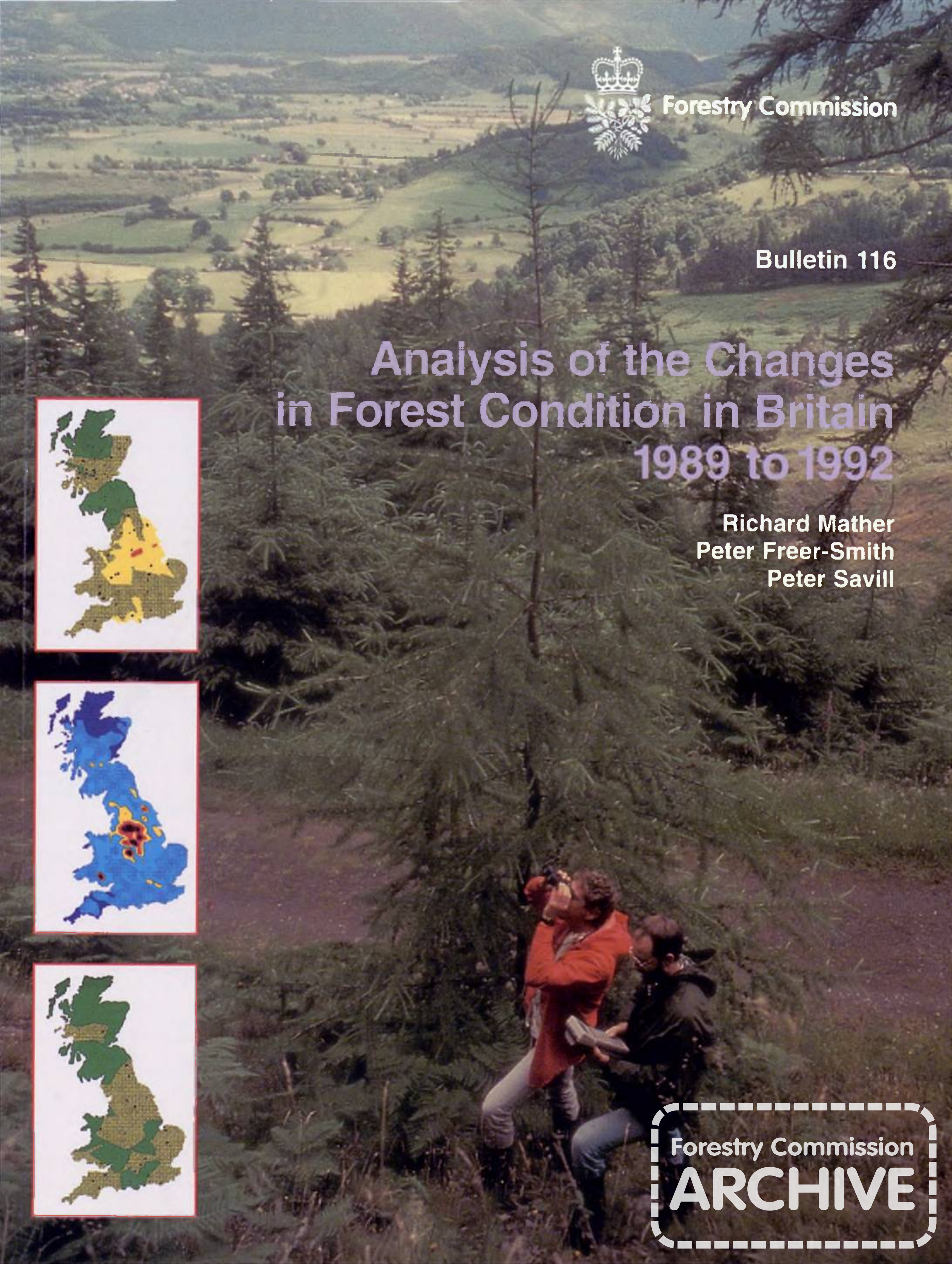

Forestry Commission

Bulletin 116

Analysis of the Changes in Forest Condition in Britain 1989 to 1992

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FORESTRY COMMISSION BULLETIN 116

Analysis of the Changes in Forest Condition in Britain 1989 to 1992

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LONDON: HMSO

ISBN 0 11 710331 4

Mather, Richard A.; Freer-Smith, Peter H.; Savill, Peter S. 1995. Analysis of the Changes in Forest Condition in Britain 1989 to 1992. Bulletin 116. HMSO, London. xxii + 62.

FDC 425.1:423.1:181.45:524.6:(410)

KEYWORDS: Forestry, Pollution, Tree condition

Acknowledgements

This project was jointly funded by the Forestry Commission and by Directorate General VI of the European Union. The authors gratefully acknowledge the support of both of these organisations.

The development of geographical information systems (GISs) and statistical analyses within the allocated time were only possible as a result of support from several organisations and enthusiastic assistance from many individuals. The authors wish to extend thanks to the following organisations:

- the Forestry Commission for the provision of data and continuing support throughout the duration of the project;
- the Institute of Terrestrial Ecology at Bush and Monks Wood for the provision of sulphur deposition, ozone exceedance and critical loads data;
- the Meteorological Office for providing essential data which were in the process of publication;
- the International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests at Hamburg and the Coordination Centre for Effects, Bilthoven, for preparations towards future development of a GIS for European data;
- Warren Spring Laboratory, Stevenage;
- the Climatic Research Unit, University of East Anglia.

Although the authors recognise contributions from many individuals, special mention must be made for: support throughout the project by Martin Parry and Paul Brignall towards the development of the GIS; assistance with data and statistical analyses by Roger Boswell, Ron Smith, Jean Power, Quentin Cronk, Robert Whittaker and Paula Harrison; advice from Derek Redfern and John Proudfoot concerning the interpretation of forest condition data; the preparation of photographic materials at short notice on several occasions by John Baker. The contribution made by John Innes towards initiating project work is also acknowledged.

Front cover: Conducting the forest monitoring programme in 1991 when a total of 8843 trees were assessed to determine changes in tree health. *(40589). Insets* GIS maps showing overall changes in crown density in Norway spruce (top) and beech (bottom), and total sulphate deposition (middle).

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Summary

A computer system was developed for mapping the Forestry Commission's records of forest condition in Great Britain. This facility also conveniently allows forest condition records to be combined with meteorological and pollution data.

The present Forestry Commission survey was evaluated to determine how well the design represented certain regional and local variations in environmental (including pollution) conditions across Great Britain. The survey was found to provide good representation over a wide range of possible combinations of meteorological and pollution conditions for the five species assessed, namely beech, oak, Sitka spruce, Norway spruce and Scots pine.

The availability of four years of forest condition data and recently developed pollution models also provided a valuable opportunity for investigating *medium-term changes in forest condition occurring between 1989 and 1992.* The analysis of forest condition is complicated by the large number of environmental factors influencing it. Therefore, a new statistical approach had to be used to separate those observed changes in condition which could be attributed to pollution from those due to the other environmental factors for which information was available. Results suggest that, overall:

- Drought is the major factor affecting the condition of trees.
- Of the relationships *uniquely* attributable to *modelled* pollution data, those of principal importance were for:
  - dieback in beech with ozone,
  - crown density in Norway spruce with sulphur deposition,
  - the extent of flowering in Scots pine with ozone.

To appreciate the full significance of the results of analyses it is first necessary to understand the following limitations imposed by the available data and the mathematical models used:

- Firstly, all the environmental information used explained *only* between five and ten per cent of all the variation in change in crown condition between 1989 and 1992; the variation explained by modelled pollution alone was *considerably* smaller.
- Secondly, it has not so far been possible to account for the considerable effects of mechanical damage (that due to wind, snow and storms) on forest condition. This is a major limitation to the model and it is highly probable that some of the variation attributed to sulphur deposition (which tends to

be greatest in elevated and exposed areas) may in fact be due to mechanical damage.

- Thirdly, the analyses are based entirely on *modelled* meteorological and pollution data. Although representing the best available data, these can only be regarded as a rough approximation to the environmental conditions experienced at specific sites. There may also be other important factors for which we do not have information.

Any statement of the statistical findings of this report without addressing the limitations of the data and analyses is a misrepresentation of the facts. The results (which are entirely consistent with earlier work reported by the Forestry Commission) indicate that although pollution may be a factor in influencing the health of British trees, with respect to the general condition of trees throughout Britain, the role of pollution is probably small. The analyses described in this report cannot establish a causal link between pollution and the forest condition.

The main value of this work is that it suggests approaches for separating and identifying effects due to different environmental (and pollution) influences. Further work of this type is already under way and it is expected that there will be an opportunity to conduct a similar investigation of changes in forest condition which have occurred in the European Community over the last ten years.

Analysis of the Changes in Forest Condition in Britain 1989 to 1992

Abstract

A geographical information system (GIS) has been developed for analysis of forest condition in Great Britain. Primary data include site mean forest condition indices for the years 1989 to 1992, changes between years and overall change between 1989 and 1992. Environmental data comprise complete mapped surfaces for annual and monthly meteorological variation, sulphur deposition, ozone exposure and the 10 x 10 km grid for critical loads of acidity for soils. Additional environmental data supplied on a site basis only were soil moisture deficits (MORECS), and 1 x 1 km critical loads for acidity of soils and their exceedances. Data sets are identified for further development of the GIS for Great Britain and for representation of forest condition in Europe.

Because procedures for recording forest condition were standardised between 1989 and 1992, and a general decline was observed for the condition of all species, except Sitka spruce, during this period, a unique opportunity existed for investigating medium-term changes in forest condition for Norway spruce (*Picea abies* (L). Karst.), Sitka spruce (*Picea sitchensis* (Bong.) Carr.), Scots pine (*Pinus sylvestris* L.), beech (*Fagus sylvatica* L.), oak (*Quercus petraea* (Mattuschka) Lieblein, *Q. robur* L. and their hybrids). Although other approaches were considered, statistical analyses were focused upon derived site indices expressing overall changes in forest condition between 1989 and 1992. The derived indices are referred to as the 8992 change indices.

The adequacy of site representation in the annual surveys of forest condition is considered with respect to environmental and pollution gradients, crown density data, and 8992 change indices. It was found, using a hypothetical scenario for factorial analysis of sulphur, ozone and potential evapotranspiration, that most of the possible species and environmental categories were represented using only those sites that were in existence in both 1989 and 1992. Recommendations are made for future representation of environmental strata with the advent of improved species 'receptor-based' critical load and exceedance data, and for optimising data returns from a new network of intensively monitored sites.

