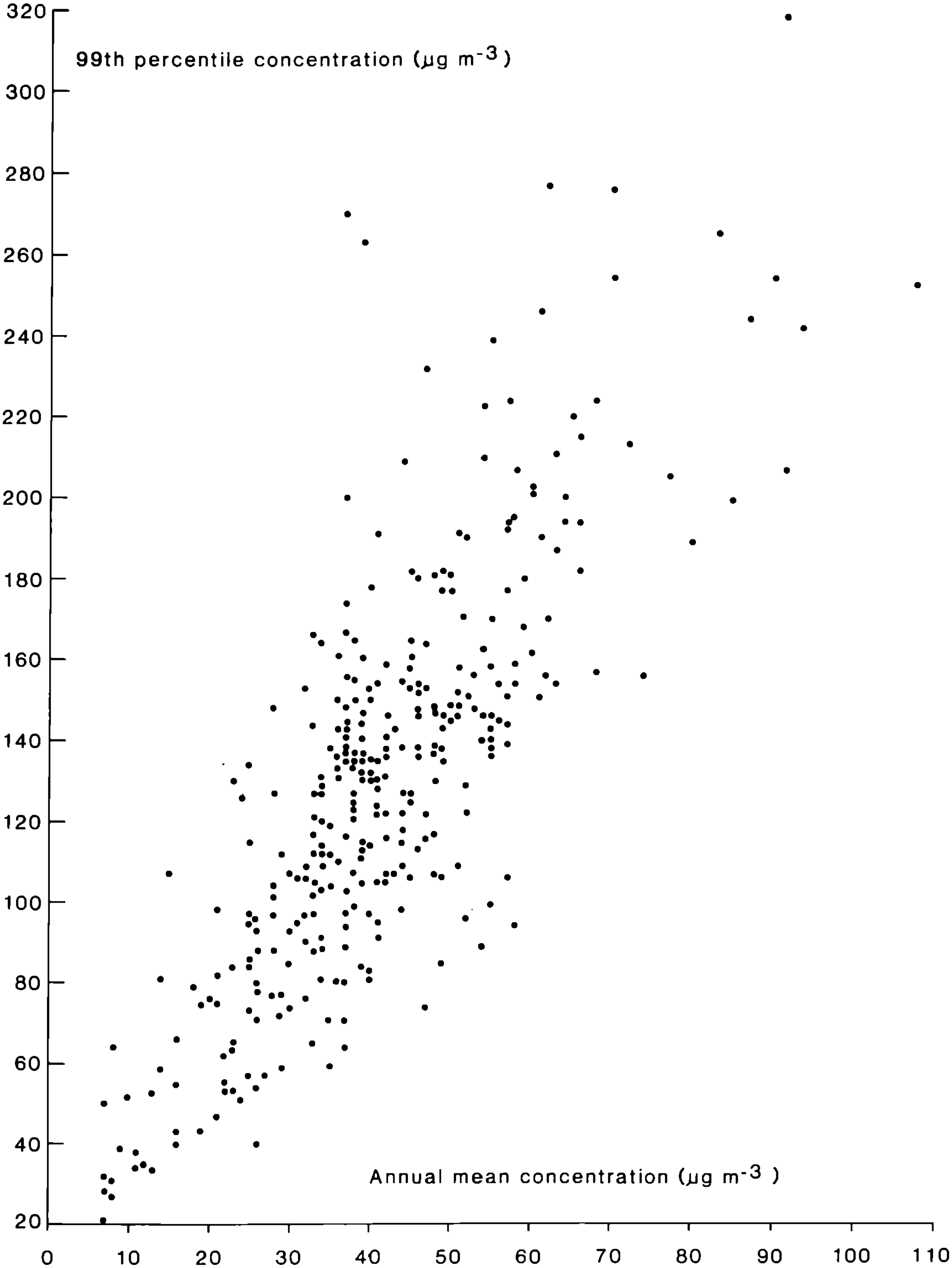


Figure 11. *Relationship between annual mean concentration of sulphur dioxide and the 99th percentile concentration. Data from WSL (1988).*

500 m above sea level and only 12 per cent lie between 300 m and 500 m. These altitudes are below those where significant increases in pollutant concentrations were recorded at Great Dun Fell (Fowler *et al.*, 1988). However, the results from Great Dun Fell are site-specific and enrichment of pollutant concentrations in rainfall may occur at lower altitudes in areas where the cloud base tends to be lower.

Emphasis has been placed here on the use of mean pollutant concentrations. This is the information that is generally available from the Warren Spring Laboratory and from Harwell Laboratory. However, extreme values may be of greater biological significance. To a certain extent, the mean values of some of the pollutants provide a good indication of the peak values. An example is given in Figure 11 where the relationship between the annual mean concentration of sulphur dioxide at the predominantly urban measuring sites throughout Britain and the 99th percentile concentration is shown. The data used refer to the period April 1986–March 1987 (Warren Spring Laboratory, 1988). While a general relationship exists, for any given mean there is a wide range of 99th percentiles, suggesting that the value of the mean for predicting extreme values is limited.

Ozone shows marked diurnal variations in concentration and is extremely difficult to characterise, despite a number of attempts to produce an appropriate methodology. Only very limited data are available for ozone concentrations in the United Kingdom, although annual mean concentrations have been modelled for the whole of the country. The biological relevance of these long-term values remains uncertain. In the United States, there has been much work on the characterisation of biologically-meaningful ozone concentrations. However, there appears to be some disagreement over the optimal index (e.g. Heck *et al.*, 1984; Lee *et al.*, 1988; Lefohn and Mohnen, 1984; Lefohn *et al.*, 1988; Musselmann *et al.*, 1988; Rawlings *et al.*, 1988). Difficulties also exist over the characterisation of other gases (Hauck and Kolb, 1988) and rainfall acidity (Cape and Fowler, 1986; Irwin, 1985).

Information on the number of instances of hourly average ozone concentrations exceeding 60 parts per hundred million during the summer (April–September) of 1987 were made available after the main analysis had been completed (Bower, personal communication). The highest number of exceedances occurred in Kent and east Sussex, a pattern that was repeated in the summer of 1988. A second area with a high number of exceedances extended from Lancashire to Leicestershire. An inspection of the maps in Figures 4 to 8 does not suggest an immediate link between high ozone concentrations and any of the crown indices, with the possible exception of total discoloration in Scots pine.

The above discussion has been restricted to single pollutants, although pollutants are known to act in combination and synergistic effects may be particularly important. To take this into account, hourly concentration data would be needed as peak concentrations of different pollutants may occur at different times, on different days or in different seasons (e.g. Martin and Barber, 1981). The development of databases for pollutant concentrations may facilitate the evaluation of combined pollutant loadings in future, as techniques for doing this are already available (e.g. van der Eerden and Duym, 1988).

To summarise, the pollutant values used in this study are the best available. However, the fact remains that they are estimates and they may not necessarily be a particularly good indicator of the actual pollution dose received by individual trees at each site.

Soils data

In 1988, soils were sampled at the majority (262) of sites. At each site, trees are normally located in four groups of six, frequently at opposite sides of a stand. Soil was sampled from pits dug at the centre of each group of trees. Samples were taken at 10 cm and 40 cm depth. For analysis, the four samples from each sub-plot were bulked, giving two bulked samples (one for each depth) for each site. The aim of this work was to obtain basic information on the soil conditions at each site. As such, it should be regarded as a pilot survey: much more detailed sampling would be required to determine the precise physical and chemical status of the soil at each site.

A list of the soil variables used in the analysis is given in the inside back-cover of the report. A description of the techniques used to derive the variables, together with a more detailed analysis of them, will be presented elsewhere.

Correlation analysis

The presence of a high degree of multicollinearity in the data (Innes and Boswell, 1988) makes any interpretation of the statistical analysis difficult. The value of techniques such as multiple regression is severely limited when the explanatory variables are inter-correlated and, consequently, the statistical analysis of the 1988 data has been restricted to correlation analysis. The aim is to identify possible relationships between the indices of crown condition and environmental variables. Because of the multicollinearity, the presence of a significant correlation does not necessarily imply a causal relationship.

A second problem with this approach is that different processes may lead to the same end result (equifinality). It is likely that a crown index, such as crown density, is affected by a number of environmental variables. A significant relationship will only occur between any one variable and the index if the variables affecting an index are spatially correlated. It is possible that this problem could be resolved by using multivariate statistical techniques and this is currently being investigated. A related problem is that the response of a tree index to an environmental variable may be non-linear. For example, both extremely acidic and extremely basic soils will not only adversely affect most trees but do so to a different extent between species.

The results cannot be presented in the same way as in 1987 because of the large number of variables that are now involved. Instead, each of the tree indices has been taken and the environmental variables that appear to influence it have been examined. The large number of potential correlations inevitably means that some significant correlations may occur by chance. In addition, there is the possibility that spurious correlations may be obtained because of the presence of a small number of extreme values. To minimise these problems, only correlations significant at $p < 0.001$ have been discussed. For each relationship significant at this level, a scattergram was prepared in order to enable a decision to be reached as to the validity of the correlation. The scattergrams have been not presented here but are available from the authors on request. In each of the tables presented below, correlations significant at $p < 0.05$, $p < 0.01$ and $p < 0.001$ have been presented. The tables enable possible associations to be identified, with a minimum risk of a Type II error being made (failing to identify a significant relationship). However, there is an associated high risk of making a Type I error (identifying a spurious relationship as significant) and the tables should be interpreted with care.

Sitka spruce

Crown density

As in 1987, crown density was apparently independent of the environmental variables examined (Table 20a). Age affected crown density significantly, as already reported. There is a considerable amount of scatter amongst the data and the scattergram suggests that the relationship may be non-linear. The absence of a relationship with any of the environmental variables confirms the results of the geostatistical analysis; there is no readily discernible pattern in the crown density of Sitka spruce in Great Britain.

Browning of current needles

A small number of correlations were identified (Table 20b), but none of these was significant at $p < 0.001$.

Browning of older needles

There appears to be a relationship between the degree of browning in older needles and the soil conditions within a stand (Table 20c). Conductivity, pH and buffering capacity were all positively correlated with the extent of browning. However, the scattergrams indicate that the

Table 20a. Significant correlations between the crown density index of Sitka spruce and the environmental variables. High index values indicate low densities, therefore a positive correlation indicates lower densities with increased values of the environmental variable.
In this and subsequent similar tables, the significance levels are indicated as follows: p <0.05 — italics, p <0.01 — normal type, p <0.001 — bold.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
				dfse	0.326	age	**0.503**

Table 20b. Significant correlations between browning of current needles of Sitka spruce and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HHCl	*0.286*	WSH	*0.299*				
HpHCl	*0.257*						
HCldry	*0.298*						
HCltot	*0.278*						

Table 20c. Significant correlations between browning of older needles of Sitka spruce and environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HNOwet	*−0.281*					Age	*−0.268*
						ApH	**0.619**
						Acond	**0.639**
						ABufc	**0.625**
						Apcwat	0.365
						BpH	**0.554**
						Bcond	**0.536**
						BBufc	**0.607**
						Bpcwat	*0.327*
						Bpcorg	*0.276*
						Bcat	0.351

Table 20d. Significant correlations between yellowing of current needles of Sitka spruce and environmental variables. No significant correlations were identified for yellowing of older needles.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HNH3	*0.245*						

correlations are the result of a single extreme value and they can therefore be discounted.

Browning of older needles in Sitka spruce is believed to be primarily due to *E. abietinum* and the link with soil conditions must therefore be indirect. One possibility is that Sitka spruce is better suited to base-poor soils and that relatively high quantities of bases result in reduced vigour, thereby encouraging insect infestation. There is no evidence of a relationship between browning and climatic conditions although it is well-known that the frequency of *E. abietinum* outbreaks can be related to mild winters (Carter 1972, 1977).

Table 20e. Significant correlations between overall discoloration of Sitka spruce and environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HHNO3	*−0.247*			JSrain	*0.264*	ApH	**0.598**
HNO3	*−0.288*					Acond	**0.621**
HNH4	*−0.283*					ABufc	**0.618**
HCl	*−0.249*					Apcwat	0.370
HpNO3	*−0.283*					BpH	**0.536**
HpNH4	*−0.269*					Bcond	**0.521**
HNOwet	−0.337					BBufc	**0.598**
HNOtot	*−0.297*					Bpcwat	*0.301*
HNHwet	*−0.294*					Bcat	*0.331*
HNHtot	*−0.281*						
HSOwet	*−0.272*						

Table 20f. Significant correlations between the number of Sitka spruce with less than 7 years' needle retention at each site and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HNH3	0.358	WSNH4	*0.275*	dfs	−0.346	AMgCa	*−0.296*
HNO3	*0.273*	WSH	−0.361	hor	*0.245*		
HNH4	0.352	WSNH4d	*0.270*	dfsw	−0.366		
HpNO3	*0.266*	WSHd	*−0.318*	dfse	**0.688**		
HpNH4	**0.408**			hew	**−0.478**		
HNOwet	0.352			JMairt	**0.409**		
HNOtot	*0.268*			AJairt	**0.399**		
HNHdry	**0.468**			JSairt	0.397		
HNHwet	**0.533**			ODairt	**0.525**		
HNHtot	**0.554**						
HSOwet	*0.311*						

Table 20g. Significant correlations between the number of Sitka spruce with shoot death in the live crown at each site and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HNO	*0.314*	WSnmSO4	0.328	hee	*−0.245*	Age	**0.559**
HHO2	*0.306*	WSNO3	0.338	rug	*−0.268*	Apcwat	*−0.290*
HHNO3	*0.314*	WSNH4	0.364	JMrain	−0.373		
HO3	*−0.306*	WSTSO4	*0.286*	AJairt	*0.261*		
HSO2	*0.301*	WSHd	*−0.305*	AJrain	−0.365		
HNO3	0.336			JSairt	*0.261*		
HNH4	0.334			JSrain	*−0.317*		
HSO4	*0.273*			ODrain	−0.339		
HCl	*0.287*						
HpNO3	0.334						
HpNH4	0.348						
HpSO4	*0.305*						
HNOdry	*0.316*						
HNOtot	*0.316*						
HNHdry	0.347						
HNHtot	*0.281*						
HSOdry	*0.304*						
HSOwet	*0.278*						
HSOtot	*0.314*						

Yellowing of needles

Neither yellowing of current nor yellowing of older needles appears to be strongly affected by any of the environmental parameters examined. The single correlation obtained ($p < 0.05$, between current needle yellowing and *HNH3*) was very weak and has been discounted.