Analyses of statistical distributions for 8992 change indices show that: (1) discoloration indices were relatively poor at identifying differences between sites (a fact later confirmed in multivariate analyses), and (2) sample sizes were adequate for statistical representation of crown density in all species except Scots pine. Analyses of individual tree data for 1992 demonstrated that considerable between- and within-site variation existed for the crown densities of conifers, this being particularly evident in Sitka spruce. Spatial distributions of crown densities for the years 1989 to 1992 corroborated earlier observations. Data distributions also revealed that crown density is both temporally and spatially dynamic, and subject to considerable regional variations; this being particularly so for oak and Sitka spruce.

Although correlation analyses demonstrated that strong relationships exist between 8992 change data and environmental variables, the presence of multicollinearity amongst data (the interdependence of environmental and pollution variables) precluded inferences about possible causes and effects.

Redundancy analysis (the canonical form of principal component analysis) was chosen as the means for investigating 8992 change data because of its abilities to: (1) resolve partially confounding effects of multicollinearity; (2) constrain ordinations to be linear combinations of environmental data; (3) explore the possible usefulness of composite indices. Results of redundancy analyses indicated that most of the variation in 8992 change data could be attributed to the effects of water stress (as indicated by relationships with potential evapotranspiration and soil moisture deficit data). Results of partial redundancy analyses of residual variation (that remaining after explaining variation due to non-pollution factors), however, indicated that residual variation in many 8992 response variables was *uniquely* attributable to modelled pollution data. Although other significant relationships existed between individual 8992 change indices and pollution components of ordination axes, those of principal importance were: (1) dieback in beech with ozone exceedance; (2) crown density in Norway spruce with wet and dry deposition of sulphur; (3) the extent of flowering in Scots pine with ozone.

Analyse des changements observés dans l'état des forêts en Grande-Bretagne de 1989 à 1992

Résumé

Un système informatique a été mis au point pour faire la représentation cartographique des informations recueillies par la Forestry Commission sur l'état des forêts en Grande-Bretagne. Ce système fournit aussi un moyen commode de combiner les informations recueillies sue l'état des forêts avec des données météorologiques et de pollution.

On a procédé à l'évaluation du présent inventaire de la Forestry Commission pour déterminer l'exactitude avec laquelle sa conception représente certaines variations régionales et locales des conditions environnementales (pollution comprise) trouvées dans l'ensemble de la Grande-Bretagne. Il s'est avéré que l'inventaire offrait une bonne représentation des cinq espèces évaluées, à savoir: le hêtre, le chêne, l'épicéa de Sitka, l'épicéa commun et le pin d'Ecosse, et ce en prenant en compte un vaste éventail de combinaisons possibles des conditions météorologiques et de pollution.

La disponibilité de données relevées sur l'état de la forêt pendant quatre années et celle de modèles récemment mis au point pour simuler la pollution fournissaient une précieuse occasion d'étudier *les changements à moyen terme survenus dans l'état des forêts entre 1989 et 1992.* L'analyse de l'´tat des forêts se trouve compliquée par l'importance du nombre de facteurs environnementaux l'influençant. Il a donc fallu avoir recours à une nouvelle approche statistique pour séparer les changements d'état observés pouvant être attribués à la pollution, de ceux qui étaient dûs à d'autres facteurs environnementaux à propos desquels des informations étaient disponibles. Les résultats suggèrent que dans l'ensemble:

- la sécheresse est le principal facteur affectant l'état des arbres;
- parmi les relations *uniquement* attribuables aux données *obtenues par modélisation* de la pollution, celles qui avaient une importance principale concernaient:
  - le dépérissement des hêtres exposés à l'ozone,
  - la densité du couvert des épicéas communs avec dépôt de soufre,
  - l'importance de la floraison des pins d'Ecosse exposés à l'ozone.

Pour apprécier pleinement la signification des résultats obtenus lors de ces analyses, il faut tout d'abord comprendre les limitations suivantes qui sont imposées par les données existantes et les modèles mathématiques utilisés:

- Premièrement, toutes les informations environnementales utilisées n'expliquaient *que* de cinq à dix pour cent de toutes les variations constatées

dans le changement de l'état du couvert entre 1989 et 1992; la variation expliquée par la modélisation de la pollution à elle seule était *considérablement* moindre.

- Deuxièmement, il n'a pas été possible jusqu'à présent de rendre compte des effets considérables qu'ont les dommages d'origine mécanique (dûs au vent, à la neige et aux orages) sur l'état des forêts. Ce qui apporte des limitations importantes au modèle: il est fort probable qu'un certain nombre de variations attributées au dépôt de soufre (qui tend à être à son maximum dans les sites élevés et exposés aux éléments) puissent en fait être dues à des dommages d'origine mécanique.
- Troisièmement, les analyses sont entièrement basées sur des données météorologiques et de pollution *obtenues par modélisation.* Bien que représentant les meilleures données dont on dispose, elles ne peuvent être considérées que comme l'approximation sommaire des conditions environnementales survenant dans des sites particuliers. Il peut aussi y avoir d'autres facteurs importants aux sujet desquels nous ne possédons pas d'informations.

Toute formulation des conclusions statistiques de ce rapport qui serait faite sans aborder le problème des limitations présentées par les donnés et les analyses équivaudrait à une présentation déformée des faits. Les résultats (qui sont entièrement compatibles avec le compte rendu de travaux précédents effectué par la Forestry Commission) indiquent que bien que la pollution puisse être un facteur influençant la santé des arbres, si on considère l'état général des arbres dans l'ensemble de la Grande-Bretagne, le rôle joué par la pollution est probablement peu important. L'analyse décrite dans ce rapport ne peut établir de lien de cause à effet entre la pollution et l'état des forêts.

L'utilité essentielle de ces travaux est qu'ils suggèrent des façons de séparer et d'identifier les effets dûs aux différentes influences liées à l'environnement (et à la pollution). D'autres travaux de ce genre sont déjà en cours. Il est aussi prévu d'avoir la possibilité de réaliser une investigation similaire portant sur les changements de l'état des forêts survenus dans la Communauté européenne pendant ces dix dernières années.

Analyse des changements observés dans l'état des forêts en Grande-Bretagne de 1989 à 1992

Abrégé

On a procédé au développment d'un système d'information géographique (SIG) pour analyser l'état des forêts en Grande-Bretagne. Les données primaires utilisées se composent des indices d'état moyen des forêts concernant les années de la période 1989-1992, des changements survenant d'une année sur l'autre et du changement global survenu entre 1989 et 1992. Les données environnementales comprennent les représentations cartographiques de superficies entières montrant les variations météorologiques, le dépôt de soufre et l'exposition à l'ozone, annuels et mensuels, et font état d'un quadrillage de 10 x 10 km pour mesurer les taux critiques de l'acidité des sols. Les données environnementales supplémentaires fournies pour certains sites seulement étaient les déficits en eau du sol (MORECS), les taux critiques de l'acidité des sols et leurs dépassements, mesurés suivant un quadrillage de 1 x 1 km. On a identifié des groupes de données pour procéder à un plus ample développement du SIG propre à la Grande-Bretagne et pour aider à la représentation de l'état des forêts en Europe.

Du fait que les méthodes utilisées pour consigner l'état des forêts ont été standardisées entre 1989 et 1992, et qu'on a observé pendant cette période un déclin général de l'état de toutes les espèces à l'exception de l'épicéa de Sitka, il existait une occasion unique d'étudier les changements à moyen terme de l'état des forêts d'épicéas communs *(Picea abies* (L). Karst.), d'épicéas de Sitka *(Picea sitchensis* (Bong.) Carr.), de pins d'Ecosse *(Pinus sylvestris* L.), de hêtres *(Fagus sylvatica* L.) et de chênes *(Quercus petraea* (Mattuschka) Lieblein, *Q. robur* L. et leurs hybrides). Bien que d'autres approches aient été prises en considération, les analyses statistiques ont été concentrées sur les indices de site dérivés exprimant les changements globaux survenus dans l'état des forêts entre 1989 et 1992. Ces indices dérivés sont appelés les indices de changement 8992.

Dans les études annuelles portant sur l'état des forêts, on evalue la représentativité des sites en fonction des gradients environnementaux et de pollution, des données de densité du couvert et des indices de changement 8992. On a trouvé en ayant recours à un scénario hypothétique en vue de faire l'analyse factorielle du soufre, de l'ozone et de l'évapotranspiration potentielle, que la plupart des espèces possibles et des catégories environnementales étaient représentées uniquement à l'aide des sites existant à la fois en 1989 et en 1992. Des recommandations sont formul;ées pour effectuer la représentation future des couches de données environnementales avec la prise en compte de données améliorées concernant les taux critiques et leur

dépassement pour les espèces réceptrices, et pour optimiser les statistiques obtenues à partir des données provenant d'un nouveau réseau de sites faisant l'objet d'un suivi intensif.

Les analyses portant sur la distribution statistique des indices de changement 8992 montrent que: (1) les indices de décoloration étaient relativement peu capables d'identifier les différences existant entre les sites (un fait qui devait plus tard être confirmé par les analyses multivariables), et que (2) les tailles des échantillons convenaient lorsqu'il s'agissait de faire la représentation statistique de toutes les espèces à l'exception du pin d'Ecosse. Les analyses des données recueillies en 1992 sur les arbres en tant qu'individus démontraient qu'il existait des variations considérables dans la densité du couvert des conifères, que ce soit dans un même site ou entre les différents sites, ce qui était particulièrement évident dans le cas de l'épicéa de Sitka. La distribution spatiale de la densité du couvert au cours des années allant de 1989 à 1992 corroborait les observations antérieures. La distribution des données révélait aussi que la densité du couvert est à la fois dynamique dans le temps et l'espace, et sujette à des variations régionales considérables; ceci étant particulièrement vrai pour le chêne et l'épicéa de Sitka.

Bien que l'analyse des corrélations ait démontré l'existence de relations fortes entre les données de changement 8992 et les variables environnementales, la présence d'une multicollinéarité entre les données (l'interdépendance des variables ayant trait à l'environnement et à la pollution) empêchait d'en déduire les causes et effets possibles.

L'analyse de 'redondance' (la forme canonique de l'analyse en composantes principales) a été choisie comme moyen d'étudier les données de changements 8992 du fait de ses capacités de: (1) résoudre le problème des effets partiellement confondus de la multicollinéarité; (2) contraindre les ordinations à être des combinaisons linéaires de données environnementales; (3) explorer l'utilité possible des indices composites. Les résultats obtenus par les analyses de 'redondance' ont indiqué que la plupart des variations trouvées dans les données de changement 8992 pouvaient être attribuées aux effets du stress hydrique (comme l'indiquent les relations existant entre les données d'evapotranspiration potentielle et de déficit en eau du sol). Les résultats des analyses de redondance partielle portant sur les variations résiduelles (ce qui demeure après explication des variations dues aux facteurs étrangers à la pollution) indiquaient néanmoins que les variations résiduelles trouvées dans de nombreuses variables expliquant la réponse des arbres 8992 étaient *uniquement* attribuables aux données obtenues par modélisation de la pollution. Bien que d'autres relations significatives aient existé entre les indices individuels de changement 8992 et les axes d'ordination des composantes de la pollution, celles qui revêtaient une importance principale étaient: (1) le dépérissement du hêtre en présence d'un excès d'ozone; (2) la densité du couvert trouvée chez l'épicéa commun présentant un dépôt de soufre sec ou humide; (3) l'importance de la floraison chez le pin d'Ecosse exposé à l'ozone.

Analyse von Veränderungen im Forstzustand in Britannien von 1989 bis 1992

Zusammenfassung

Es wurde ein Computerprogramm entwickelt, um die forstbehördlichen Berichte des Forstzustandes in Großbritannien auszurbeiten. Diese Einrichtung hat auch den Vorteil, daß Forstzustandsberichte einfach mit meteorologischen und Umweltverschmutzungsdaten verbunden werden können.

Das gegenwärtige Gutachten der Forestry Commission wurde ausgewertet, um zu bestimmen wie gut der Entwurf gewisse regionale und lokale Unterschiede der Umwelteinflüsse (einschließlich Verschmutzung) in Großbritannien darstellt. Es wurde festgestellt, daß das Gutachten ein weites Spektrum von möglichen Kombinationen verschiedener Wetter- und Umweltbedingungen gut darstellte. Die fünf untersuchten Baumarten sind: Buche, Eiche, Sitkafichte, Fichte und Kiefer.

Das Vorhandensein von Forstzustandsdaten über einen Zeitraum von vier Jahren und vor kurzem entwickelten Verschmutzungsmodelle, bot eine gute Gelegenheit, um *mittelfristige Veränderungen des Forstzustandes zwischen 1989 und 1992* zu untersuchen. Die Analyse des Forstzustandes wird durch die große Anzahl der äußerlichen Umwelteinflüsse erschwert. Daher wurde eine neue, statistische Methode benutzt, um die Veränderungen aufgrund von Verschmutzung, von denen aufgrund anderer, bekannter Umwelteinflüsse zu trennen. Die Ergebnisse deuten allgemein an, daß:

- Trockenheit der Hauptfaktor ist, der den Zustand der Bäume beeinflußt;
- von den Zusammenhägen, die sich '*einzig* auf *simulierte* Verschmutzungsdaten zurückführen lassen, die folgenden die wichtigsten waren:
  - Absterben von Buche mit Ozon,
  - Kronendichte bei Fichte mit Schwefelablagerung,
  - Umfang der Kiefernblüte mit Ozon.

Um die volle Bedeutung der Analyseergebnisse zu beurteilen, ist es nötig, die folgenden Begrenzungen durch vorhandene Daten und mathematische Modelle zu verstehen:

- Erstens, durch die Benutzung aller Umweltinformationen konnten *nur* fünf bis zehn Prozent der Variationen in Kronenzustand zwischen 1989 und 1992 erklärt werden; bei Benutzung simulierter Verschmutzung alleine war dieser Prozentstatz *bedeutend* niedriger.
- Zweitens, ist es bisher noch nicht möglich die besonderen Auswirkungen auf den Forstzustand durch mechanische Schäden (durch Wind, Schnee und Sturm) zu belegen. Dies stellt eine große Einschränkung für das Model

dar und es ist gut möglich, daβ ein Teil der Variation, die der Schwefelablagerung (die in gehobenen und offenen Lagen am gröβten ist) zugeschrieben wird, in Wirklichkeit aufgrund von mechanischen Schäden ist.

- Drittens, die Analysen sind einzig auf *simulierte* meteorologische und Verschmutzungsdaten gestützt. Obwohl diese die besten, vorhandenen Daten darstellen, können sie nur als grobe Schätzung der Umweltbedingungen bestimmter Standorte angesehen werden.

Jegliche Aussage über die statistischen Ergebnisse dieses Berichts, die nicht die Beschränkung der Daten und Analysen erwähnt, ist eine Verdrehung der Tatsachen. Die Ergebnisse (welche vollkommen mit früheren Erkenntnissen der Forestry Commission übereinstimmen) deuten an, daβ Verschmutzung zwar ein Faktor sein kann, der die Gesundheit britischer Bäume beeinfluβt, aber in Bezug auf den Allgemeinzustand von Bäumen in ganz Britannien spielt Verschmutzung wahrscheinlich nur eine kleine Rolle. Die Analyse, die in diesem Bericht beschrieben wird, kann keinen Kausalzusammenhang zwischen Umweltverschmutzung und Forstzustand aufstellen.

Der Hauptwert dieser Arbeit liegt darin, daβ sie Wege zur Trennung und Identifizierung von Auswirkungen aufgrund verschiedener Einflüsse durch Umwelt (und Verschmutzung) darlegt. Weitere Arbeit dieser Art ist schon im Gange und es ist zu erwarten, daβ es eine Gelegenheit geben wird, eine ähnliche Untersuchung, der Veränderungen im Forstzustand in der Europäischen Union während der letzten zehn Jahre, durchzuführen.

Analyse von Veränderungen im Forstzustand in Britannien von 1989 bis 1992

Auszug

Es wurde ein geographisches Informationssystem (GIS) entwickelt, um den Forstzustand in Groβbritannien zu analysieren. Die Primärdaten beinhalten standortliche, mittlere Forstzustands-Anzeiger, Veränderungen von Jahr zu Jahr und Gesamtveränderungen zwischen 1989 und 1992. Die Umweltdaten enthalten komplett kartographierte Darstellungen jährlicher und monatlicher meteorologischer Veränderungen, Schwefelablagerungen, Ozonbelastung und das 10 x 10 km Gitter der kritischen Bodenbelastung durch Säuren. Zusätzliche Umweltdaten, die nur auf einer Standortbasis angegeben wurden, waren Bodenfeuchtigkeitsmangel (MORECS), 1 x 1 km Gitter der kritischen Bodenbelastung durch Säuren und deren Überschreitungen. Es werden Datenreihen angegeben, um das GIS in Groβbritannien weiter zu entwickeln und, um den Forstzustand in Europa darzustellen.

Da zwischen 1989 und 1992 die Methoden zur Aufzeichnung des Forstzustandes standardisiert wurden, und während dieses Zeitraumes eine allgemeine Zustandsverschlechterung aller Arten, auβer Sitkafichte, festgestellt wurden, bot sich eine einzigartige Gelegenheit mittelfristige Verändurungen im Zustand folgender Arten zu untersuchen: Fichte (*Picea abies* (L.) Karst.), Sitkafichte (*Picea sitchensis* (Bong.) Carr.), Kiefer (*Pinus sylvestris* L.), Buche (*Fagus sylvatica* L.), Eiche (*Quercus petraea* (Mattuschka) Lieblein, Q. *robur* L. und deren Kreuzungen). Obwohl andere Verfahren in Erwägung gezogen wurden, haben sich die statistichen Analysen auf die gewonnenen Standortregister konzentriert die die allgemeinen Zustandsveränderungen von 1989 bis 1992 beschreiben. Diese gewonnenen Register werden 8992 Veränderungsanzeiger genannt.

Die Eignung der Standortdarstellung in den jährlichen Gutachten des Forstzustandes wurde, in Bezug auf Umwelt- und Verschmutzungsanstieg, Kronendichtedaten und 8992 Veränderungsanzeiger, geprüft. Es wurde, anhand eines hypothetischen Szenarios zur realen Analyse von Schwefel, Ozon und möglichem Wasserverlust von Boden und Pflanzen (Evapotranspiration), herausgefunden, daβ die meisten möglichen Arten und Umweltkategorien dargestellt wurden, indem man nur die Standorte benutzte, die sowohl 1989 als auch 1992 vorhanden waren. Es werden Vorschläge gemacht, zur zukünftigen Darstellung der Umweltschichten durch das Erscheinen verbesserter Arten- 'Emphänger gestützter' kritischer Belastungs- und Überschreitungsdaten und zur Optimalisierung der Datenmeldung durch ein neues Netz von intensiv beobachteten Standorten.

Die Analyse der statistischen Verteilung der 8992 Veränderungsanzeiger zeigt, daβ (1) Verfärbung ein relativ schlechter Anzeiger war, um die Unterschiede zwischen Standorten zu identifizieren (eine Tatsache die später durch Multivariantenanalyse bestätigt wurde) und, daβ (2) die Stichprobengröβe in allen Arten auβer Kiefer zur statistischen Darstellung der Kronendichte ausreichend war. Analyse der Daten einzelner Bäume in 1992 zeigte, daβ, in Bezug auf Kronendichte bei Nadelbäumen, groβe Unterschiede zwischen und innerhalb von Standorten bestehen, dies ist besonders deutlich in der Sitkafichte. Die räumliche Verteilung der Kronendichte in den Jahren 1989 bis 1992 bestätigt frühere Beobachtungen. Die Datenverteilung zeigte auch, daβ Kronendichte sowohl zeitlich als auch räumlich dynamisch ist und erheblichen regionalen Variationen unterliegt, dies gilt vor allem für Eiche und Sitkafichte.

Obwohl Vergleichsanalysen zeigten, daβ es eine starke Beziehung zwischen 8992 Veränderungsanzeigern und umweltlichen Variationen gibt, verhindert es die vorhandene Multikollinearität zwischen Daten (die gegenseitige Abhängigkeit der Umwelt- und Verschmutzungsvariablen) Folgerungen über mögliche Urscahen und Auswirkungen zu ziehen.