Overall discoloration

The overall discoloration in Sitka spruce is primarily determined by the amount of browning in older needles ($r = 0.909$). Consequently, Table 20e shows many similarities with the correlation table for browning in older needles and individual scattergrams have not been reproduced.

Needle retention

Needle retention showed a marked spatial trend, with the proportion of trees with less than 7 years' retention generally being higher in Wales and the south-west of England than elsewhere in the country. A number of highly significant correlations are present (Table 20f). However, the relationship between needle retention and the various pollution indices is not particularly clear-cut. The relationships with *dfse* and *hew* reflect the overall pattern of better retention in the north and east of the country and appear to be genuine relationships. The relationships with air temperature are difficult to interpret, but there is some indication of higher retention in cooler areas.

Shoot death in the live crown

Although a number of correlations were identified (Table 20g), only one of these (with age) was highly significant. The scattergram suggests that this is a real relationship, with the number of trees with shoot death increasing significantly with stand age. This is consistent with other studies (e.g. Westman and Lesinski, 1986).

Norway spruce

Crown density

While many of the environmental variables are significantly correlated with crown density (Table 21a), only age is highly correlated. The correlations were all much higher than in 1987. The reasons for this are unclear: it may be the result of the improved coverage of Norway spruce in Britain or the refinements that have been made to the pollution models over the past year. Denser crowns were found in areas with higher levels of most pollutants. There is no correlation between crown density and the climatic variables, suggesting that any confounding influence of a relationship between climate and pollution is not readily apparent in the results.

Browning of current needles

Although browning of current needles of Norway spruce was relatively rare in 1988, some was recorded. The distribution was correlated with a number of environmental variables (Table 21b), although only one of these (with *WSH*) was highly significant. This relationship appears to be the result of two or three stands with relatively high levels of browning and high hydrogen ion concentration values. When these are removed, no relationship is apparent.

Browning of older needles

Browning of older needles is believed to be largely attributable to the effects of *E. abietinum*. The only highly significant correlation that was identified was with *WSHd* (Table 21c). The scattergram of this relationship suggests that high levels of browning were associated with high levels of hydrogen ion deposition, but there is no indication of a linear relationship between the two variables. As the levels of hydrogen ion deposition currently experienced in Great Britain are believed to be insufficient to cause direct foliar damage, any causal relationship must be indirect.

Yellowing of current needles

Several variables appear to affect the extent of yellowing in current needles of Norway spruce (Table 21d). The correlation analysis indicates that yellowing increases with tree age and with soil organic matter and moisture capacity. The relationship with age appears to be the result of

Table 21a. Significant correlations between crown density index of Norway spruce and the environmental variables. A positive correlation indicates that crown density decreases with increasing values of the environmental variable.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HNO	−0.310	WSnmSO4	*−0.276*	slos	0.299	Age	**0.718**
HNO2	−0.292	WSNO3	*−0.281*			Bpcwat	*0.262*
HHNO3	*−0.268*	WSNH4	*−0.236*				
HO3	0.292	WSH	*−0.236*				
HSO2	*−0.287*	WSTSO4	−0.293				
HHCl	*−0.242*	WSNO3d	*−0.229*				
HNO3	*−0.257*						
HNH4	*−0.263*						
HCl	*−0.245*						
HpNO3	*−0.258*						
HpNH4	*−0.287*						
HpSO4	*−0.286*						
HpHCl	*−0.251*						
HNOdry	*−0.280*						
HNOtot	*−0.230*						
HNHdry	−0.296						
HSOdry	−0.305						
HSOtot	−0.296						
HClwet	*−0.262*						
HCltot	*−0.233*						

Table 21b. Significant correlations between browning of current needles of Norway spruce and environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HNO2	*0.260*	WSnmSO4	0.308	slow	0.317	AMgCa	0.335
HHNO3	*0.240*	WSNO3	0.292	AJrain	*−0.240*	BMgCa	0.317
HO3	*−0.260*	WSH	**0.402**	JSairt	0.316		
HSO2	*0.260*	WSTSO4	0.317				
HHCl	0.334	WSHd	*0.228*				
HCl	*0.289*						
HpSO4	*0.246*						
HpHCl	0.333						
HNOdry	*0.248*						
HSOdry	*0.236*						
HCldry	*0.287*						
HClwet	*0.247*						
HCltot	*0.280*						

Table 21c. Significant correlations between browning of older needles of Norway spruce and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
		WSnmSO4d	0.295	rug	*0.255*	Apcwat	*0.254*
		WSNO3d	0.299				
		WSHd	**0.388**				
		WSTSO4d	*0.257*				

Table 21d. Significant correlations between yellowing of current needles of Norway spruce and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HNH3	*−0.239*	WSNO3	*−0.233*	hee	*0.278*	Age	**0.412**
HNHdry	*−0.271*	WSNH4	*−0.236*			Apcwat	0.342
						Apcorg	**0.490**
						Acat	*−0.247*
						Bpcwat	**0.525**
						Bpcorg	**0.605**
						Bcat	*−0.261*

Table 21e. Significant correlations between yellowing of older needles of Norway spruce and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
		WSNO3d	*−0.231*			Age	**0.385**
						Apcwat	*0.258*
						Apcorg	**0.440**
						Acat	−0.356
						Bpcwat	**0.453**
						Bpcorg	**0.640**
						Bcat	*−0.274*

a single anomalous value and can therefore be discounted. The relationships with the soil variables also appear to be determined by a single extreme value and probably can be discounted.

Yellowing of older needles

The correlations between yellowing of older needles and the environmental variables show a similar pattern to current needles (Table 21e). Stand age again appears to be important, but can be attributed to a single anomalous value. The correlations with the soil parameters are clearly the result of a single extreme value and can be discounted.

Total discoloration

As with Sitka spruce, total discoloration in 1988 was primarily determined by the extent of browning of older needles (r = 0.938). Consequently, the correlation table (Table 21f) shows many similarities to that for browning of older needles. Although a number of significant correlations were identified, none was significant at $p<0.001$.

Needle retention

The number of trees with less than 7 years' needle retention at each site showed a similar pattern to Sitka spruce, with the highest numbers of trees in Wales and the south-west. However, there were also isolated stands elsewhere where retention was poor. A number of correlations were obtained (Table 21g). The relationship with *HNHwet* appears to be attributable to a number of stands with high needle retention and low rainfall concentrations of ammonium. It does not appear to be a real relationship. The relationship with *WSH* is better, and it seems that there is a real association between high hydrogen ion concentrations in rainfall and low needle retention. Although a highly significant correlation was also found for rates of hydrogen ion deposition, the scattergram does not reveal any clear tendency. The relationship with distance from the east coast reflects the low needle retention figures for Wales and the south-west, as does the relationship with *hew*. Neither of these are considered to be causal relationships.

Table 21f. Significant correlations between overall discoloration in Norway spruce and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HNO	*−0.258*	WSNH4	−0.299	slow	*0.272*	Apcwat	0.353
HNO2	*−0.241*	WSnmSO4d	*0.240*	hee	0.291	Bpcwat	*0.240*
HHNO3	*−0.283*	WSNO3d	*0.226*	rug	0.326		
HO3	*0.241*	WSHd	0.356	JMrain	0.320		
HSO2	*−0.250*	WSTSO4d	*0.224*	AJrain	*0.251*		
HNO3	−0.321			JSrain	0.329		
HNH4	−0.337			ODrain	0.302		
HSO4	*−0.246*						
HCl	*−0.258*						
HpNO3	−0.317						
HpNH4	−0.337						
HpSO4	*−0.273*						
HNOdry	*−0.270*						
HNOwet	*−0.231*						
HNOtot	−0.299						
HNHdry	−0.329						
HNHwet	*−0.258*						
HNHtot	−0.298						
HSOwet	*−0.238*						

Table 21g. Significant correlations between the number of Norway spruce trees with less than 7 years' needle retention at each site and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HHCl	*−0.243*	WSH	**−0.502**	dfsw	−0.358	Age	0.356
HNOwet	*0.271*	WSNH4d	*0.239*	dfse	**0.544**		
HNHwet	**0.377**	WSHd	−0.337	hew	**−0.395**		
HNHtot	0.347			JMairt	*0.276*		
HCldry	*−0.267*			ODairt	0.354		
HCltot	*−0.241*			ODrain	*0.251*		

Table 21h. Significant correlations between the number of Norway spruce trees at each site with shoot death in the live crown and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HNH3	**−0.371**			rug	*0.237*	Age	**0.669**
HNHdry	−0.308					Bpcwat	*0.262*
HSOdry	*−0.243*						

Shoot death

Only a small number of correlations were identified for shoot death in the live crown (Table 21h). The relationship with *HNH3* is unclear and may be fortuitous. The relationship with stand age shows a clear tendency for increasing numbers of trees with shoot death in older stands.

Scots pine

Crown density

As in 1987, the crown density of Scots pine appears to be correlated with a large number of environmental variables (Table 22a). A major problem exists in the interpretation of these correlations as a result of the two stands with

Table 22a. Significant correlations between crown density index of Scots pine and the environmental variables. A positive correlation indicates that crown density decreases with increasing values of the environmental variable.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HNO	−**0.369**	WSnmSO4	−**0.368**	elev	0.348	Apcwat	0.358
HNO2	−**0.368**	WSNO3	−**0.389**	slope	0.313	Apcorg	**0.406**
HHNO3	−**0.417**	WSNH4	−**0.412**	dfsw	−0.340	Acat	0.341
HO3	**0.368**	WSTSO4	−**0.390**	hee	0.299	ANcont	*0.278*
HNH3	*0.274*	WSHd	0.307	rug	0.324	Bpcwat	0.339
HSO2	−0.357			JMairt	−0.331		
HHCl	*−0.257*			JMrain	**0.445**		
HNO3	−**0.453**			AJairt	−**0.448**		
HNH4	−**0.399**			AJrain	**0.444**		
HCl	−**0.411**			JSairt	−0.346		
HpNO3	−**0.450**			JSrain	**0.517**		
HpNH4	−**0.398**			ODairt	−**0.392**		
HpSO4	−**0.384**			ODrain	**0.427**		
HpHCl	−0.307						
HNOdry	−**0.405**						
HNOtot	−**0.365**						
HSOdry	−0.315						
HSOtot	−0.298						
HCldry	*−0.228*						
HClwet	*−0.255*						
HCltot	*−0.239*						

Table 22b. Significant correlations between browning of current needles of Scots pine and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
		WSnmSO4d	0.293	slos	*−0.254*	ANcont	0.332
		WSHd	0.289	rug	*0.231*		
		WSTSO4d	0.311	JSairt	*−0.222*		
				ODairt	*−0.222*		

very low crown densities in the Southern Uplands of Scotland. However, it would be inappropriate to remove these from the analyses as there is some uncertainty as to why these stands have been so badly affected by insects and fungal pathogens.

HNO, HNO2, HNHO3, HNO3, HNH4, HCl, HpNO3, HpNH4, HpSO4, HNOdry, and *HNOtot* all appear to show a genuine relationship. However, there is no means of telling whether these are direct relationships or whether some other factor(s), correlated with both crown density and the pollution variables is important. The values for *WSnmSO4, WSNO3, WSNH4* and *WSTSO4* from Warren Spring show similar patterns to the variables from Harwell. In all cases, these relationships indicate that crown density is higher in areas with higher levels of the relevant type of pollution. An exception to the pattern is the relationship between crown density and the estimates of long-term average ozone concentrations from Harwell, which shows a decrease in crown density with increasing levels of ozone.

Crown density is also correlated with a number of climatic indices. These relationships suggest that crown density is higher in areas with warmer temperatures and lower rainfall. As these are also the areas where the levels of the pollutants examined in this report tend to be higher, the potential for an interaction is clear. Only one soil variable was highly correlated

Table 22c. Significant correlations between browning of older needles of Scots pine and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HNO	*0.270*			dfsw	*0.243*		
HNO2	*0.275*						
HHNO3	*0.235*						
HO3	*−0.275*						
HSO2	*0.239*						
HNO3	*0.239*						
HNH4	*0.229*						
HpNO3	*0.239*						
HpNH4	*0.252*						
HpSO4	*0.240*						
HNOdry	*0.257*						
HNOwet	*0.238*						
HNOtot	*0.285*						
HSOdry	*0.239*						
HSOwet	*0.263*						
HSOtot	*0.253*						

Table 22d. Significant correlations between yellowing of current needles of Scots pine and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
				dfs	*0.263*	Apcorg	*0.301*
						Acat	0.341

Table 22e. Significant correlations between yellowing of older needles of Scots pine and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HNO	0.323	WSnmSO4	*0.238*	*dfs*	*0.245*		
HNO2	0.293	WSNO3	*0.224*				
HHNO3	*0.244*	WSH	*0.277*				
HO3	−0.293	WSTSO4	*0.271*				
HSO2	*0.268*						
HHCl	*0.277*						
HCl	*0.222*						
HpSO4	*0.265*						
HpHCl	*0.271*						
HNOdry	*0.265*						
HNOtot	*0.225*						
HSOdry	*0.280*						
HSOtot	*0.275*						
HCldry	*0.273*						
HClwet	*0.248*						
HCltot	*0.270*						

Table 22f. Significant correlations between overall discoloration of Scots pine and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
		WSH	*0.229*				
		WSHd	*0.249*				

Table 22g. Significant correlations between the extent of male flowering in Scots pine and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HNO	**−0.382**	WSnmSO4	−0.289	slow	*−0.251*	ApH	0.342
HNO2	−0.350	WSNO3	*−0.263*	hew	**0.379**	AMgCa	*0.247*
HHNO3	−0.328	WSNH4	−0.349	JSairt	−0.335		
HO3	0.350	WSTSO4	*−0.285*				
HSO2	**−0.370**	WSnmSO4d	**−0.558**				
HHCl	−0.331	WSNO3d	**−0.587**				
HNO3	*−0.274*	WSNH4d	**−0.587**				
HNH4	−0.341	WSHd	−0.298				
HCl	−0.316	WSTSO4d	**−0.544**				
HpNO3	*−0.281*						
HpNH4	−0.361						
HpSO4	−0.359						
HpHCl	−0.337						
HNOdry	−0.338						
HNOtot	−0.326						
HNHdry	−0.311						
HNHwet	−0.320						
HNHtot	−0.347						
HSOdry	**−0.393**						
HSOwet	**−0.363**						
HSOtot	**−0.403**						
HCldry	−0.316						
HClwet	**−0.380**						
HCltot	**−0.339**						

with crown density: percentage organic matter at 10 cm. Although there is a large amount of scatter, this relationship may be genuine. It is not clear whether this is a direct relationship or whether a third factor is involved.