Redundantanalyse (die kanonische Form der Hauptkomponentenanalyse) wurde zur Untersuchung der 8992 Veränderungsdaten gewählt, da sie fähig ist: (1) verwirrende Auswirkungen der Multikollinearität teilweise zu beheben; (2) Anordunungen auf lineare Kombinationen von Umweltdaten zu begrenzen; (3) den möglichen Nutzen von Verbundsanzeigern zu untersuchen. Die Ergebnisse der Überfluβanalyse deuten an, daβ die meisten Variationen in den 8992 Veränderungsdaten den Auswirkungen von Wasserstress angerechnet werden könnten (die wird durch die Beziehung zwischen möglicher Evapotranspiration und Bodenfeuchtigkeitsmangeldaten angedeutet). Ergebnisse von teilweisen Überfluβanalysen der verbleibenden Variation (die übrigbleibt nachdem man Variationen durch Nicht-Verschmutzungsfaktoren erklärt hat) zeigt jedoch, daβ diese verbleibende Variation in vielen 8992 Antwortvariablen *einzig* aufgrund von simulierten Verschmutzungsdaten bestand. Obwohl es andere wichtige Beziehungen zwischen individuellen 8992 Veränderungsanzeigern und Verschmutzungskomponenten der Anordnungslinie gibt, sind die folgenden die wichtigsten: (1) Absterben bei Buche mit Ozonüberschreitung; (2) Kronendichte bei Fichte mit nasser und trockener Schwefelablagerung; (3) Umfang der Kiefernblüte mit Ozon.

Análisis de los Cambios en la Condición de los Bosques en Gran Bretaña 1989 a 1992

Resumen

Se desarrolló un sistema asistido por ordenador para trazar mapas de los datos de la Forestry Commission sobre la condición de los bosques en Gran Bretaña. Este sistema también permite combinar conveniontemente los datos de la condición de los bosques con datos meteorológicos y datos sobre contaminación.

Se evaluó este reconocimiento por la Forestry Commission para determinar como el diseño representa ciertas variaciones regionales y locales en las condiciones environmentales (incluido contaminación) por Gran Bretaña. Se halló que el reconocimiento da una representación buena sobre una gama amplia de combinaciones posibles de condiciones meteorológicos y contaminación para las cinco especies consideradas, es decir la haya, el roble, el abeto Sitka, el abeto rojo y el pino silvestre.

La disponibilidad de cuatro años de datos sobre la condición de los bosques, y los modelos recientes de contaminación, dio también una oportunidad valiosa para investigar *cambios de medio plazo en la condición de los bosques durante el período de 1989 a 1992.* El análisis de la condición de los bosques es complicado por los factores numerosos environmentales que lo influyen. Por eso, debe utilizar un método estadístico neuvo para separar los cambios observados en la condición imputables a la contaminación de los cambios imputables a los otros factores environmentales para los cuales información sea disponible. Los resultados indican por lo general que:

- La sequía es el factor mayor que afecta la condición de los árboles;
- Entre las relaciones imputables *únicamente* a datos *modelados* de contaminación, las más importantes fueron:
  - muerte regresiva en la haya con ozono,
  - densidad de la copa en el abeto rojo con la deposición de azufre,
  - el grado de la floración en el pino silvestre con ozono.

Para apreciar la significancia entera de los resultados del análisis, es necesario en primer lugar entender las limitaciones siguientes impuestas por los datos disponibles y por los modelos matemáticos utilizados:

- En primer lugar, toda la información environmental explicó *solamente* entre cinco y diez por ciento de la variación total en el cambio de la condición de las copas entre 1989 y 1992; la variación explicada solamente por contaminación modelada fue *mucho* más menor.
- En segundo lugar, no es posible hasta ahora tener en cuenta los efectos considerables de los daños mecánicos (por viento, nieve y temporales) sobre

la condición de bosques. Este es una limitación mayor para el modelo, y es muy probable que algo de la variación imputable a la deposición de azufre (que tiene tendencia de ser más grande en lugares elevados y desabrigados) sea de hecho debido a los daños mecánicos.

- En tercer lugar, el análisis se basa enteramente sobre datos *modelados* meteorológicos y de contaminación. Bien que los datos sean los mejores disponibles, pueden considerarse solamente como una aproximación a las condiciones environmentales que se hallan en estaciones particulares. Es posible que existen otros factores importantes para los cuales no tenemos ninguna información.

Toda declaración de las conclusiones estadísticos en este informe sin tener cuenta de las limitaciones de los datos y de los métodos analíticos es una tergiversación de los factos. Los resultados (que son completamente conformes con los informes anteriores de la Forestry Commission) indican que aunque la contaminación sea un factor que influye la sanidad de los árboles en Gran Bretaña, el papel de contaminación es probablemente pequeño. El análisis descrito en este informe no puede establecer una relación causal entre contaminación y la condición de los bosques.

La importancia principal de este trabajo es que indica métodos para separar y identificar los efectos debidos a varias influencias environmentales (y contaminación). Más trabajo de este tipo es ya en marcha, y se espera que vendrá una oportunidad para hacer una investigación semejante de los cambios en la condición de los bosques que han ocurrido en la Comunidad Europea durante los diez años pasados.

Análisis de los Cambios en la Condición de los Bosques en Gran Bretaña 1989 a 1992

Abstracto

Se ha desarrollado un sistema de información geográfica (SIG) para el análisis de la condición de los bosques en Gran Bretaña. Los datos primarios incluyen índices de la condición media del bosque por estaciones para los años 1989 a 1992, cambios entre años, y cambios globales entre 1989 y 1992. Los datos environmentales son mapas completas para la variación, meteorológica anual y mensual, la deposición de azufre, la exposición a ozono, y la red 10 x 10 km para cargas críticas de acidez para los suelos. Datos environmentales adicionales disponibles solamente para estaciones individuas fueron; el déficit de la humedad del suelo (MORECS), cargas críticas de acidez del suelo en una red 1 x 1 km, y sus excedentes. Se identifican conjuntos de datos para el desarrollo del SIG para Gran Bretaña y para la representación de la condición de los bosques en Europa.

Porque los procedimientos para registrar la condición de los bosques se uniformaron entre 1989 y 1992, y se observó una declinación general en la condición de todas las especies, con excepción del abeto Sitka, durante este período, existía una oportunidad única para investigar cambios de medio plazo en la condición de los bosques para el abeto rojo (*Picea abies (*L.) Karst.), el abeto Sitka (*Picea sitchensis* (Bong.) Carr.), el pino silvestre (*Pinus sylvestris* L.), la haya (*Fagus sylvatica* L.), y el roble (*Quercus petraea* (Mattuschka) Lieblein, *Q. robur* L. y sus híbridos). Aunque otros métodos fueron considerados, se enfocó el análisis estadístico sobre índices de estación derivados que expresan cambios globales en la condición de los bosques entre 1989 y 1992. Los índices derivados se llaman los índices de cambio 8992.

Se trata la suficiencia de la representación de estaciones en los reconocimientos anuales de la condición de los bosques con respeto a los gradientes environmentales y los gradientes de contaminación, los datos de la densidad de las copas, y los índices de cambio 8992. Utilizando un escenario hipotético por el análisis factorial de azufre, ozono y evapotranspiración potencial, se determinó que la mayoría de las especies y de las categorías environmentales posibles se representaron solamente con esas estaciones que existían en 1989 y también en 1992. Se hacen recomendaciones para la representación futura de estratos environmentales con la disponibilidad de datos mejorados sobre las cargas críticas y los excedentes para especies 'receptores', y recomendaciones para optimizar los datos que vienen de una red nueva de estaciones con monitoring intensivo.

Los análises de distribuciones estadísticas para los índices de cambio 8992

indican que: (1) los índices de discoloración fueron relativamente inútil para identificar diferencias entre estaciones – facto confirmado más tarde por análisis con múltiples variables, y (2) los tamaños de las muestras fueron adecuados para la representación estadística de la densidad de las copas en todas las especies con excepción del pino silvestre. El análisis de los datos para árboles individuos por 1992 demostró que existía una variación considerable entre y dentro estaciones para las densidades de las copas de las coníferas, especialmente en el abeto Sitka. Las distribuciones espaciales de la densidad de las copas para los años 1989 a 1992 confirmaron las observaciones anteriores. Las distribuciones de los datos demonstraron también que la densidad de las copas tiene una dinámica temporal y espacial, y manifiesta variaciones regionales considerables; este vale especialmente para el roble y el abeto Sitka.

Aunque el análisis de corelación demonstró que existen relaciones fuertes entre los datos de cambio 8992 y variables environmentales, la presencia de multicolinearidad entre datos (interdependencia de variables environmentales y contaminación) excluye inferencias sobre causas y efectos posibles.

Se eligió el análisis de redundancia (la forma canónica del análisis de componentes principales) como el método para investigar los datos de cambio 8992, porque puede: (1) resolver los efectos parcialmente confundibles de multicolinearidad; (2) constreñir ordenaciones para ser combinaciones lineales de datos environmentales; y (3) explorar la utilidad posible de índices compósitos. Los resultados del análisis de redundancia indicaron que puede imputar la mayoría de la variación en los datos de cambio 8992 a los efectos del stress hídrico (como se muestra por las relaciones con evapotranspiración potencial y datos del déficit de la humedad del suelo). Sin embargo, los resultados del análisis de redundancia parcial de la variación residual (lo que queda después de explicar la variación debida a los factores otros que contaminación) indican que la variacion residual en muchos variables de la respuesta 8992 fue *únicamente* imputable a los datos modelados de contaminación. Aunque existían otras relaciones significativas entre índices individuales de cambio 8992 y componentes de contaminacion en los ejes de ordenación, los más importantes fueron: (1) muerte regresiva de la haya con un excedente de ozono; (2) densidad de la copa en el abeto rojo con la deposición húmeda y seca de azufre; y (3) el grado de la floración en el pino silvestre con ozono.

Chapter 1

Introduction

Historical background

Signs of extensive dieback first appeared in the early 1970s in silver fir (*Abies alba* Mill.) growing at high altitude in Germany. Further reports followed of declines in Norway spruce (*Picea abies* (L). Karst.) and in other species in Europe (Anon., 1990; Innes, 1987; Pearce, 1987). By 1984 many nations were conducting independent surveys of forest condition, to determine the extent of what was widely accepted to be pollution damage to forests throughout Europe (von Weissenberg *et al.*, 1993). The 'International Cooperative Programme on the Assessment and Monitoring of Air Pollution Effects on Forests' (ICP Forests), launched under the auspices of the 1985 Convention on Long-range Transboundary Air Pollution (CLRTAP) in 1985, became responsible for establishing an internationally standardised network of sites for monitoring the condition of European forests.

As a result of the joint activities of the then Commission of the European Communities (CEC) and independent states of Europe, in adopting the guidelines for 'harmonised survey' recommended by ICP Forests (representing the United Nations Economic Commission for Europe, UN–ECE), 34 countries now contribute to a common annual inventory representing 73 per cent of the total European forested area. This is based on assessments centred on a 16 × 16 km grid network, and comprises 113 000 trees at 4900 sites. Although a considerable undertaking, this only represents a small fraction of the total inventory undertaken in other independent national surveys (Anon, 1993; Landmann and Wermann, 1993).

In addition to agreements formed under CLRTAP (1985), international commitments to continue monitoring forest condition have been formalised in a growing body of European Union (EU) and other legislation. Two important sources include Council Regulation (EEC) No. 3528/86 (on the Protection of the Community's Forests against Atmospheric Pollution), and Strasbourg Resolution 1 (Sound Forestry – Sustainable Development) which concerns permanent sample plot monitoring of forest ecosystems. Although 'intensive' and 'ecosystem' studies based on permanent plots are also requirements of EC and ICP programmes, the extensive European network is based on nationwide assessments of crown density and foliage discoloration, conducted at the intersects of a systematic 16 × 16 km grid network. ICP Forests (1992) describe three 'levels' of sampling intensity. These comprise the extensive level I network which is primarily concerned with assessments of crown condition; level II 'intensive studies on permanent plots', involving additional survey of growth and yield, soil analysis and deposition; and level III sites for 'special forest ecosystem analyses', requiring detailed investigations of meteorological, deposition, soil and nutrient cycling processes.

The first of the annual inventories on forest condition in Great Britain was undertaken by the Forestry Commission in 1984 (Binns *et al.*, 1985). Until 1989 survey procedures were revised on many occasions. Although partly responding to changing perceptions of possible causal factors, alterations also complied with new Council Regulation (EEC) No. 1696/87, requiring contribution to a formal EC inventory

(Innes and Boswell, 1988), and the enforcing of ICP Forest recommendations to assess crown density in 5 per cent classes (Council Regulation (EEC) No. 2995/89) (Innes and Boswell, 1989). These changes have had the result that data from 1987 onwards cannot be compared with records for years 1984 to 1986. Other 'internal inconsistencies' in data collection, and new procedures for recording crown density, also prevented records for 1989 to 1994 being reliably compared with earlier data (Innes and Boswell, 1989).

In the absence of any strictly causal relationships and the recovery of many affected areas, the controversy surrounding forest decline continues. Early hypotheses, such as those proposing mechanisms of soil-mediated aluminium toxicity for declines in beech (*Fagus sylvatica* L.) and silver fir (Ulrich *et al.*, 1980; Ulrich, 1981), assumed an antecedent role for air pollution in decline. Other workers were unable to find sufficient evidence to support associations between acid deposition and damage to forest soils and crops (Binns and Redfern, 1982; Rehfuess, 1981). It is now widely accepted that the aetiology of forest decline rests upon 'multiple-stress' mechanisms (which may or may not involve pollution), and that processes vary considerably according to the species and site factors involved (for examples see Innes 1987, 1992a, 1993a; Kandler, 1993; Schlaepfer, 1993; Schulze and Freer-Smith, 1991). Nutritional imbalances are frequently implicated in declines, although the influence of acid deposition in soil mediated processes remains uncertain (Cape *et al.*, 1990; Innes, 1993b; Tomlinson, 1991; Zöttl and Hüttl, 1991). Difficulties in determining the nature of declines have been further compounded by problems relating to the consistency of field assessments, and the interpretation of defoliation data (Innes, 1992b; Innes *et al.*, 1993).

Project outline and objectives

The period 1989 to 1992, during which procedures for data collection had been standardised, was of particular interest. General aims were: to investigate the Forestry Commission's inventory of forest condition; to identify and suggest possible reasons for geographical and temporal variations in the crown conditions (principally as represented by crown density in the first instance) of Norway spruce (*Picea abies* (L). Karst.), Sitka spruce (*Picea sitchensis* (Bong.) Carr.), Scots pine (*Pinus sylvestris* L.), beech (*Fagus sylvatica* L.), oak (*Quercus petraea* (Mattuschka) Lieblein, *Q. robur* L. and their hybrids). The two main objectives were:

- To develop a geographical information system (GIS) to represent and integrate, where available, meteorological data, deposition and other pollution models and other factors believed to influence crown condition with UK forest inventory records for the period 1989 to 1992.
- To determine possible sources of variation in overall changes in forest condition between 1989 and 1992 in relation to available environmental data and pollution models.

In May 1993 additional objectives were added:

- To determine how effectively parameters recorded in the present survey explain variations in observations of crown condition.
- To comment, on the basis of information gained from the principal objectives, on survey design in preparation for 'intensive' monitoring (level II observation plots) survey required by a 1992 amendment to Commission Regulation (EEC) No. 3528/86.

GIS development proceeded alongside preparations for European forest condition and deposition data. Details of constraints to project progress, involving the availability of data and GIS development, are covered in an interim report (Mather, 1993). Many models for UK meteorological data, deposition, critical loads, and exceedances have only recently been developed and, therefore, were only available for release during the later stages of the project; final additions of critical load and meteorological data were made to the GIS in December 1993.

Chapter 2

Geographical Information System (GIS) and data

SPANS 5.2 was selected as the working GIS platform because of its abilities to perform quadtree data compressions (Burrough, 1992), and contend with multiple attribute data sets. A base map for Great Britain was provided by TYDAC Technologies Ltd and geocoded using the Universal Transverse Mercator (UTM) Coordinate System. The specifications of the systems currently in use and supporting software are:

Hardware A Viglen IBM compatible PC equipped with a 66 MHz CPU, 500 MB hard disk, 120 MB tape streamer (for data back-up), 8514/a and VGA graphics cards working in tandem and a high-resolution 43 cm 8514/a compatible monitor; HP LaserJet 4 printer with PostScript upgrade; HP PaintJet (for colour inkjet printing); V.22 bis modem for connection with Oxford University's 'Vax' mainframe computer; and Numonics Gridmaster digitising tablet.

Operating systems Two disk operating systems, OS/2 v.2.1 and MS DOS v.5.1 (with MS Windows v.3.1), residing on the same hard disk and working as a 'dual-boot' system for both OS/2 and DOS based GISs.

GIS software Systems were SPANS GIS v.5.2, SPANS MAP v.2.0 (for editing maps) and IDRISI GIS v.4. A terminal emulation and data transfer software were also installed for use on the University's mainframe resident Arc/Info v.6 (a vector based GIS). MS Windows based software was required for further graphical editing and for printing maps. Additional digitising software and. drivers were installed for the Numonics Gridmaster digitiser.

Supporting data handling and statistical software This includes the spreadsheet package MS Excel v.4.0, statistical packages Minitab v.8.2 Extended (MS DOS) and v.9 (Windows), StatGraphics v.6+, Canoco v.3.1 and CanoDraw v.3.0 multivariate analyses packages.

Data for Great Britain included site indices of forest condition for the years 1989 to 1992, meteorological data, and deposition and ozone models. Forest survey data were referenced by site number, Ordnance Survey eastings and northings, and longitude and latitude. Other site physical data were elevation, slope and aspect. Data used for UK based GIS work and analyses, and other data thought to be potentially useful for future UK and European/EC analyses were as follows.

Forest condition data

Both the individual tree data and site mean indices were obtained from the national inventory. The main focus for multivariate data analysis was the *change* in site 'mean' crown condition indices for the period 1989 to 1992. For example, a site where the mean crown density index of 15 per cent was recorded in 1989 and 25 per cent in 1992, would have undergone a 10 per cent reduction in crown density (or increase in transparency) over a three-year period.

The procedures used for assessing crown condition and the meaning and interpretation of data are fully described by Innes (1990, 1993a), and ICP Forests (1992). Site mean indices for crown condition (with corresponding codes in parentheses) are:

crown density (cd) An estimate of the proportion of light passing through the crown, more accurately termed crown transparency. It is visually assessed in 5 per cent classes relative to photographic standards; higher density classes (confusingly) indicate more extensive defoliation.

discoloration in conifers (bc, bo, yc, yo, di) and broadleaves (bn, ye, di) Site discoloration indices are based on the individual tree assessments of the percentage of discoloured foliage expressed in five categories (Innes, 1990). Conifer indices indicate the extent of browning (bc) (necrosis) and yellowing (yc) (chlorosis) of the current year's needles, and browning (bo) and yellowing (yo) of older foliage respectively. In beech and oak foliage is similarly assessed for browning (bn) and yellowing (ye). Assessments of overall discoloration (di) are also made for both conifers and broadleaves.

crown dieback (db) in broadleaves Expressed as a percentage of the crown that would have been there if no defoliation or dieback had been present.

crown form (cf) in broadleaves Use of Roloff categories to assess progressive stages of declining vigour of apical and side shoot growth (Roloff, 1985).

insect damage (id) and fungal damage (fd) Assessed as the proportions of foliage affected.

degree (rd) and frequency (rf) of leaf rolling in beech Believed to be responses to moisture stress, and recorded in seven and three progressive categories respectively.

premature loss of leaves (pl) for beech Assessed in classes indicating the abundance of green leaves on the ground below surveyed trees.

leaf size (ls) in beech Three classes indicating the presence of particularly small leaves, normal leaves and large leaves.

fruiting (ma, ac and co) Recorded in classes reflecting the abundance of beech mast (ma), acorns (ac) and cone production (co).

epicormics (ep) in oak Recorded in categories of abundance.

crown shoot death location (cr) and extent (sd) in spruce and Scots pine Seven location categories (cr) reflecting the progressive spread of shoot death throughout the crown and five 'extent' categories (sd) for the abundance of dead shoots.

the number of needle years (na and n7) Expressed both as the average (na) of all 24 assessed trees per plot, and as the proportion of trees in which the number of needle years represented were 7 (n7).

flowering in the upper crown (ft) and lower crown (fb) for Scots pine Recorded in five abundance categories reflecting the percentage of branches flowering.

derived site-mean change indices (xx_8992) Representing overall change in the site index between the 1989 and 1992 surveys, and used in multivariate analyses. Derived change data are indicated in text, figures and tables by attaching the suffix 8992, for example cd8992.

Meteorological data

Complete GIS digitised surfaces (Plate 1) for annual mean precipitation and temperature in Great Britain (variables coded anppt and antmp respectively), based on averages for the period 1951 to 1980, were edited from European data in the public domain. A surface for annual potential evapotranspiration (PET) was derived from these data using the Thornwaite method which, although overestimating PET under some circumstances (Kenny and Harrison, 1992), was thought to be an accurate indicator of relative PET throughout the UK. Digitised surfaces showing monthly values for precipitation and temperature based on 1951 to 1980 means were also included.

Recent Meteorological Office monthly records for precipitation and temperature could only be provided for sites on a 'nearest station' basis (for which many values were known to be missing), as opposed to more desirable interpolated values. Rainfall and temperature were, therefore, mapped on a monthly basis by creating a GIS template from the map of meteorological regions in the annual summary of Monthly Weather Reports (MWRs) (Meteorological Office, 1991). District values from published MWRs were attached to the GIS template to create 118 digital maps expressing *departures* from 1951 to 1980 monthly norms of rainfall and temperature, for the period January 1987 to September 1992.