Browning of needles

Although a number of correlations were identified (Tables 22b and 22c), none of these was highly significant.

Yellowing of needles

Several correlations were identified (Tables 22d and 22e), but none was highly significant.

Total discoloration

The extent of total discoloration is not highly correlated with any of the environmental variables examined (Table 22f). It is primarily determined by the yellowing and browning of older needles, although it is also significantly correlated with the browning and yellowing of current needles. As mentioned above, there is a possible association between the distribution of hourly exceedances (60 p.p.b.) of ozone and overall discoloration. It has not been possible to confirm this statistically.

Flowering

The amount of flowering shows a large number of correlations with environmental variables (Table 22g). The scattergrams suggest that some of these may be real relationships, although most show a large amount of variation. The most marked trends are for an ill-defined decrease in flowering with increasing values for *WSnmSO4d*, *WSNO3d*, *WSNH4d* and *WSTSO4d*.

Needle retention

Absolute figures are available for needle retention in Scots pine, enabling stand means to be calculated. There are relatively few highly significant correlations (Table 22h). In each case, no clear relationship is apparent.

Table 22h. Significant correlations between the mean needle retention (years) in Scots pine and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HNO	*0.232*	WSnmSO4	*0.261*	slope	*−0.265*	BNcont	−0.353
HNO2	*0.255*	WSNO3	*0.256*	slow	*−0.244*		
HO3	*−0.255*	WSH	**0.394**	dfsw	0.312		
HNH3	**−0.370**	WSTSO4	*0.281*	dfse	−0.294		
HSO2	*0.239*	WSNH4d	*−0.277*	hew	*0.267*		
HHCl	0.354			JSrain	*−0.231*		
HCl	*0.267*						
HpSO4	*0.235*						
HpHCl	0.341						
HNOdry	*0.224*						
HNHdry	*−0.221*						
HNHwet	*−0.266*						
HNHtot	*−0.279*						
HSOdry	*0.273*						
HSOtot	*0.239*						
HCldry	**0.392**						
HClwet	*0.264*						
HCltot	**0.363**						

Table 22i. Significant correlations between the number of Scots pine trees at each site with shoot death in the live crown and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HHNO3	*−0.230*	WSNH4	*−0.242*	elev	*0.251*	Apcwat	0.353
HNO3	−0.298	WSHd	*0.272*	dfsw	*−0.228*	Apcorg	*0.310*
HNH4	−0.300			hee	0.315	Bpcwat	*0.296*
HpNO3	−0.291			rug	0.304		
HpNH4	−0.310			JMairt	**−0.381**		
HNHdry	−0.300			JMrain	0.350		
				AJairt	**−0.393**		
				AJrain	0.351		
				JSairt	−0.291		
				JSrain	**0.418**		
				ODairt	**−0.444**		
				ODrain	0.361		

Shoot death

There is no readily discernible pattern in the spatial distribution of the proportion of trees with shoot death in the live crown (Figure 6g). The correlation analysis suggests that a primary determinant of this index may be climate (Table 22i). However, the scattergrams show a large amount of scatter amongst the data and some other factor may be important.

Oak

Crown density

Several correlations exist between the crown density of oak and the environmental variables (Table 23a). The highly significant relationships are all with the Harwell pollution variables. The scattergrams suggests that real relationships may exist between crown density and *HSO2*,

Table 23a. Significant correlations between crown density index of oak and the environmental variables. A positive correlation indicates that crown density decreases with increasing values of an environmental variable.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HNO	−0.439	WSnmSO4	*−0.344*	hew	*0.316*	AMgCa	*−0.320*
HNO2	−0.437	WSNO3	*−0.359*	hee	*0.323*	BpH	*−0.319*
HHNO3	−0.382	WSNH4	−0.365	JMairt	*−0.349*	Bpcwat	*0.377*
HO3	0.437	WSH	*−0.324*	AJairt	−0.379		
HSO2	**−0.464**	WSTSO4	−0.427	AJrain	*0.284*		
HHCl	**−0.480**			JSairt	*−0.324*		
HNO3	*−0.303*			JSrain	*0.316*		
HNH4	*−0.296*			ODairt	*−0.342*		
HCl	−0.436						
HpNO3	*−0.313*						
HpNH4	*−0.306*						
HpSO4	**−0.450**						
HpHCl	**−0.488**						
HNOdry	−0.404						
HNOtot	*−0.322*						
HSOdry	**−0.481**						
HSOwet	*−0.315*						
HSOtot	**−0.468**						
HCldry	**−0.470**						
HClwet	−0.442						
HCltot	**−0.470**						

Table 23b. Significant correlations between the amount of browning in oak and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
		WSnmSO4d	**0.500**	slow	*0.292*	propf	*0.342*
		WSNO3d	0.452			propi	0.426
		WSHd	**0.482**			Acond	*0.324*
		WSTSO4d	**0.474**			Bbufc	*0.351*

Table 23c. Significant correlations between the amount of yellowing in oak and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
				JMairt	*0.349*	Apcwat	*0.352*
				AJairt	*0.311*	Bpcwat	*0.345*
				JSairt	*0.362*		
				ODairt	0.381		

Table 23d. Significant correlations between the amount of epicormics on the branches of oak and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HHCl	**−0.471**					Bpcwat	0.434
HpHCl	−0.413						
HCldry	**−0.518**						
HClwet	−0.422						
HCltot	**−0.499**						

HpSO4, HSOdry and *HSOtot*. In all cases, crown density is higher in areas with higher levels of the relevant pollutant. The relationships with the chlorine variables appear to be unduly influenced by a small number of sites.

Browning and yellowing of leaves

A few correlations were found between the extent of browning and yellowing and the environmental variables (Tables 23b and 23c). The scattergrams suggest that these relationships are not very strong.

Number of epicormic branches

Again, there were a small number of highly significant correlations (Table 23d). However, the scattergrams indicate that the relationships were determined by a small number of extreme values.

Crown dieback

No correlations were found between the extent of crown dieback and any of the pollution variables (Table 23e). A number of correlations were identified with climatic variables, but none was highly significant.

Beech

Crown density

As with oak, a considerable number of correlations are present between crown density and the environmental variables (Table 24a). The relationships with *HC1* and *WSNO3* appear to be genuine trends; the relationships with *HHCl, HpHC1, WSnmSO4* and *WSH* either show a large amount of scatter or appear to be unduly influenced by a small number of sites.

Browning and yellowing

Two correlations were highly significant (Tables 24b and 24c): between browning and *HNHwet* and *HNHtot*, but the scattergrams do not suggest the presence of a genuine relationship. Interestingly, the only correlation between chlorosis and the soil parameters was very weak, suggesting that lime-induced chlorosis is not the only cause of yellowing.

Crown dieback

A number of correlations were identified but none was highly significant (Table 24d).

Premature leaf loss

None of the environmental variables appear to be particular important in determining the extent of premature leaf loss (Table 24e).

Degree and frequency of leaf-rolling

The significance of leaf-rolling, which was particularly noticeable in the south-east of England in 1988, remains uncertain. It is correlated with a number of environmental variables (Table 24f), although the scattergrams are difficult to interpret. Generally, the degree and frequency of rolling is lower in areas with low values for *HSO4, HpNO3, HpNH4, HNH4, HNO3* and *HNH4*. At higher levels for these pollutants, the degree of leaf-rolling and, to a lesser extent, the frequency, are increased. However, there is a considerable amount of scatter amongst the data. There was no indication that leaf-rolling was related to crown density, as reported from the Federal Republic of Germany by Gärtner (1988).

Further analyses

The interpretation of the results presented here is limited by the presence of multicollinearity within the data sets. In the past, step-wise multiple regression has been used to identify the most important environmental variables (Binns *et al.*, 1985, 1986; Innes *et al.*, 1987; Innes and Boswell, 1988). However, the multicollinearity means that the regression coefficients were highly unstable and although on occasion a substantial proportion of the variance was accounted for, it has not been possible to use the regression equations for prediction. Consequently, regression analysis has not been used this year. The data are amenable to analysis by some of the more recent multivariate statistical techniques and these are now being tried.

Element contents of needles

As part of the monitoring exercise, foliar samples were collected in 1985 from all the

Table 23e. Significant correlations between the extent of crown dieback in oak and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
				elev	0.377		
				hew	**0.482**		
				JMairt	−0.442		
				AJairt	−0.419		
				AJrain	*0.303*		
				JSairt	*−0.287*		
				JSrain	*0.289*		
				ODrain	−0.436		

Table 24a. Significant correlations between crown density index of beech and the environmental variables. Positive correlations indicate that crown density decreases with increasing values of the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HNO	−0.449	WSnmSO4	**−0.591**	dfs	*−0.370*		
HNO2	−0.518	WSNO3	**−0.620**	hor	*0.343*		
HHNO3	−0.492	WSNH4	−0.454	JMairt	*0.349*		
HO3	0.518	WSH	**−0.540**	JMrain	*0.347*		
HSO2	**−0.534**	WSTSO4	−0.469				
HHCl	**−0.535**	WSnmSO4d	*−0.340*				
HNO3	*−0.393*	WSNO3d	*−0.346*				
HNH4	*−0.344*	WSHd	*−0.344*				
HCl	**−0.598**						
HpNO3	*−0.405*						
HpNH4	*−0.412*						
HpSO4	0.519						
HpHCl	**−0.574**						
HNOdry	−0.503						
HNOtot	*−0.384*						
HSOdry	−0.524						
HSOtot	−0.496						
HCldry	−0.510						
HClwet	−0.522						
HCltot	−0.520						

Table 24b. Significant correlations between the extent of browning in beech and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HNO3	*−0.397*	WSNH4	*−0.390*	dfse	−0.502	propf	0.452
HNH4	−0.435	WSHd	0.431			propi	0.455
HSO4	−0.438						
HpNO3	*−0.386*						
HpNH4	−0.431						
HNOwet	−0.524						
HNOtot	*−0.393*						
HNHwet	**−0.543**						
HNHtot	**−0.544**						
HSOwet	*−0.350*						

Table 24c. Significant correlations between the extent of yellowing in beech and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
		WSnmSO4	*0.336*	dfs	*0.348*	BBufc	*0.369*

Table 24d. Significant correlations between crown dieback in beech and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HNO	*−0.423*	WSNO3	*−0.382*	hor	*0.429*	propf	**0.648**
HNO2	*−0.403*	WSNH4	*−0.420*	AJairt	*−0.341*		
HHNO3	−0.459	WSTSO4	*−0.360*	JSrain	*0.389*		
HO3	*0.403*						
HSO2	*−0.394*						
HNO3	−0.491						
HNH4	−0.457						
HCl	*−0.392*						
HpNO3	−0.490						
HpNH4	−0.473						
HpSO4	*−0.425*						
HNOdry	−0.443						
HNOtot	*−0.396*						
HSOdry	*−0.345*						

Table 24e. Significant correlations between premature leaf loss in beech and the environmental variables.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
		WSnmSO4d	*0.379*	hor	*−0.398*	Acat	*0.406*
		WSNO3d	*0.381*				
		WSHd	*0.417*				
		WSTSO4d	*0.413*				

Table 24f. Significant correlations between the frequency of leaf-rolling in beech and the environmental variables. The frequency and degree of leaf-rolling in beech are highly correlated (r = 0.987); a correlation table is therefore presented only for the frequency of leaf-rolling.

Harwell		*Warren Spring*		*Topography/climate*		*Age and soils*	
HNO	0.448	WSnmSO4	0.472	slope	*−0.363*		
HNO2	*0.374*	WSNO3	*0.432*	dfs	0.549		
HHNO3	0.455	WSNH4	0.500	dfsw	*0.365*		
HO3	*−0.374*	WSTSO4	*0.407*				
HNO3	0.527						
HNH4	**0.619**						
HSO4	**0.687**						
HpNO3	0.522						
HpNH4	0.547						
HNOdry	*0.431*						
HNOwet	*0.438*						
HNOtot	0.477						
HNHdry	0.514						
HNHwet	*0.401*						
HNHtot	0.458						

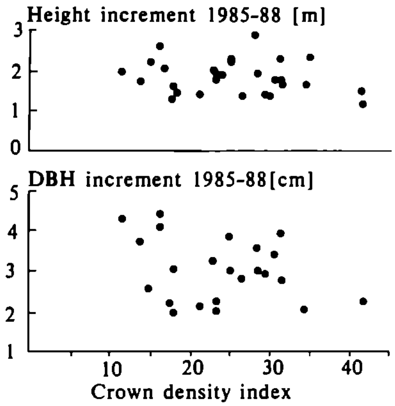


Figure 12. *Relationship between mean crown density score (1988) and mean height (upper) and dbh (lower) increment (1985-88) for Sitka spruce.*

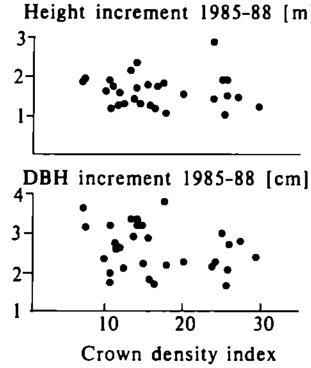


Figure 13. *Relationship between mean crown density score (1988) and mean height (upper) and dbh (lower) increment (1985-88) for Norway spruce.*

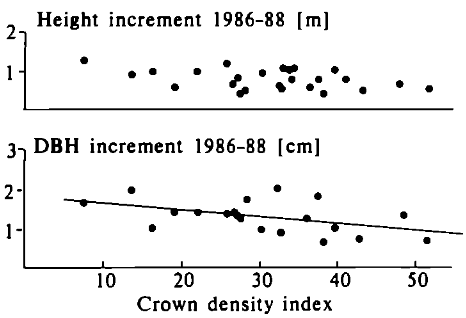


Figure 14. *Relationship between mean crown density score (1988) and mean height (upper) and dbh (lower) increment (1986–88) for older Norway spruce.*

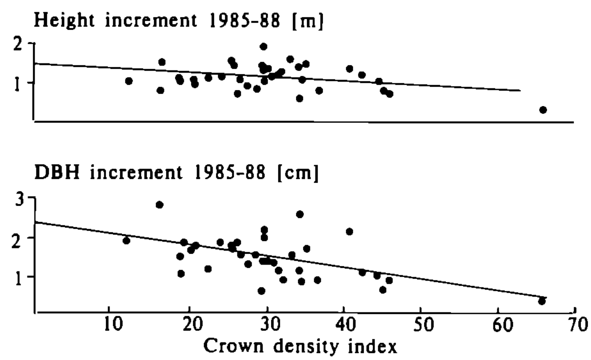


Figure 15. *Relationship between mean crown density score (1988) and mean height (upper) and dbh (lower) increment (1985–88) for Scots pine.*

sample stands then being assessed. Chemical analyses have been undertaken on these samples, and the results have been analysed and interpreted. Some of the results have already been published (Innes and Boswell, 1989) and the remainder will appear in due course.

Growth analysis

Height and breast-height diameter (dbh) measurements were obtained for all trees in 1985. In 1986, assessments were extended to include Norway spruce aged between 50 and 100 years and these trees were also measured. In 1988, all trees first measured in 1985 and 1986 and still being assessed were remeasured.

The data provide information on the relationship between crown density and dbh and height increment. In addition, increment can be used as a measure of tree condition, provided that a number of stand-related factors are taken into account. For the analysis, the 1988 crown density scores have been used. Height and dbh increment over the period 1985–88 have been used, together with increment for 1986–88 for older Norway spruce.

The data have been analysed on a stand-to-stand basis. In Figures 12 to 15, the total mean height and dbh increments have been plotted against mean crown density for each stand. In all cases, there appears to be a trend in the relationship, with stands having thinner crowns also having lower height and dbh increment. However, the trends are only significant for dbh ($p < 0.01$) and height ($p < 0.05$) for Scots pine and dbh ($p < 0.05$) in older Norway spruce.

In Sitka spruce and Scots pine, there was no evidence that either height or diameter increment was related to stand age. Diameter increment in Norway spruce was significantly ($p < 0.01$) correlated with age, with increment being lower in older trees. The lack of a relationship in Sitka spruce and Scots pine is probably attributable to the relatively short sampling interval (3 years) and the restricted age range (30–50 years) of the trees that were sampled.

Environmental factors affecting increment

In Sitka spruce, a small number of weak correlations were obtained for diameter and height increment. None of these is considered important.

In Norway spruce, diameter increment was unrelated to any of the variables, but several significant results were obtained for height increment. These generally suggested increased height increment in the south and east of the country. There was no indication of a climatic or pedological influence on the height increment, nor was a relationship apparent with crown density (Figure 13).

With Scots pine, no pattern was found for height increment, but a number of relationships were apparent for diameter increment. In general, these also suggested higher increment in the south and east of the country.

The work on increment presented in this section is of a preliminary nature. The sampling interval was only two or three growing seasons and the natural year-to-year variation, combined with measurement error, is likely to obscure any relationship. A more detailed analysis will be feasible when more data are available.

Discussion

Short-term factors affecting tree condition in 1987 and 1988

Weather

The impact of short-term climatic factors was dominated by gales in the south of England in March and October 1987 and in Scotland in July 1988. The October 1987 gale was particularly damaging and resulted in the loss of a number of sample plots. Severe damage to surviving trees was noted in a number of oak stands and this undoubtedly influenced the results. The July 1988 gale in Scotland resulted in widespread damage, but it does not appear to have unduly affected the results of the survey.

The winter of 1987–88 was exceptionally mild, with above-normal monthly temperatures being recorded consistently from December 1987 until June 1988. Minimum temperatures in most parts of Britain remained above −10°C throughout the winter.

After a very wet October, rainfall was below average in November and December. Rainfall was higher than average from January to April and may have resulted in waterlogging at some sites. May and June were generally drier than average but nowhere appears to have approached drought conditions.

Both the temperature and rainfall conditions were generally favourable for tree growth and the slight deterioration recorded in the condition of some species cannot be attributed to these causes. Wind damage was severe at some sites, and appears to have been particularly important for oak. It may also have been the cause of the browning of older Scots pine needles in Kent. The Norway spruce stands in the south-east of England were badly affected, but this is not reflected in the monitoring results as the sample stands were all destroyed and were therefore not assessed in 1988.

Insect and fungal problems

The Pathology Advisory Service of the Forestry Commission noted a number of problems probably associated with the mild winter. In Sitka spruce, *E. abietinum* was widespread and this is reflected by the amount of browning of older needles that was recorded. In Norway spruce, 'top dying' was noted on a number of occasions, but there was little new evidence of this in the sample stands. Scots pine in the north of England and Scotland continued to show the adverse effects of one or more of *L. seditiosum*, *A. abietina* (= *B. pinea*) and *T. piniperda*. Browning of current Scots pine needles by *Lophodermella sulcigena* (Rostr.) Hoehn. was common in parts of Scotland, but did not appear to unduly affect sample trees (only 4 per cent of trees were reported as having any browning of current needles).

Nothing unusual was reported in oak, although some areas were badly defoliated early in the season by *Tortrix viridana* L.; Lepidoptera. At the time of the assessments, much of the defoliation caused by this insect would have been replaced by lammas growth. With beech, leaf browning caused by *Discula umbrinella* (Berk. and Br.) Sutton and *Rhynchaenus fagi* L.; Coleoptera, was common in England (as in 1987) and shoot death caused by *Nectria ditissima* Tul. was locally abundant.

Summary of analyses

Sitka spruce

The reduced crown density in older, as compared with younger, trees identified in previous years (Innes *et al.*, 1986; Innes and Boswell, 1988) was again found. Discoloration of current needles was negligible although some yellowing was seen. Browning of older needles was more common on younger trees; yellowing of older needles was more apparent on older trees. Needle retention showed a bimodal distribution, with approximately a quarter of the stands having most trees with less than 7 years' needle retention.

The crowns of Sitka spruce were, on average, thinner than in 1987. However, the trees with the thinnest crowns in 1987 had all improved by 1988. Reductions in crown density were identified in south-west Scotland and Wales. There was no overall change in the amount of discoloration, although there was a major increase in the amount of browning of older needles in western Scotland. This has been tentatively attributed to outbreaks of *E. abietinum*.

A geostatistical analysis did not reveal any spatial pattern in the crown density of Sitka spruce. Adjacent stands showed as much variation as stands separated by large distances. Discoloration was regionally distributed, being greatest in western Scotland. Needle retention also showed a marked spatial pattern, being lowest in the south and west of Britain.

Most of the crown indices were independent of the environmental variables. Needle retention was higher in cooler areas, suggesting some form of climatic control. Alternatively, tree genetics may be important as there is a tendency for provenances other than Queen Charlotte Island (e.g. north Oregon, west Washington and Vancouver Island) to be planted in south-west England and Wales (Lines, 1987). As provenance is not recorded in the assessments, no cause can be attributed to the low needle retention in the south and west.

Norway spruce

As compared with younger stands, older stands had thinner crowns and more trees with dead branches in the live crown. Browning of current needles was negligible whereas browning of older needles was quite common, occurring more frequently on younger trees. In contrast, yellowing of both younger and older needles was more common on older trees. Needle retention was slightly higher than in Sitka spruce. Almost three quarters of the stands had trees with dead branches in the live crowns.

Crown density showed no change between 1987 and 1988 and needle retention was higher. Trees with high levels of defoliation in 1987 either improved or remained stable during the year. However, the amount of browning of older needles was greater, particularly in west Scotland.

Three stands had abnormally thin crowns. These were all old and, in one case, the thin crowns were attributed to waterlogging at the site. At the other two, exposure was cited as a possible factor influencing the crown densities.

There were clear spatial patterns in the crown densities of Norway spruce. Stands separated by less than 80 km were generally fairly similar; stands further apart showed significant differences. Differences were more pronounced in a north–south direction than in an east–west direction. Crowns were denser in areas where most forms of pollution are greater. This does not appear to be a climatically-determined relationship. Height increment was also greater in the south and east, but no such relationship was identified for dbh increment.

Areas with lower needle retention were significantly correlated with the hydrogen ion concentration in rainfall, although there was no clear relationship with total hydrogen ion deposition. The potential role of provenance is less clear than for Sitka spruce, although it is known that most of the pre-1939 planting came from relatively high altitude sites in Austria and the Federal Republic of Germany whereas younger trees tend to be of East European origin (Lines, 1987). There is no indication that particular provenances have been preferentially planted in Wales and south-west England.

Scots pine

Crown densities of Scots pine did not decrease with age. However, crowns were generally thinner than with the two spruce species. Seven trees have died since the start of the monitoring programme in 1984, but no mortality was recorded in the 1987–88 period. Small numbers of trees remain in a critical state (>70 per cent loss of foliage). Some discoloration was present, with browning of older needles being more apparent on older trees. Yellowing occurred more frequently on younger trees. The majority of trees had 2 or 3 years' needle retention and only small numbers had either 1 year or 4. Male flowering had occurred in half the trees assessed. Shoot death in the live crown was identified in most stands, but the number of trees involved was variable.

Generally, crown densities were lower in 1988 than in 1987. Needle retention was also shorter in 1988. Some trees showed a major loss of foliage over the period, the maximum loss recorded being 70 per cent. A substantial proportion (25 per cent) of the trees with more than 60 per cent loss of foliage deteriorated further during the year, in marked contrast to the two spruce species. The reduction in crown density was most marked in central and north Wales and Cornwall.

Two stands had anomalously low levels of crown density: both were in southern Scotland/northern England where problems associated with insect and fungal attacks have been identified in the past. Both stands are at relatively high altitudes (300 and 310 m), where the problems appear to be particularly severe.

Geostatistical analysis indicates that there were marked patterns in crown condition. North–south variations were important over short (<150 km) distances, east–west variations become more important over longer distances. Crown density was generally highest in areas with relatively high levels of pollution, but also appeared to be related to climate, being higher in warmer and drier areas. Dbh increment showed a similar pattern. No statistical relationships were identified between the environmental variables and needle retention, discoloration or the number of trees with shoot death in the live crown.

Although no statistical relationships were identified for discoloration, visual interpretation of the map of the number of occurrences of ozone concentrations in excess of 60 p.p.b. suggests a qualitative correlation. Two areas with above average discoloration were identified, one in Kent, the other in West Yorkshire. Both coincide with areas with relatively high numbers of 60 p.p.b. exceedances. Detailed examination of the stand records for these areas indicates that the majority of discoloration was associated with discoloration of older needles, both yellowing and browning being involved. Several possible causes of discoloration of older needles exist. Damage by relatively low concentrations of ozone is usually fairly distinctive, taking the form of chlorotic mottling (Skelly *et al.*, 1988), but this symptom was not assessed. Other causes of discoloration include autumnal senescence, damage by salt and the effects of *Cyclaneusma minus* (Butin) DiCosmo *et al.* and *L. seditiosum*. Given that air pollution might affect the incidence of some of these, the association identified here warrants careful monitoring.

Table 25. Defoliation and discoloration in British woodlands as determined from the grid survey of forest health, 1988. All figures refer to the percentage of trees in each category within each species..

		Crown density category				*Discoloration category*			
	n	*0* *0–10%*	*1* *11–25%*	*2* *26–60%*	*3+4* *>60%*	*0* *0–10%*	*1* *11–25%*	*2* *25–60%*	*3* *>60%*
English oak	132	20	36	39	5	80	17	2	1
Ash	78	44	44	12	0	99	0	1	0
Beech	73	40	48	11	1	47	34	19	0
Downy birch	63	40	54	6	0	78	22	0	0
Sycamore	61	78	16	5	1	72	28	0	0
Other broadleaves	247	45	38	15	2	90	10	0	0
Sitka spruce	540	35	34	24	7	73	15	10	2
Scots pine	224	20	50	25	5	87	13	2	0
Lodgepole pine	127	20	45	27	8	39	46	13	1
Japanese larch	88	32	50	17	1	92	8	0	0
Douglas fir	70	46	39	14	1	91	9	0	0
Other conifers	97	59	29	12	0	95	5	0	0
All broadleaves	654	41	39	18	2	81	16	3	0
All conifers	1146	33	40	22	5	76	16	7	1
All trees	1800	36	39	21	4	78	16	5	1

Oak

The majority (96 per cent) of oaks showed at least 10 per cent reduction in crown density as compared with an ideal tree. Over half showed 30 per cent or more reduction. Both browning and yellowing were present, but no trees showed high levels of discoloration. Crown dieback was present in 37 per cent of the trees assessed. Damage by leaf-eating insects was recorded in more than half of the trees. A wide variety of species is likely to have been involved.

Changes in crown density between 1987 and 1988 showed no clear trend. Dense crowns in 1987 were generally rather thinner in 1988 and thin crowns in 1987 tended to be denser in 1988. Only three trees (out of 44) with 60 per cent or more reduction in crown density in 1987 deteriorated further. Both improvements and deteriorations of up to 50 per cent foliage occurred. Stands in north-west Scotland, south Wales and the Midlands generally showed an improvement, stands in the rest of the country deteriorated.

Two stands had anomalously thin crowns. No explanation is available for these, although both were in areas of Scotland that may not be particularly suited to oak. Some evidence of a regional effect was found, operating at a scale of approximately 200 km.

Higher crown densities were generally recorded in areas with higher levels of sulphur pollution (sulphur dioxide, sulphate aerosol, dry deposition of sulphur). No correlations were identified for discoloration or the extent of crown dieback. The latter was surprising given the correlation between crown dieback and the crown density index (r = 0.705).

Beech

The small number of beech stands reflects the comparative rarity of the species in Britain (4 per cent of the total forested area). In 1988, no trees had 60 per cent or more loss of crown density, the four trees in this category in 1987 having improved. Browning of leaves was fairly frequent, occurring in just over a quarter of the trees and yellowing was present in over half of them. In 18 per cent of trees, yellowing was moderate to severe. Crown dieback was noted in 38 per cent of trees, indicating that its frequency in beech is similar to that of woodland oak. Light to moderate leaf-rolling occurred in 21 per cent of the trees. Damage by leaf-eating insects was noted in 59 per cent of trees.