Although expressions for departures from mean monthly rainfall and temperature were effective in explaining much variation in crown condition, there were uncertainties concerning their biological interpretation. This was particularly the case with respect to the percentage departures for rainfall and the crude representation of regional variations. Multivariate statistical analyses were therefore repeated using Meteorological Office Rainfall and Evapotranspiration System (MORECS) data.

MORECS uses the Penman-Monteith equation for evapotranspiration to estimate weekly and monthly evaporation and soil moisture deficits (SMD). Values were provided for the intersects of a 40 × 40 km grid over Great Britain. These were calculated using daily synoptic weather data for a variety of surface covers ranging from bare soil, through agricultural crops to deciduous and coniferous forest (Thompson *et al.*, 1981). MORECS data for the period April 1984 to September 1991 became available in December 1993. These were provided for forested surfaces, interpolated for sites by inverse quadratic distance weighting, and then corrected for site soil types. Monthly site mean values were calculated for the period October 1988 to September 1991 (the latter being the last available month for which data existed) and used in analyses of 8992 change data.

Deposition and ozone data

At the time of GIS development many deposition, critical load and meterological models available from ITE and the Meteorological Office were being revised. We were fortunate, therefore, to be provided with 20 × 20 km grid surfaces reflecting distribution of the two pollutants most frequently implicated in forest decline, namely sulphur dioxide and ozone, and also with data for critical loads for soil acidity and their exceedances.

In contrast to UK precipitation monitoring, which is based on a network of approximately 70 sites (the United Kingdom Review Group on Acid Rain (RGAR),1990), the national network for monitoring ozone comprises only 16 rural locations managed by Warren Spring Laboratory (The United Kingdom Photochemical Oxidants Review Group (PORG), 1987, 1993; Bower *et al.*, 1989, 1990, 1991; RGAR, 1990), supplemented with records from universities and other institutions. The exceedances of hourly average concentrations of 60 ppb were included in the GIS (Plate 2), and are based on the records of the Warren Spring Laboratory operated network for the period 1987 to 1991. These were interpolated on a 20 × 20 km grid network provided by ITE.

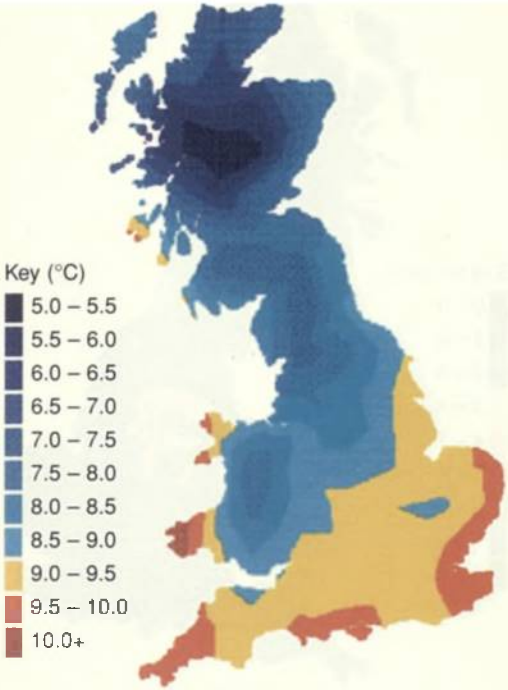
Spatial, seasonal, annual and chemical dynamics of ozone are complex and greatly influenced by the presence of oxides of nitrogen (NO_x), which act as sinks in urban areas (Bower *et al.*, 1989). Procedures for modelling ozone behaviour are described by Fowler and co-workers (1994). Interpretation of results based on associations with modelled ozone exceedances should proceed with caution. Although the indications are that the greatest potential for effects of ozone on vegetation exists in the SW, S and SE of England (Bower *et al.*, 1990), other models suggest that ozone episodes may also exceed daily vegetation thresholds in remote parts of Scotland (Bower *et al.*, 1991).

Mean annual dry, wet and cloud droplet sulphur depositions were provided as point data representing 20 × 20 km grid squares. The wet and cloud droplet deposition was calculated from non-marine sources of sulphate only. Wet deposition incorporates corrections for orographic effects on precipitation chemistry, such as the scavenging of cap clouds by the seeder-feeder process. Dry depositions are corrected for the influence of land-use on deposition velocity, but only on the basis of the proportions of land-use types within each grid square. Total sulphur deposition (Plate 3(d)) represents the sum of wet deposited sulphate, including seeder-feeder enhancement (Plate 3(a)), dry deposited SO_2 (Plate 3(b)) and occult deposition (sulphate deposited in cloud water) (Plate 3(c)) (RGAR, 1990). The sulphur models represented by the GIS were updated with records for 1989 to 1991, and were the most recent editions of the 1986 to 1988 models described in RGAR (1990) and United Kingdom Critical Load Advisory Group, CLAG (1994).

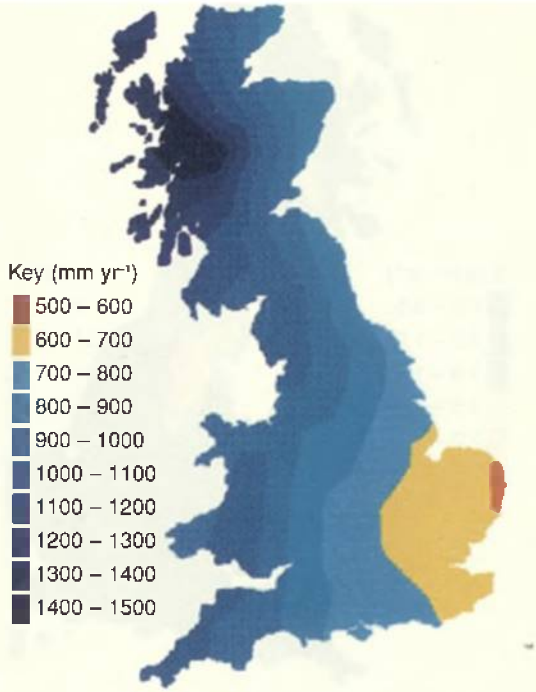
Because critical load mapping is now an integral part of the acid abatement strategy in Europe (Downing *et al.*, 1993), the critical load concept deserves some introduction. A critical load may be defined as '...the highest deposition of a compound that will not cause chemical changes leading to long-term harmful effects on ecosystem structure and function' (Downing *et al.*, 1993 after Nilson, 1986). The main focus of European efforts under the UN–ECE Convention on Long-Range Transboundary Air Pollution (CLRTAP) is to map critical loads for acidity and, by comparing these with pollutant deposition data, determine those areas in which deposition exceeds critical loads. Areas of 'exceedance' indicate where present levels of pollutant deposition increase the risk of damage to ecosystems. The greater deposition velocities associated with forested surfaces, due to their greater interception, have wide ranging implications for both soil and water exceedances (Freer-Smith and Benham, 1994).

At the European level, the Cooperative Programme for the Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe (EMEP) measures and models emissions and deposition patterns on a grid composed of 150 × 150 km cells. The Coordination Centre for Effects (CCE) uses EMEP data and supplements of national and IIASA (International Institute for Applied Systems Analysis) forest and soils data, to produce maps for critical loads at the same 150 × 150 km grid resolution (Hettelingh *et al.*, 1993a). Forestry information exists as a database file (FOREST.DBF) and may be made available for use in a European GIS for forest condition. Higher resolution mapping at national levels largely follows processes recommended by the CCE. In the UK critical loads for acidity of soils are available at 1 km resolution, and are now in the process of being modelled for a variety of receptors. These include a provisional map assuming complete cover by Norway spruce (Downing *et al.*, 1993).

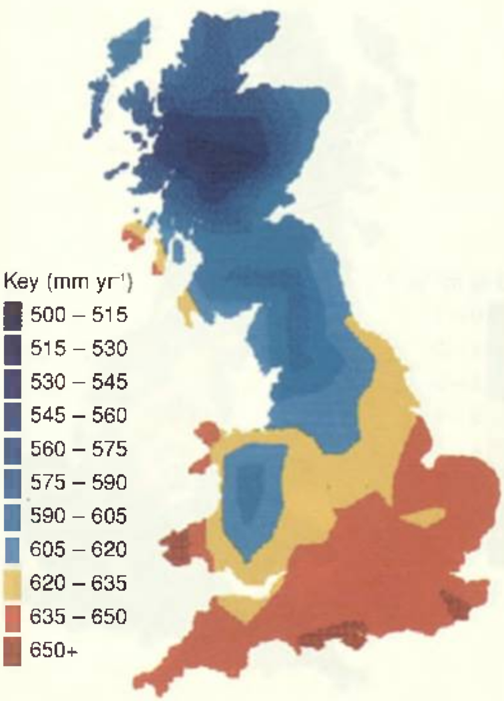
Two resolutions of critical loads data were made available by the Institute of Terrestrial Ecology, Monks Wood. British data directly incorporated within the GIS were based on critical loads for acidity of soils on a 10 km grid. These represented the dominant critical load for each 10 km square, deposition corrected on the basis of mean altitude for each 20 × 20 km square, and were derived from the 1 km data set. At a later stage data were obtained for individual 1 km squares corresponding to survey site locations. These were critical load classes for acidity for soils, with and without land-use modifications, and classes of exceedance of critical loads for acidity of soils. Exceedances are based on land-use modified critical loads and the mean deposition (sulphur plus nitrogen less non-marine base cations) for 1986-1988. Critical load and exceedance data were calculated using the 'level zero' empirical method for soils (Hettelingh *et al.*, 1991, 1993b; Downing *et al.*, 1993; CLAG, 1994).