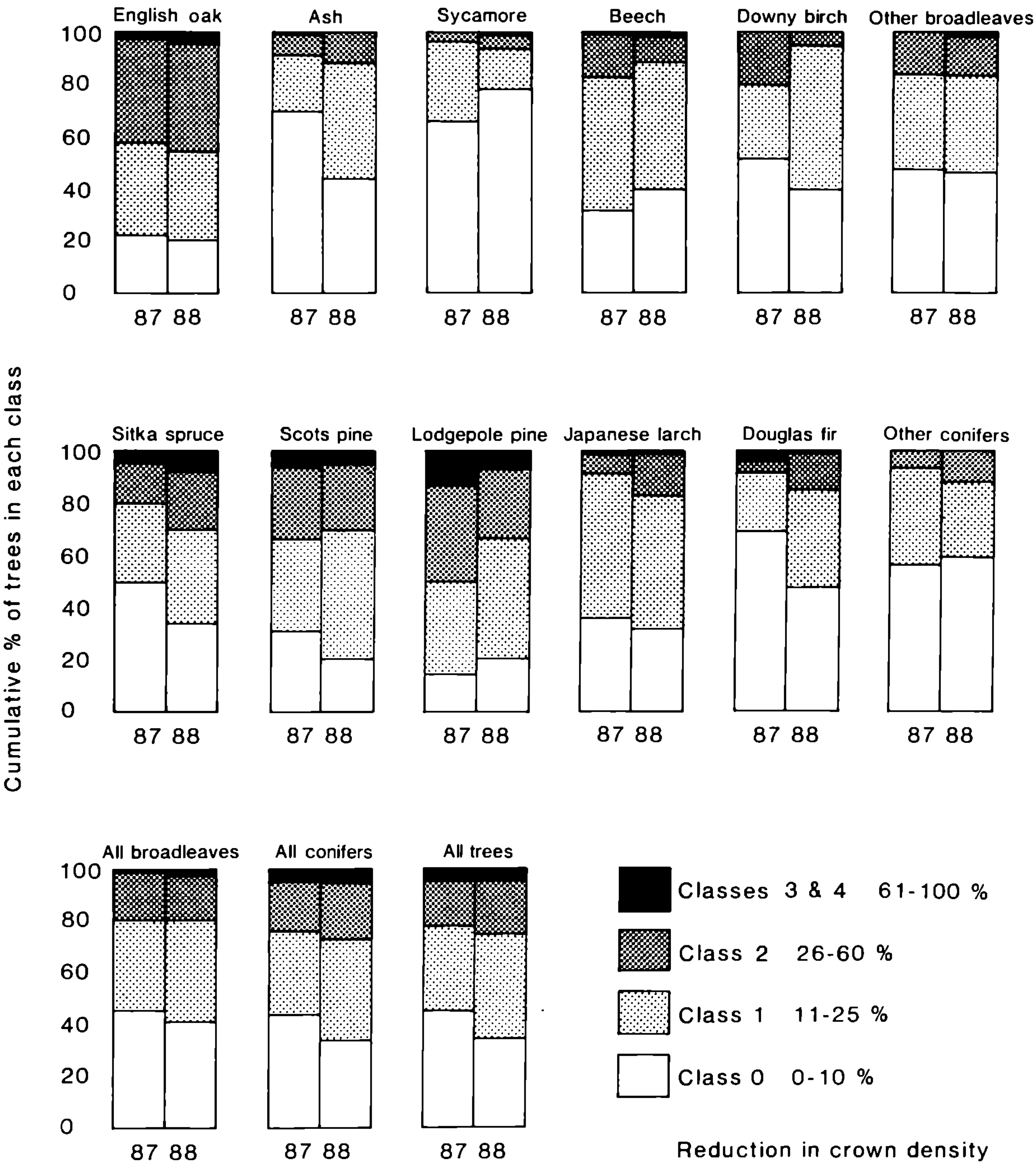


Figure 16. *Comparison between 1987 and 1988 EC inventory results.*

During the year, there was a general improvement in crown density, particularly in north-east England, the Midlands and south Wales. As with oak, both improvements and deteriorations of individual trees were noted. There was a major increase in the amount of yellowing, from 14 per cent of trees in 1987 to 53 per cent in 1988.

No anomalous stands were identified and the small sample size precluded any reliable geostatistical analysis. The thinnest crowns were recorded in Scotland and along the south coast of England. Leaf-rolling was common in the south-east, but the cause and significance of this remains unknown.

The role of air pollution

One of the main aims of the monitoring programme is to identify possible links between air pollution and crown condition in British trees. There is already evidence that the sulphur contents of needles from stands throughout Britain are closely related to levels of sulphur dioxide (Innes and Boswell, 1989). However, no association has been found in Britain between the sulphur content of needles and crown condition.

A number of significant correlations have been identified between pollution variables and crown indices. As shown above, some of these can be discounted for a number of reasons. In the remaining cases, some pattern is evident. Four of the species, the exception being Sitka spruce, have denser crowns in areas with higher levels of most forms of pollution. These correlations tend to be stronger than with any other group of variables, notably climate and soil.

Other variables do not show such a consistent pattern. With Norway spruce, the number of trees in each stand with less than 7 years' needle retention appears to be inversely related to hydrogen ion concentration in rainfall. A positive relationship is apparent between the browning of older needles and hydrogen ion deposition. In Scots pine, there may be a relationship between overall discoloration and areas with high ozone concentrations, but this requires confirmation. Flowering appears to be inversely related to the level of pollution. In beech, the extent and degree of leaf-rolling appears to be related to the degree of nitrogen pollution. There is therefore some indication of an interaction between certain indices of tree condition and air pollution in Britain.

Clear evidence now exists that air pollution has adversely affected some forest ecosystems in north-west Europe. Acidification of forest soils has been widely reported in Britain and elsewhere (e.g. Billett *et al.*, 1988; Falkengren-Grerup, 1987; Tamm and Hallbäcken, 1988); while some of this may be associated with normal tree growth, the degree of acidification that has been reported strongly suggests that acidic deposition has been important. There appear to have been responses amongst the more sensitive parts of forest ecosystems, with loss of lichens such as *Lobaria pulmonaria* (L.) Hoffm. from Northumberland woodlands being attributed to acidification of the bark (Gilbert, 1986). Elsewhere in Europe, reductions in the numbers of ectomycorrhizal fungi have been reported (e.g. Arnolds, 1985; Jansen, 1988; Schlechte, 1986). However, the effects of soil acidification on tree condition remain unclear with the results of many case-studies being site-specific and more information is needed before any generalisations can be made.

EC forest health inventory

A second assessment of forest condition undertaken by the Forestry Commission is based on a systematic sampling design. Stands are located on a 16 km by 16 km grid where intersections occur in woodland. At each site, 24 trees were assessed, regardless of age or species. Assessments of crown density were made using the European classification system, which is based on five classes rather than the ten used in the long-term monitoring scheme. The inventory covers the whole of the United Kingdom and involves 1800 trees.

The results are given in Table 25. Only the five most important conifers and the five most important broadleaves have been listed, in line with standard EC/ECE procedures. It is possible to compare the results with those of 1987 (Figure 16). The changes over the year have been rather variable. Ash, Sitka spruce and Douglas fir appear to have deteriorated, sycamore, beech and lodgepole pine have improved and the remainder have remained about the same. Overall, there was a slight increase in the percentage of trees in classes 1 and 2. The proportion of trees in classes 3 and 4 remained constant.

As part of the inventory, assessors were

Table 26. Easily identifiable damage types recorded in individual species assessed in the EC inventory. All figures refer to the numbers of trees in which a particular damage type was identified. Damage types: 1: game and grazing; 2: insects; 3: fungi; 4: abiotic agents; 5: direct action of man; 6: fire; 7: known local/regional pollutant; 8: other.

	Damage type							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Acer pseudoplatanus	1	7	12	1			1	1
Alnus glutinosa		14		2				
Betula pendula		11			1			
Betula pubescens	4	15		4	1			
Carpinus betulus		20		8				
Castanea sativa			1		1			
Corylus avellana		5						
Eucalyptus sp.				1				
Fagus sylvatica	2	47		4	1			
Fraxinus excelsior		16		2			1	
Ilex aquifolium			1					
Populus tremula			1					
Prunus avium		3						
Quercus petraea		3			1			
Quercus robur		54	1	22	1			1
Sorbus aucuparia				3				
Ulmus glabra		1						
Ulmus minor		4	2					
Abies grandis		1						
Larix decidua				6				
Larix kaempferi		5		14	2		6	1
Picea abies		17		4	2			
Picea sitchensis	7	240		89				20
Pinus contorta	13	12	11					
Pinus nigra		2		1				
Pinus radiata				1				
Pinus sylvestris	1	88	19	25				30
Pseudotsuga menziesii		4		10	11			
Thuya sp.				1				
Tsuga sp.				1				

requested to record 'easily identifiable causes of damage'. Such records do not signify a cause–effect relationship, they simply record the incidence of particular types of damage. Eight categories are identified within the European Community: game and grazing, insects, fungi, abiotic agents (mainly climatic), direct action of man, fire, known local/regional pollutants and other causes. The results are presented by species in Table 26. By far the most common type of damage was caused by insects, followed by abiotic effects. However, a table such as this is strictly dependent on the ability of the assessors to recognise particular types of damage.

An international perspective

The results of this inventory are broadly comparable with results from other countries, although some important differences of technique remain (Innes, 1988). Bearing in mind the difficulties in interpreting international summary statistics, in the rest of Europe in 1988 there appears to have been a general improvement in conifer condition in many areas. National results reveal lower figures for 'forest damage' although these may conceal marked regional variations (e.g. Anon., 1988). The situation with broadleaves is less clear, with continued decline of oak and beech in many areas. Data for a selection of

Table 27. Comparison of UK results with those from selected other European countries in 1988.

	Density category 0	1	2	3+4
NORWAY SPRUCE				
Austria	77	21	2	0
FRG	51	34	14	1
Switzerland	53	32	13	2
UK[1]	79	13	8	0
SCOTS PINE				
Austria	58	38	3	1
FRG	47	41	11	1
Switzerland	37	41	16	6
UK	20	50	25	5
OAK				
Austria	36	46	15	3
FRG	30	45	23	1
Switzerland	56	37	6	1
UK	20	36	39	5
BEECH				
Austria	53	41	5	1
FRG	37	46	16	1
Switzerland	65	28	6	1
UK	40	48	11	1

[1] Based on 48 trees only.

countries in central Europe are presented in Table 27. Only those countries where the methods are believed to be directly comparable have been included.

The United Kingdom results suggest that the condition of trees is poor compared with some European countries. Both Scots pine and oak have markedly thinner crowns than elsewhere. However, no trend can be established from these data and it is not possible to determine from them whether the trees in the United Kingdom are in a state of decline.

Conclusions

This study has not found any clear indication that the condition of trees in more polluted parts of Britain is worse than in cleaner areas. Other investigations have reached similar conclusions. In a study dealing with several European locations, Hauhs and Wright (1986) failed to find any single pollution factor that explained the distribution of decline. Landolt (1984) found no clear relation between the pattern of damage in Switzerland and the distribution of air pollution sources and similar results have been obtained in the Federal Republic of Germany (Krause, 1987; Kandler, 1989). In northern Scandinavia, crown density generally decreases northwards, as do the levels of air pollution (Andersson, 1986; Jukola-Sulonen *et al.*, 1987; NIS, 1988). Fluchiger *et al.* (1986) found no link between defoliation in beech and soil pH. In the Netherlands, the distribution of forest decline does not correlate with the distribution of sulphur dioxide, ozone or the oxides of nitrogen, but a correlation with the distribution of ammonium is present (van Breemen and van Dijk, 1988). Conversely, Paffrath and Peters (1988) and Ammer *et al.* (1988) report a correlation between the altitudinal distribution of damage in central Europe and the altitudinal distribution of ozone.

The evidence linking air pollution to regional forest decline in Europe remains circumstantial. Frequently, air pollution is cited as a factor on the grounds that there is insufficient evidence that other factors are responsible. Given the lack of evidence for the involvement of air pollution, this argument seems unsound. There is an increasing concern about the role of soil acidification, since this has been demonstrated to have occurred. Several detailed studies have emphasised changes in soil chemistry as a major potential factor affecting forest condition (e.g. Krzak *et al.*, 1988; Meyer *et al.*, 1988; Oren *et al.*, 1988), although the precise mechanisms remain uncertain. In this study, no relationship has been found between tree condition and soil pH, cation exchange capacity or buffering capacity. However, these have not been measured over time; trees are likely to respond to changes in the soil chemical status and these cannot be determined from a single assessment.

The results presented in this study indicate that a potential problem exists. Currently, it is suspected that the condition of trees in Britain is not deteriorating, but a longer time series is required before any firm conclusions can be reached. The patterns in crown density observed in 1987 and 1988 do not suggest an adverse effect of air pollution on forest condition in Britain. Concentrations of some pollutants, such as ozone, were relatively low in 1987 and 1988, and there is a possibility that effects might be noted in years with higher concentrations.

However, it is clear that air pollution, particularly in the form of acidic deposition, is affecting many aspects of forest ecosystems in Britain and there is an obvious need for continued detailed monitoring.

ACKNOWLEDGEMENTS

The results presented in this report could not have been obtained without the help of the staff of the Forestry Commission's Forest Surveys Branch. Their hard work, often under extremely unpleasant conditions, is gratefully acknowledged. During the course of the year, several people have helped with data collection and analysis, and we would particularly like to thank Miss Heike Neumann and Miss Lisa Smith for their assistance. Dr R. Webster of Rothamsted Experimental Station generously provided the computer programs for the geostatistics and gave much useful advice on the subject. Data related to pollution were provided by Dr R.G. Derwent of the Environmental and Medical Sciences Division of the United Kingdom Atomic Energy Authority at Harwell and Drs J.S. Bower and G.W. Campbell of the Warren Spring Laboratory of the Department of Trade and Industry. The data from the Warren Spring Laboratory came from the Department of the Environment Research Programme. Dr M.P. Coutts provided many useful comments on an earlier version of the manuscript.