(a) Temperature



(b) Precipitation



(c) Potential evapotranspiration

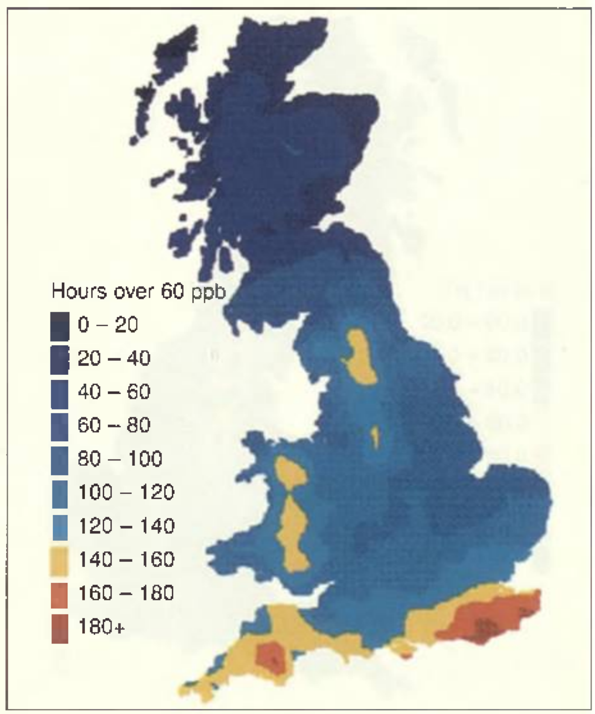


Plate 1(a)–(c) Annual mean temperature, precipitation and potential evapotranspiration, based on records for the period 1951 to 1980.

Plate 2 Ozone exposure: number of hours in which hourly average concentration exceeds 60 ppb, during the period April to September. Modelled on records for 1987 to 1991 and reproduced with kind permission of the Institute of Terrestrial Ecology.

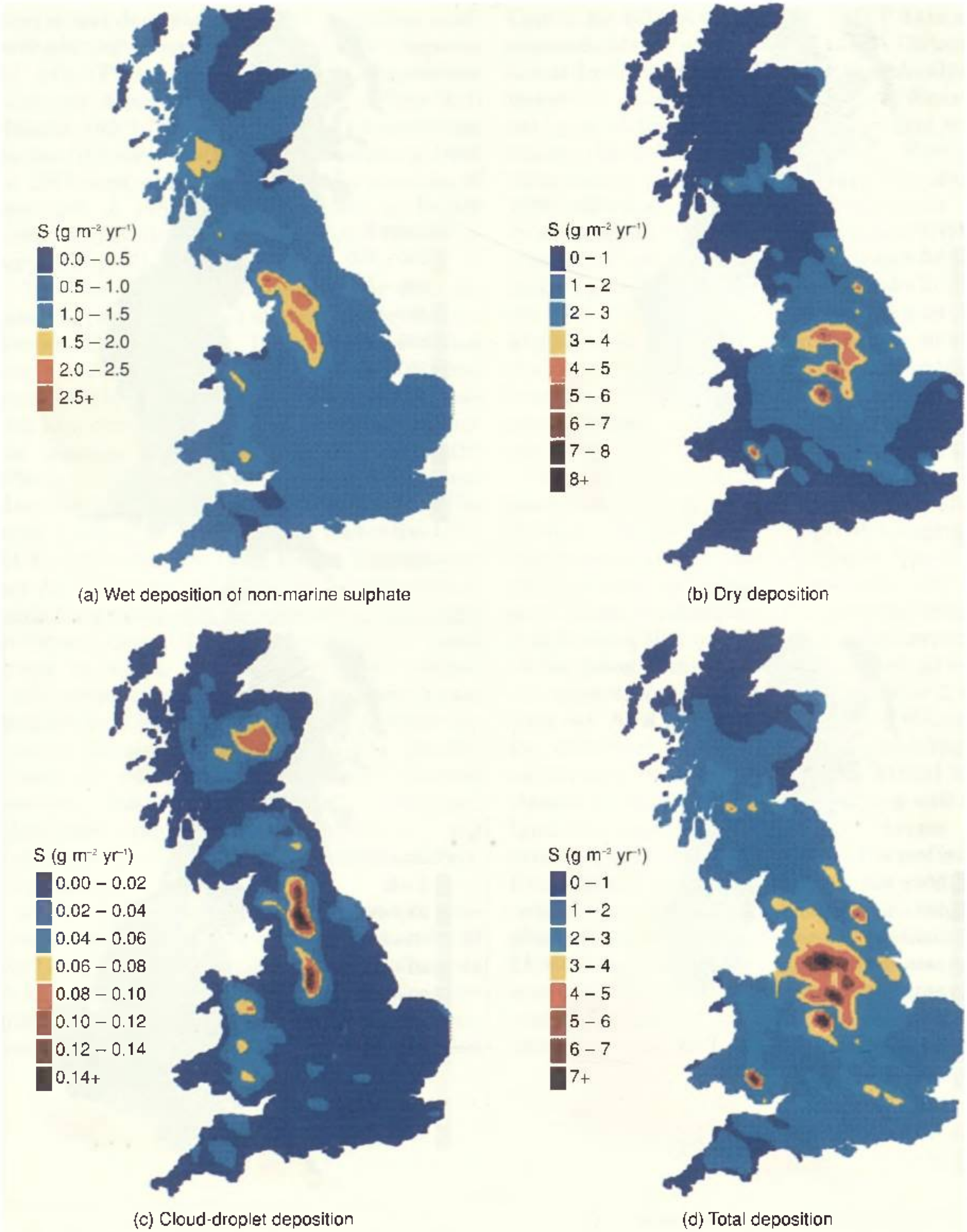


Plate 3(a)–(d) Mean annual deposition of sulphate. Modelled on records for 1989 to 1991 and reproduced with kind permission of the Institute of Terrestrial Ecology.

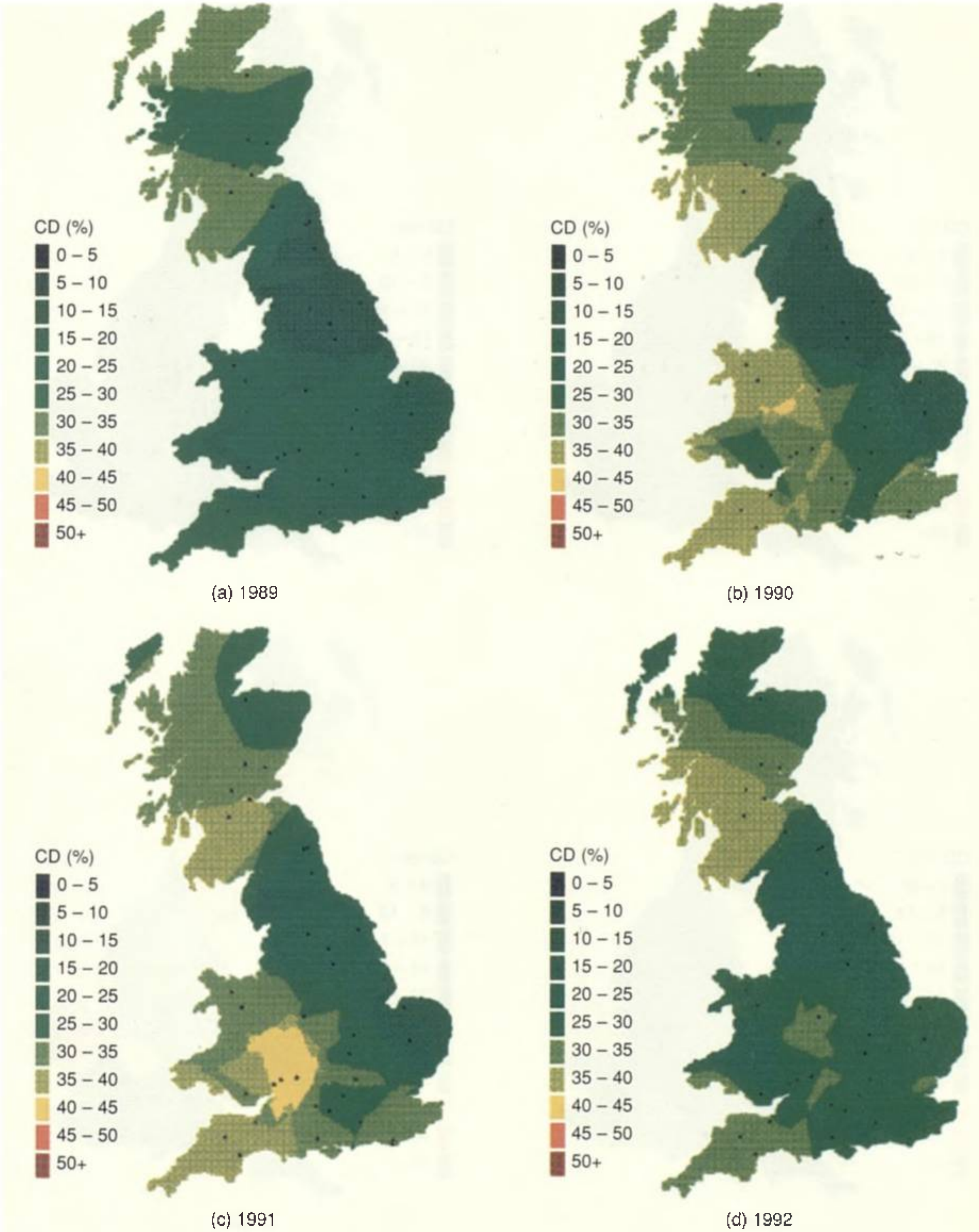


Plate 4(a)–(d) Beech crown density index 1989 to 1992. High scores indicate greater transparency; surfaces are interpolated as moving averages of three nearest sites within a maximum radius of 250 km, with inverse quadratic weighting for distance.