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Appendix

Spatial analysis of the data

In 1988, geostatistical techniques were employed for the first time. The techniques are based on regionalised variable theory which has been described by Journel and Huibregts (1978) as:

$$Z(x) = m(x) + \epsilon'(x) + \epsilon'' \qquad (1)$$

where x is a position in one, two or three dimensions, $Z(x)$ is the value of a variable Z at x, $m(x)$ is a deterministic function describing a large-scale component of variation in Z, $\epsilon'(x)$ describes the stochastic, locally varying, spatially dependent residuals from $m(x)$ and ϵ'' is a residual, spatially independent Gaussian noise term having zero mean and variance δ^2. Two assumptions are made, one of stationarity of difference, the other of finite variance of differences. Basically, these mean that once $m(x)$ has been accounted for, $\epsilon'(x)$ becomes purely a function of the distance between sample stands.

The parameters describing tree condition are known to vary spatially (Innes and Boswell, 1988) and also according to factors such as age and provenance. Large-scale variations are likely to be the result of spatially dependent variables such as climate. Small-scale variations caused by, for example, soil conditions, may also be spatially dependent and similar to the type of factor described by the $\epsilon'(x)$ term. Superimposed on these are factors such as provenance, insect or fungal attack and other phenomena restricted to individual trees or stands. In certain cases, these will be accounted for by the $\epsilon''(x)$ term, in other cases they may fall into the $\epsilon'(x)$ term or even the $m(x)$ category. Stand age is one factor that is difficult to incorporate into the above scheme. Age affects the crown density of both spruce species, but has not been demonstrated to be important for Scots pine, oak or beech in Britain over the age range studied. Here, age effects have been accounted for using the relationship between crown density and age described in the following equations:

Sitka spruce $Y_{SS} = 10.47 + 0.3925X$
(VAF 24.1 per cent) (2)

Norway spruce $Y_{NS} = 3.2 + 0.3849X$
(VAF 50.9 per cent) (3)

where Y_{SS}: stand crown density index for Sitka spruce
Y_{NS}: stand crown density index for Norway spruce
X : stand age

The semi-variograms described below for the two spruce species are therefore based on crown density indices adjusted to take into account the effects of stand age.

An additional alteration has been made to the basic data set. The object of the analysis is to identify broad trends in crown density across the country. The techniques being used rely on the comparison of stands and these comparisons could be heavily biased by the presence of extreme values. In the case of Scots pine, there are two clear outliers to the distributions of the crown density indices. Both of these stands are in south Scotland, where problems with the health of high-altitude Scots pine have been identified in the past. The problem appears to be local although its actual extent is yet to be determined. As the crown density indices for the stands have a substantial effect on the semi-variograms (see below), they have been removed from the data set.

Spatial autocovariation can be examined

using semi-variograms (Jongman *et al.*, 1987). The semi-variance $\hat{\gamma}(h)$ is estimated from:

$$\hat{\gamma}(h) = \Sigma_{i=1}^{n-h}[Z(x_i + h) - Z(x_i)]^2/[2(n-h)] \quad (4)$$

where h is the distance between one stand and the next and n is the number of stands. For a second-order stationarity series (defined by Jongman *et al.* (1987) as being a series in which the mean is constant, the autocovariance is determined only by the sampling interval and the variance is finite and constant),

$$\hat{\gamma}(h) = \hat{C}(0) - \hat{C}(h) \quad (5)$$

with

$$\hat{C}(0) = \Sigma_{i=1}^{n} [Z(x_i) - \bar{z}]^2/n \quad (6)$$

and

$$\hat{C}(h) = \Sigma_{i=1}^{n-h} [Z(x_i+h) - z][Z(x_i) - \bar{z}]/(n-h) \quad (7)$$

where $C(h)$ is the covariance function.

In a semi-variogram, $\gamma(h)$ is plotted against h. The ideal form of a semi-variogram, together with its component parts, is given in Figure A1. It has been presented to help those unfamiliar with the technique to understand the following section. Essentially, the semi-variogram shows the variation between stands separated by a given distance (h). Similar stands will have a low semi-variance, stands that differ widely will have a high semi-variance. If it is expected that stands close together will be more similar than stands separated by large distances, then the semi-variogram should take the form shown in Figure A1. In most cases, there is a gradual rise in $\gamma(h)$ up to a point where $\gamma(h)$ then remains constant for increasing values of h. The distance between the x axis and the point at which the fitted model crosses the y axis represents the ϵ'' term in equation (1). It is termed the nugget variance and describes the variation that is random and not spatially correlated at the shortest sampling interval used. The distance between the x axis and the point at which $y(h)$ ceases to increase is termed the range. This indicates the distance over which the observations are spatially dependent. The final component is the sill, which describes the level at which $\gamma(h)$ remains constant. Samples separated by distances occurring on the sill are spatially independent.

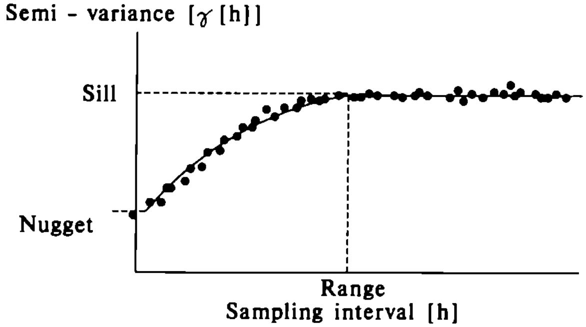


Figure A1. *An ideal semi-variogram showing the various components.*

The semi-variogram shown in Figure A1 represents the 'ideal' form. In the literature, such examples are frequently confined to analyses of the spatial variation occurring over short distances (e.g. Webster and Burgess, 1984; Webster and Nortcliff, 1984; Webster, 1985). Where variation has been examined over larger distances, the semi-variances show more scatter (e.g. Byers *et al.*, 1987; Yost *et al.*, 1982; Lefohn *et al.*, 1988). In this study, semi-variances have been calculated for distances of up to 400 km and a considerable amount of scatter is apparent in the semi-variograms.

Semi-variograms have been constructed for each species, with variation being restricted to a field of 45° in north–south and east–west directions. They have been presented in Figures A2 to A6. As might be expected, the semi-variograms for each direction are different. Accordingly, it is necessary to interpret the semi-variograms separately. In the literature, there is no mention of the number of pairs that are required to estimate a reliable semi-variance. The figures illustrate that in some cases, the number of pairs used is very small (sometimes only one). An arbitrary figure of five pairs has been adopted here as the minimum number required to interpret the semi-variogram. For the semi-variogram modelling described below, all data have been used.

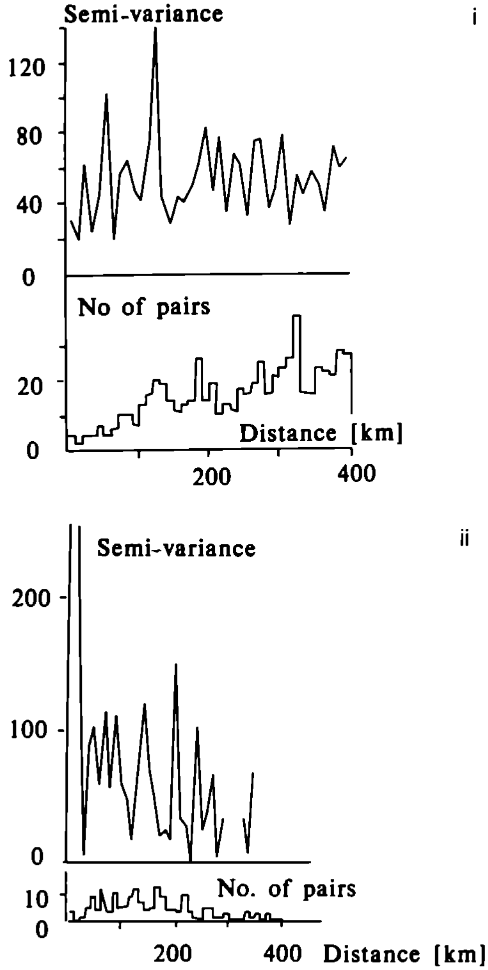


Figure A2. *Semi-variograms for Sitka spruce, i. north–south, ii. east–west.*

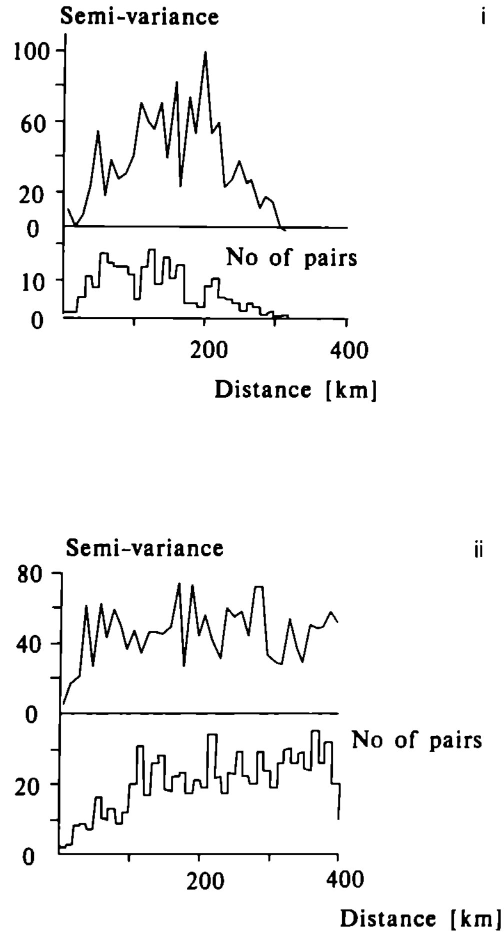


Figure A3. *Semi-variograms for Norway spruce, i. north–south, ii. east–west.*

Sitka spruce (Figure A2)

The semi-variograms for variation in east–west and north–south directions are very similar, although the east–west one is based on a very small sample size. Much of the east–west semi-variogram should be discounted because of the small numbers of pairs involved. Both indicate that there is much variation between different distance intervals although it is lower in a north–south direction than in a east–west direction. The variation appears to be structureless, having 100 per cent nugget variance. This indicates that there is as much variation between stands located close together as there is between stands that are far apart.

Norway spruce (Figure A3)

The east–west and north–south semi-variograms are very different indicating that the structure of the variation differs in each direction. In an east–west direction, there is some evidence of a range of about 50–60 km. This indicates that stands separated by distances of less than 60 km show some degree of spatial interdependence. Sites separated by greater distances show no spatial dependence. In a north–south direction, there appears to be spatial dependence of stands up to about 140 km apart. The downward trend in the semi-variances at distances of more than 170 km should be discounted because of the small numbers of pairs involved.

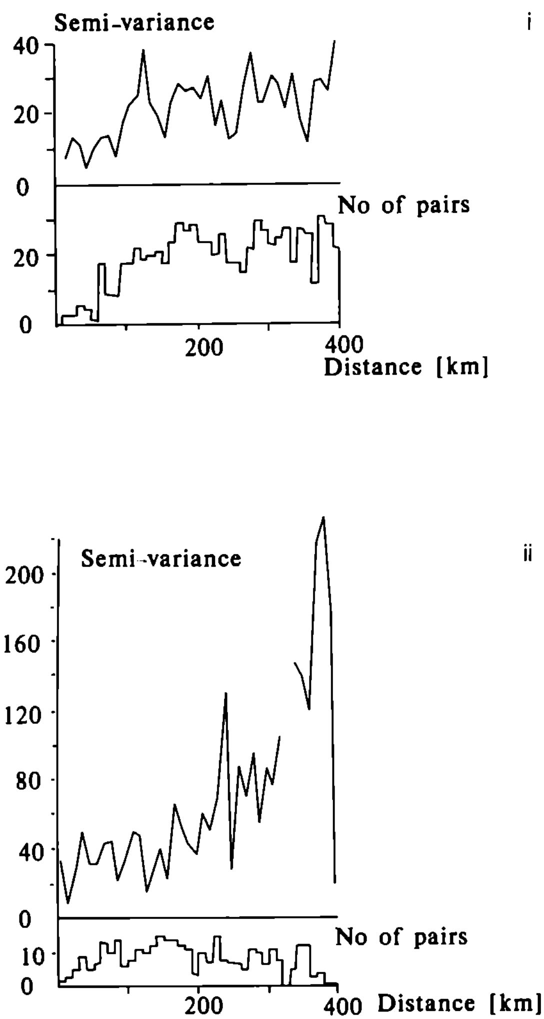


Figure A4. *Semi-variograms for Scots pine, i. north–south, ii. east–west.*

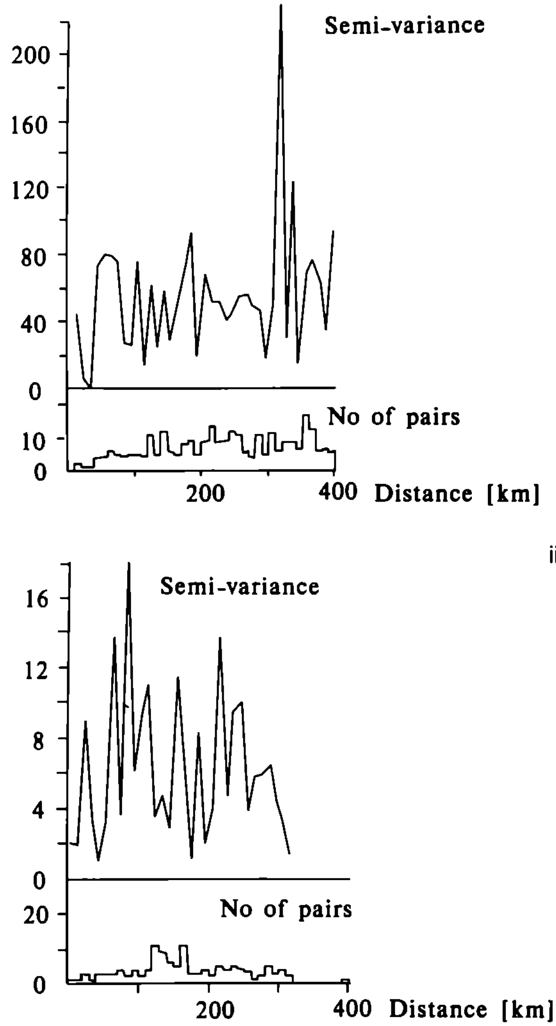


Figure A5. *Semi-variograms for oak, i. north–south, ii. east–west.*

Scots pine (Figure A4)

In an east–west direction, the degree of variation between stands remains constant over distances of up to 150 km. At greater distances, there appears to be considerable spatial dependence, although the semi-variogram becomes unreliable at distances separated by more than 300 km. In a north–south direction, there is no apparent sill, indicating that the degree of variation between stands continues to increase at all sampling intervals used in this study.

Oak (Figure A5)

The reliability of the east–west semi-variogram is doubtful given the small numbers of pairs that the semi-variances are calculated from. Neither of the semi-variograms show a clear pattern. There is more variation between the lag distances in an east–west direction, although this may be the result of the smaller sample sizes. When the semi-variograms are combined (Figure A10), there is some evidence of a range and sill, with the spatial interdependence extending over distances of up to 200 km.

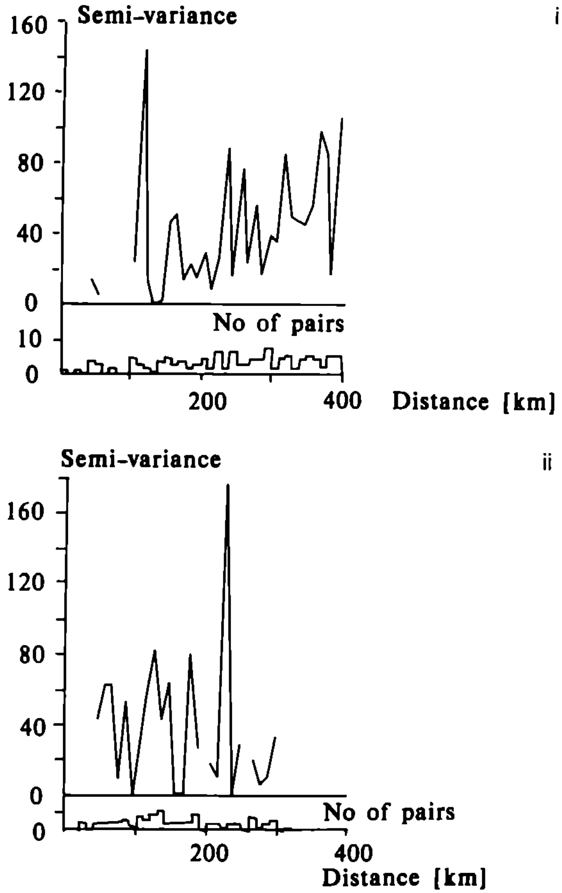


Figure A6. *Semi-variograms for beech, i. north–south, ii. east–west.*

Beech (Figure A6)

Both semi-variograms are likely to be of limited value because of the small numbers of pairs involved. Although there is considerable variation between the different lag intervals, there is a clear increase in the variation in a north–south direction. Over the distances sampled, there is no evidence of a sill indicating that the amount of variation continues to increase at lag intervals of 300 km or greater. In contrast, there is no evidence of any variation in an east–west direction.

The overall semi-variograms are presented in Figures A7-A11. Each of these shows the omnidirectional variation, and enables the spatial variation to be assessed. A discussion of each is presented in the main text.

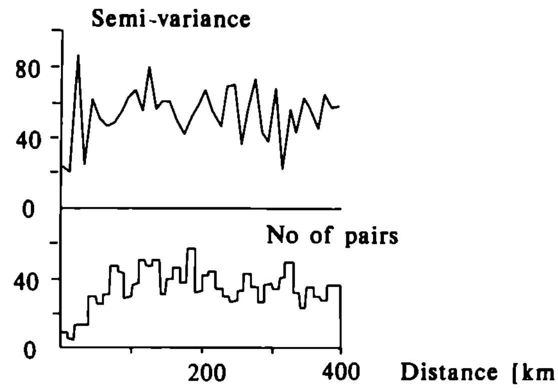


Figure A7. *Semi-variogram for Sitka spruce, all.*

Fitting models to the semi-variograms

If the semi-variograms are to be used to calculate the ranges over which interpolation can be safely undertaken, it is necessary to fit some form of model to them. A primary requirement of the model is that it be positive definite (Webster, 1985), to ensure that no negative variances are encountered. In the present study, three models were tested. In each case, they were applied to multidirectional semi-variograms. The semi-variograms, together with the fitted models, are presented in Figure A12. The three models can be described as:

(a) spherical

$$\begin{aligned}\gamma(h) &= C_0 + C_1\,[1.5(h/a) - 0.5(h/a)^3] \\ &\quad \text{for } 0 < h < a \\ &= C_0 + C_1 \\ &\quad h \geqslant a\end{aligned} \tag{8}$$

(b) exponential

$$\gamma(h)\; C_0 + C_1\,[1 - \exp(-\,h/a)] \tag{9}$$

(c) Gaussian

$$\gamma(h)\; C_0 + C_1\,[1 - \exp(-(h^2/a^2))] \tag{10}$$

In all cases, the first estimate of the parameters used all the data points from the semi-variogram. In one case, that for beech, there was a clear outlier in the data (located at the 10–20 km lag interval). Models have been generated for the beech data excluding this point. The summary statistics for each model and data set are presented in Table A1. The

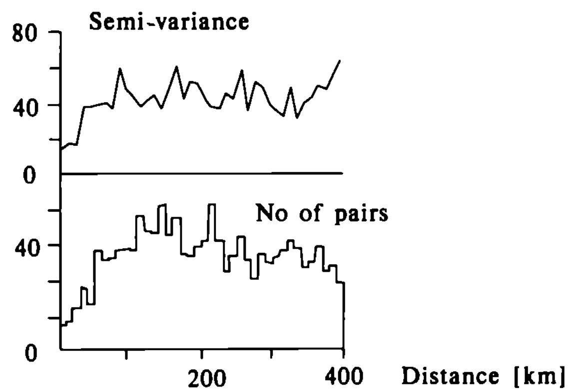


Figure A8. *Semi-variogram for Norway spruce, all.*

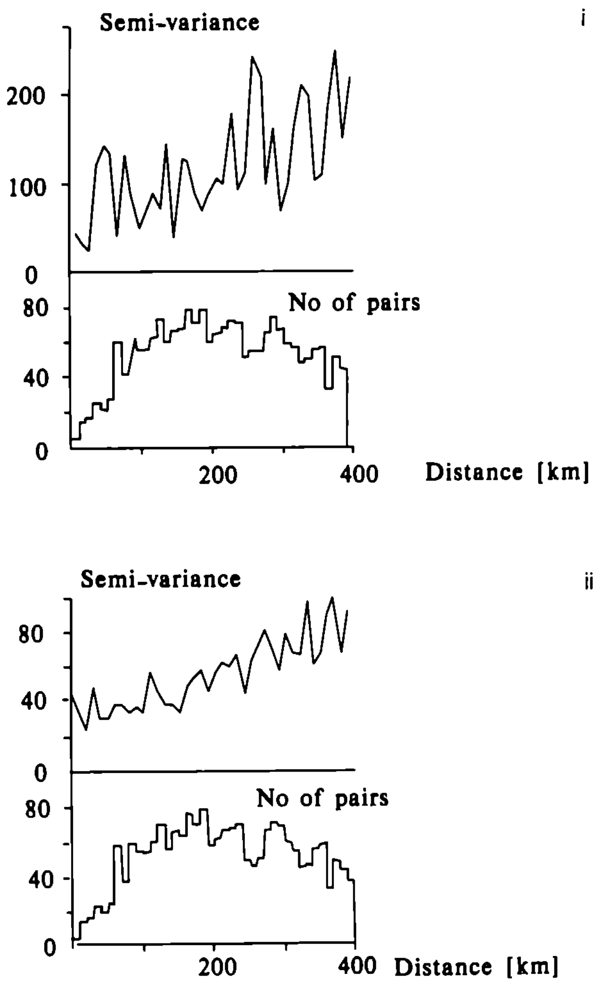


Figure A9. *Semi-variograms for Scots pine, i. all, ii. all except two sites.*

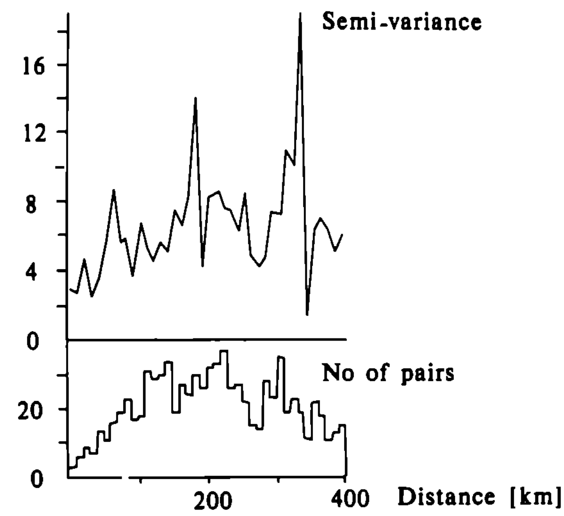


Figure A10. *Semi-variogram for oak, all.*

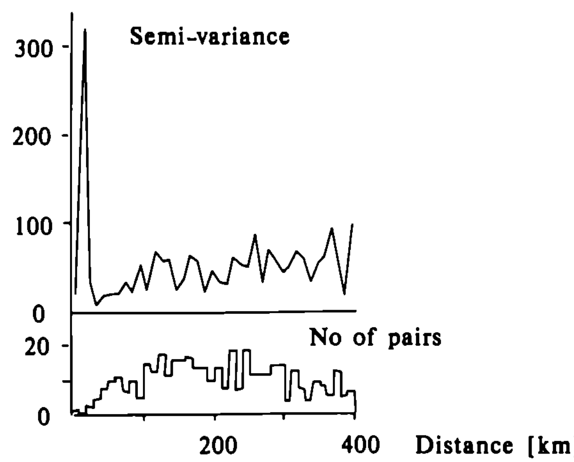
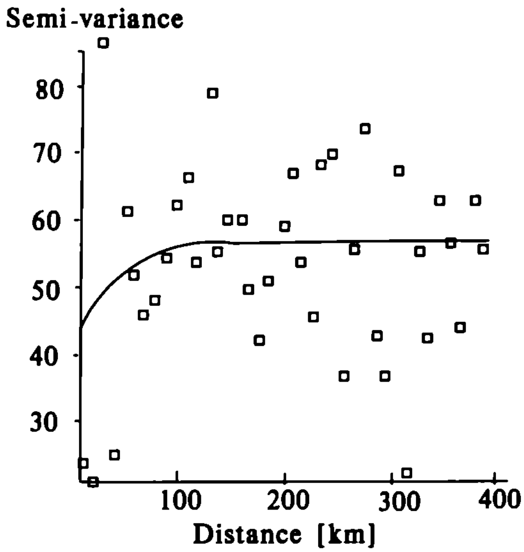
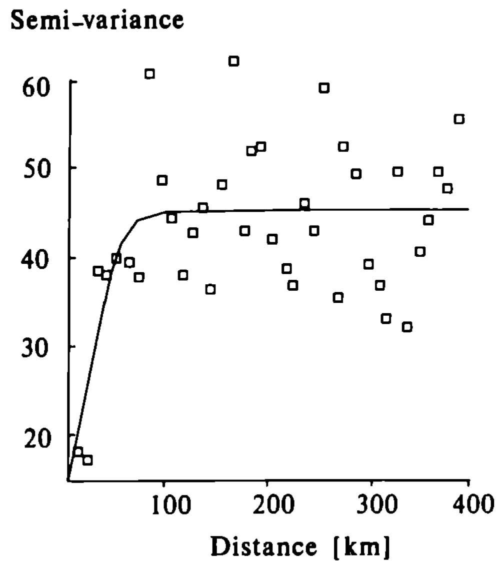


Figure A11. *Semi-variogram for beech, all.*

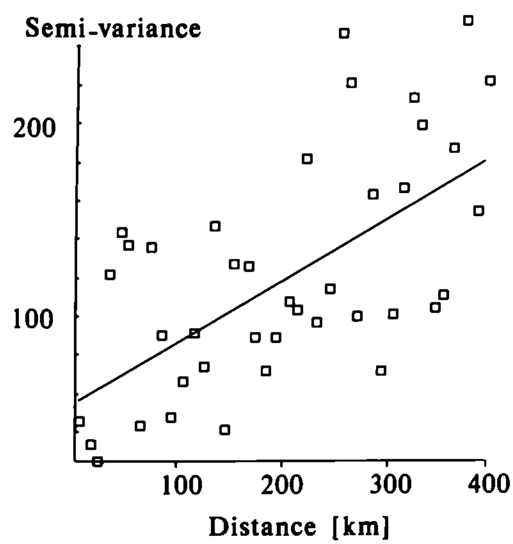
amount of variance explained by each model is generally low with the greatest amount of variation being explained with the Scots pine data set. In several cases, convergence between the model and the data was not achieved, although the final models accounted for relatively high proportions of the variance. Conversely, some of the models where convergence was reached accounted for very low proportions of the variance. None of the models could be fitted to the Sitka spruce data. For construction of the maps shown (Figures 4–9), the parameters derived from the spherical model have been used as this appears to be the most favoured model in other studies using the technique. In Table A2, the summary statistics for the other parameters describing crown condition are given. These have been used to calculate the ranges used in the construction of the maps presented in Figures 4 to 8.



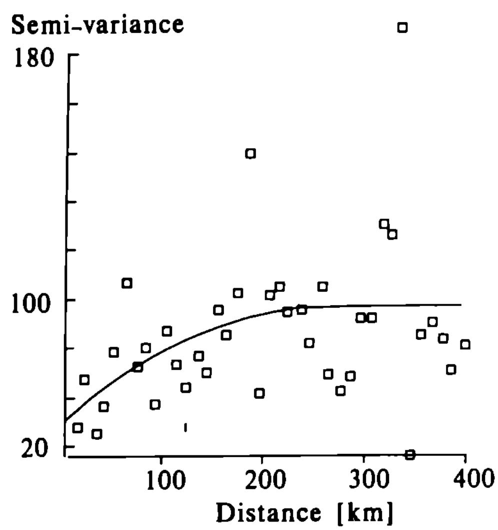
i. Semi-variogram for Sitka spruce, crown density.



ii. Semi-variogram for Norway spruce, crown density.

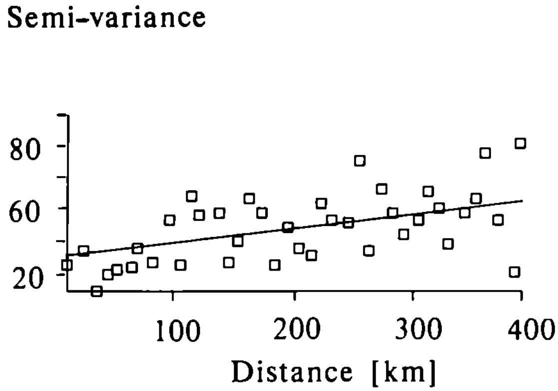


iii. Semi-variogram for Scots pine, crown density.

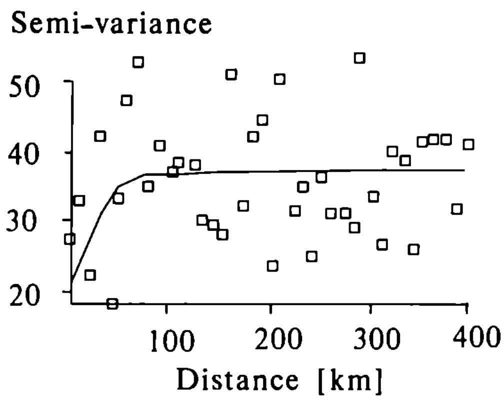


iv. Semi variogram for oak, crown density.

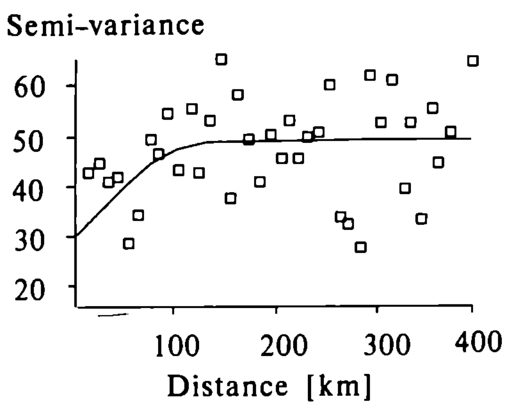
Figure A12.



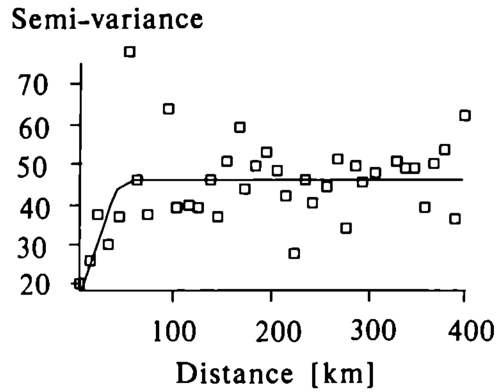
v. Semi-variogram for beech, crown density. The plot includes the anomalous point.



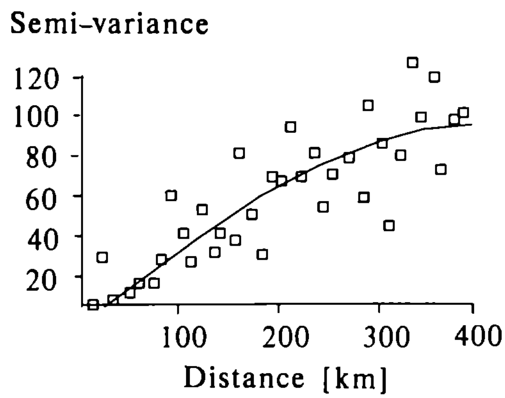
vi. Semi-variogram for Sitka spruce, dead shoots in live crown.



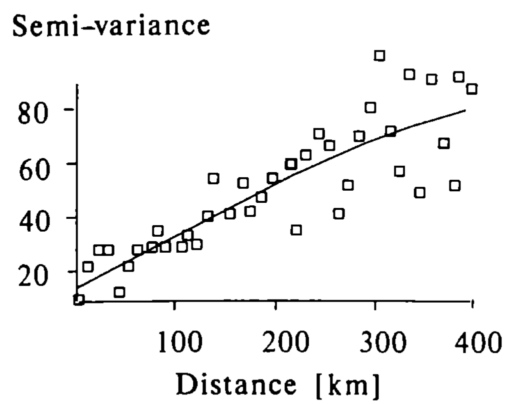
vii. Semi-variogram for Norway spruce, dead shoots in live crown.



viii. Semi-variogram in Scots pine, dead shoots in live crown.

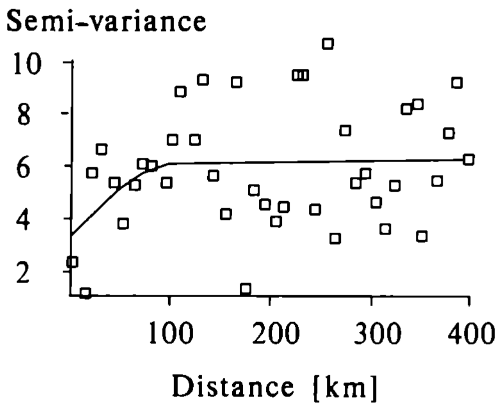


ix. Semi-variogram for Sitka spruce, less than 7 years' needle retention.

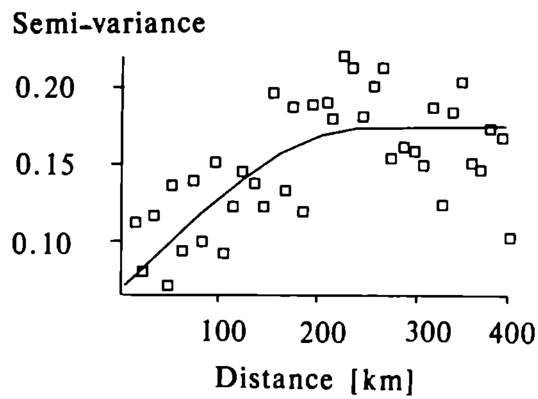


x. Semi-variogram for Norway spruce, less than 7 years' needle retention.

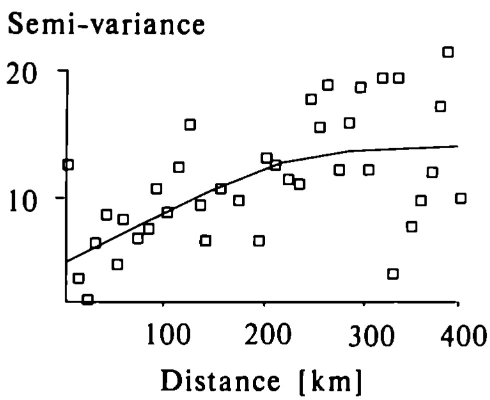
Figure A12 *(continued)*



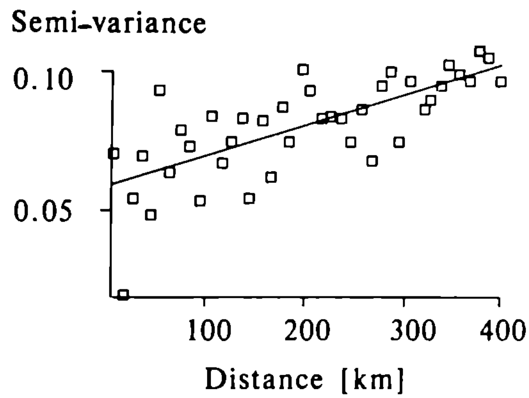
xi. Semi-variogram for Sitka spruce, yellowing of older needles.



xiii. Semi-variogram for Scots pine, needle retention.



xii. Semi-variogram for Scots pine, total discoloration.



xiv. Semi-variogram for Scots pine, flowering.

Table A1. Summary of semi-variogram models for crown density data. The models for beech were constructed omitting the large *y(h)* value at $h = 20$.

	Sitka spruce	*Norway spruce*	*Scots pine*	*Oak*	*Beech*
Isotropic spherical					
Convergence	No	No	No	No	No
% VAF	Residual exceeds *y*	20.9	29.5	7.9	23.6
range (km)	106	88	139758	233	3211
C1	13	33.61	30010	47	43
nugget variance	42	11.89	52.99	29.95	16.5
Exponential					
Convergence	No	Yes	Yes	No	No
% VAF	Residual exceeds *y*	8.5	29.5	7.3	25.1
range (km)	7	−15	36514	108	1181
C1	50	$-0.4\ E^{-10}$	11827	55	59
nugget variance	4.67	43.3	52.8	26.4	3.75
Gaussian					
Convergence	No	Yes	Yes	Yes	No
% VAF	Residual exceeds *y*	20.8	29.4	7.7	23.7
range (km)	14	38	271	134	1135
C1	35	31.8	120.1	37.4	41.2
nugget variance	19.6	13.62	67.47	41.02	14.78

Table A2. Parameters for semi-variogram models of crown indices (excluding crown density). Only those indices for which a model could be generated have been included.

Species	*Index*	*Range (km)*	*Nugget*	*C1*
Sitka spruce	Yellowing of older needles	106	3.16	2.99
Sitka spruce	Number of trees with dead branches	78	20.43	16.35
Sitka spruce	Number of trees with < 7 years' retention	396	(−5.58)	99.38
Norway spruce	Number of trees with dead branches	130	28.76	20.12
Norway spruce	Number of trees with < 7 years' retention	543	12.85	73.71
Scots pine	Total discoloration	324	4.68	9.38
Scots pine	Flowering	>70000	0.05	5.41
Scots pine	Number of trees with dead branches	59	10.73	35.52
Scots pine	Mean needle retention	247	0.07	0.11

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Dd 291275 C2011/89 [492]

Key to abbreviations used in text and tables

Tree variables

propi	: proportion of trees with insect damage
propf	: proportion of trees with fungi present

Topographic variables

east	: grid easting to nearest 100 m
north	: grid northing to nearest 100 m
dfs	: distance from sea to nearest km
elev	: elevation above sea-level to 1 m
slow	: slope due east (+ve) or west (−ve)
slos	: slope due north (+ve) or south (−ve)
hor	: change of contour line passing through site
rug	: measure of local ruggedness
dfsw	: distance to west coast to nearest km
dfse	: distance to east coast to nearest km
hew	: highest elevation at any distance due west to 10 m
hee	: highest elevation at any distance due east to 10 m
sslope	: average slope at site

Climatic variables

JMairt	: estimated mean daily temperature January-March
AJairt	: estimated mean daily temperature April-June
JSairt	: estimated mean daily temperature July-September
ODairt	: estimated mean daily temperature October-December
JMrain	: estimated total precipitation January-March
AJrain	: estimated total precipitation April-June
JSrain	: estimated total precipitation July-September
ODrain	: estimated total precipitation October-December

Harwell variables

HNO	: mean annual concentration of nitric oxide (p.p.b.)
HNO2	: mean annual concentration of nitrogen dioxide (p.p.b.)
HHNO3	: mean annual concentration of gaseous nitric acid (p.p.b.)
HO3	: mean annual concentration of ozone (p.p.b.)
HNH3	: mean annual concentration of gaseous ammonia (p.p.b.)
HSO2	: mean annual concentration of sulphur dioxide (p.p.b.)
HHCl	: mean annual concentration of gaseous hydrogen chloride (p.p.b.)
HNO3	: mean annual concentration of nitrate aerosol ($\mu g/m^3$)
HNH4	: mean annual concentration of ammonium aerosol ($\mu g/m^3$)
HSO4	: mean annual concentration of sulphate aerosol ($\mu g/m^3$)
HCl	: mean annual concentration of chlorine aerosol ($\mu g/m^3$)

Key to abbreviations used in text and tables

HpNO3	: mean annual concentration of nitrate in rain (mg N/1)
HpNH4	: mean annual concentration of ammonium in rain (mg N/l)
HpSO4	: mean annual concentration of sulphate in rain (mg S/l)
HpHCl	: mean annual concentration of chlorine in rain (mg Cl/l)
HNOdry	: total annual dry deposition of oxidised nitrogen compounds (kg N/ha/yr)
HNOwet	: total annual wet deposition of oxidised nitrogen compounds (kg N/ha/yr)
HNOtot	: total annual deposition of oxidised nitrogen compounds (kg N/ha/yr)
HNHdry	: total annual dry deposition of ammonia compounds (kg N/ha/yr)
HNHwet	: total annual wet deposition of ammonia compounds (kg N/ha/yr)
HNHtot	: total annual deposition of ammonia compounds (kg N/ha/yr)
HSOdry	: total annual dry deposition of oxidised sulphur compounds (kg S/ha/yr)
HSOwet	: total annual wet deposition of oxidised sulphur compounds (kg S/ha/yr)
HSOtot	: total annual deposition of oxidised sulphur compounds (kg S/ha/yr)
HCldry	: total annual dry deposition of chlorine compounds (kg Cl/ha/yr)
HClwet	: total annual wet deposition of chlorine compounds (kg Cl/ha/yr)
HCltot	: total annual deposition of chlorine compounds (kg Cl/ha/yr)

Warren Spring variables

WSnmSO4	: mean annual concentration of non-marine sulphate in rainfall, 1987 (μeq/l)
WSNO3	: mean annual concentration of nitrate in rainfall, 1987 (μeq/l)
WSNH4	: mean annual concentration of ammonium in rainfall, 1987 (μeq/l)
WSH	: mean annual concentration of hydrogen ions in rainfall, 1987 (μeq/l)
WSTSO4	: mean annual concentration of all sulphate in rainfall, 1987 (μeq/l)
WSnmSO4d	: wet deposited non-marine sulphate, 1987 (g S m^{-2})
WSNO3d	: wet deposited nitrate, 1987 (g N m^{-2})
WSNH4d	: wet deposited ammonium, 1987 (g N m^{-2})
WSHd	: wet deposited hydrogen ions, 1987 (g H^+ m^{-2})
WSTSO4d	: total wet deposited sulphate, 1987 (g S m^{-2})

Soil variables

prefix A	: sample from 10 cm depth
prefix B	: sample from 40 cm depth
pH	: pH measured in 1:5 soil–water mix
cond	: conductivity (μS)
Bufc	: buffering capacity (meq/100 g soil)
pcwat	: water content (%)
pcorg	: organic content (%)
cat	: cation exchange capacity (meq/100 g soil)
MgCa	: magnesium and calcium content (meq/100 g soil)
stone	: particles > 2 mm (%)
Ncont	: nitrogen content (p.p.m.)

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