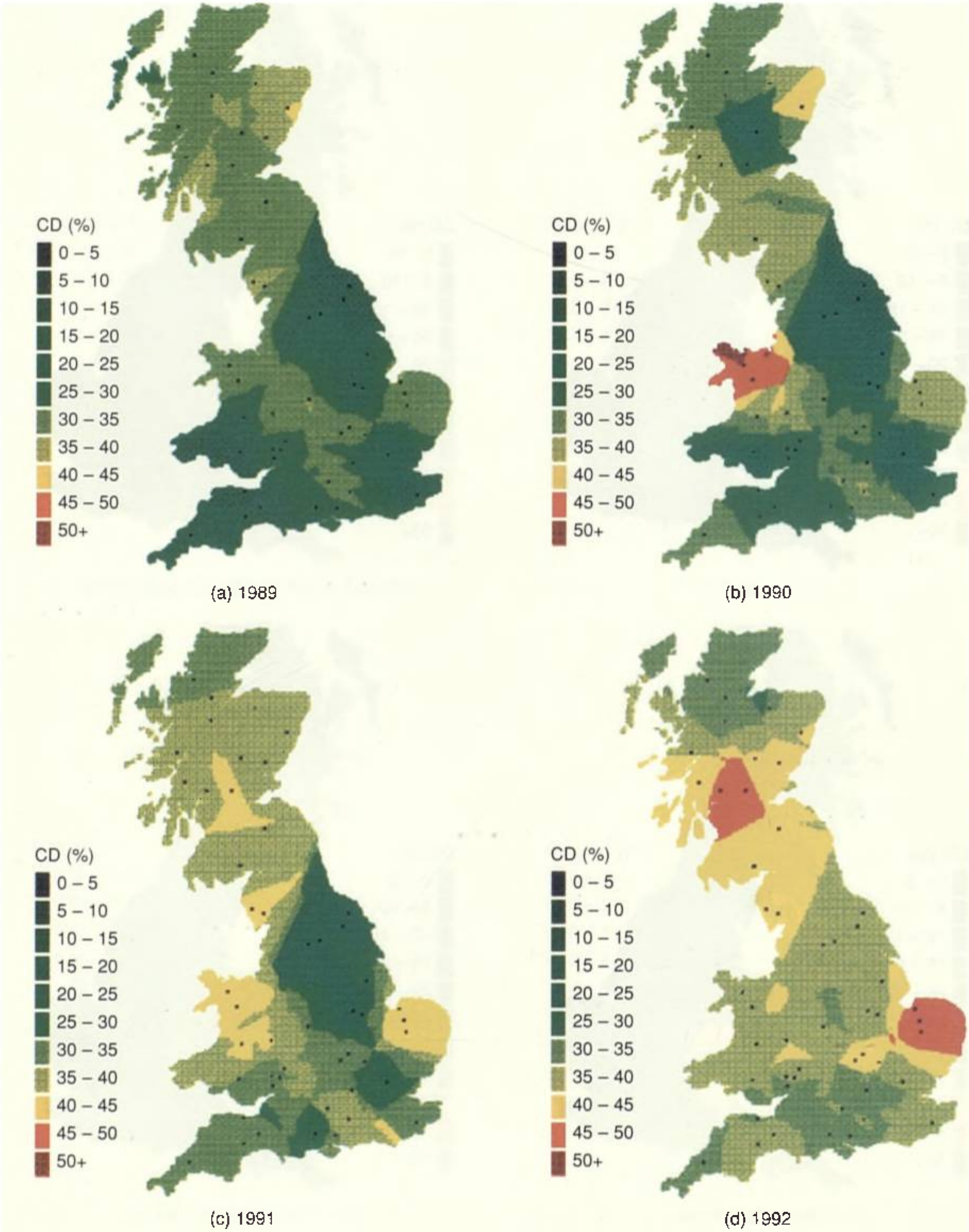


Plate 5(a)–(d) Oak crown density index 1989 to 1992. High scores indicate greater transparency; surfaces are interpolated as moving averages of three nearest sites within a maximum radius of 250 km, with inverse quadratic weighting for distance.

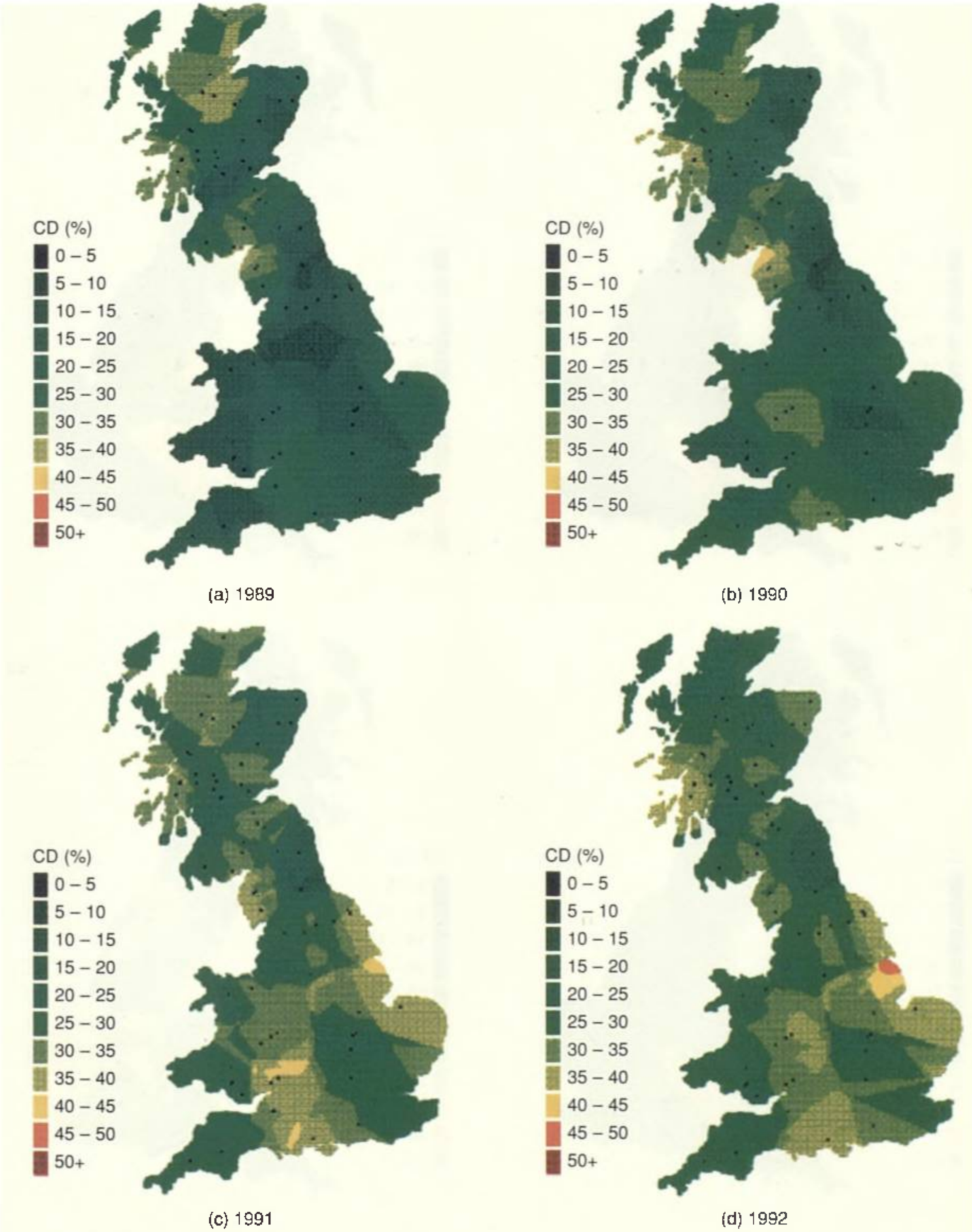


Plate 6(a)–(d) Norway spruce crown density index 1989 to 1992. High scores indicate greater transparency; surfaces are interpolated as moving averages of three nearest sites within a maximum radius of 250 km, with inverse quadratic weighting for distance.

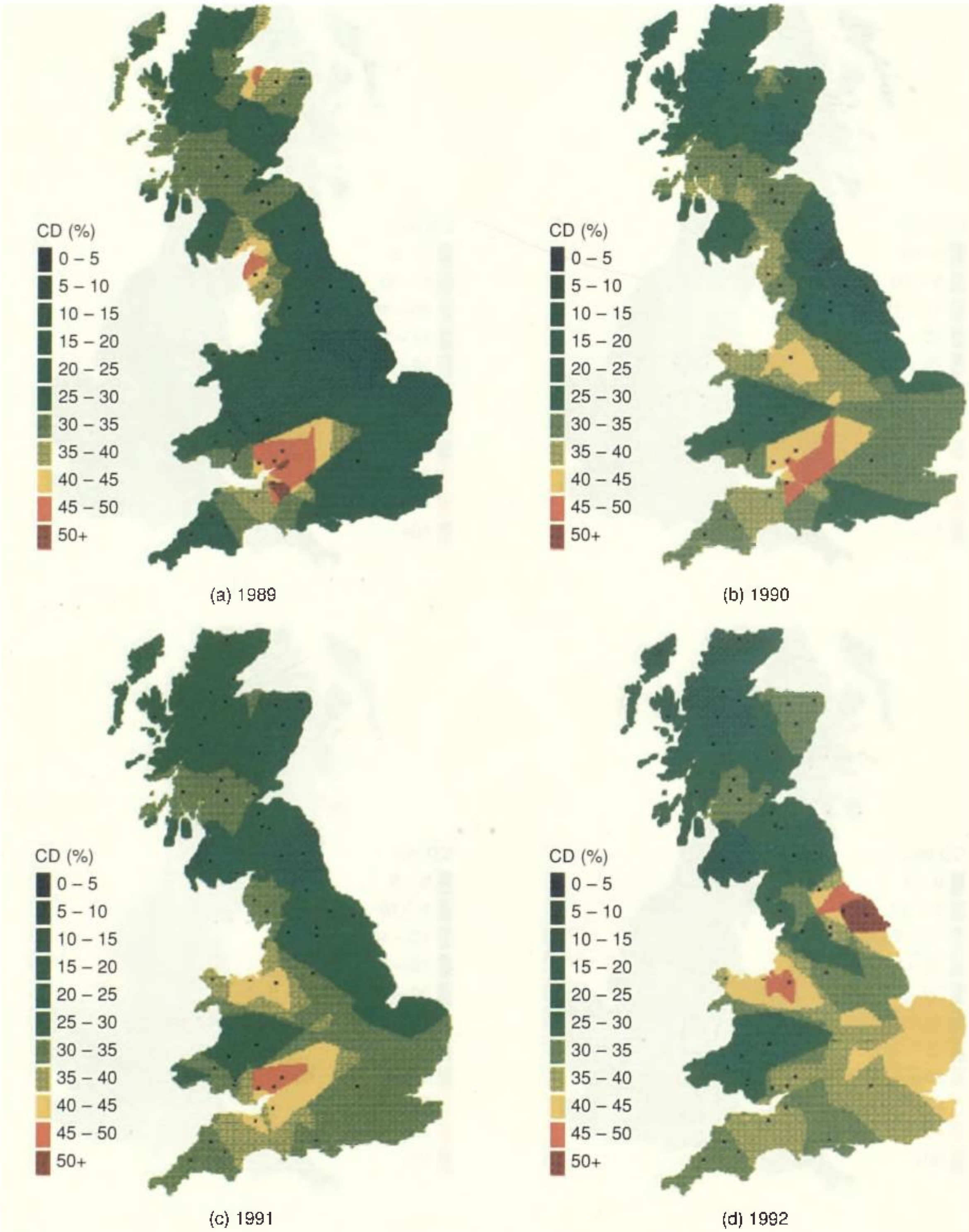


Plate 7(a)–(d) Sitka spruce crown density index 1989 to 1992. High scores indicate greater transparency; surfaces are interpolated as moving averages of three nearest sites within a maximum radius of 250 km, with inverse quadratic weighting for distance.

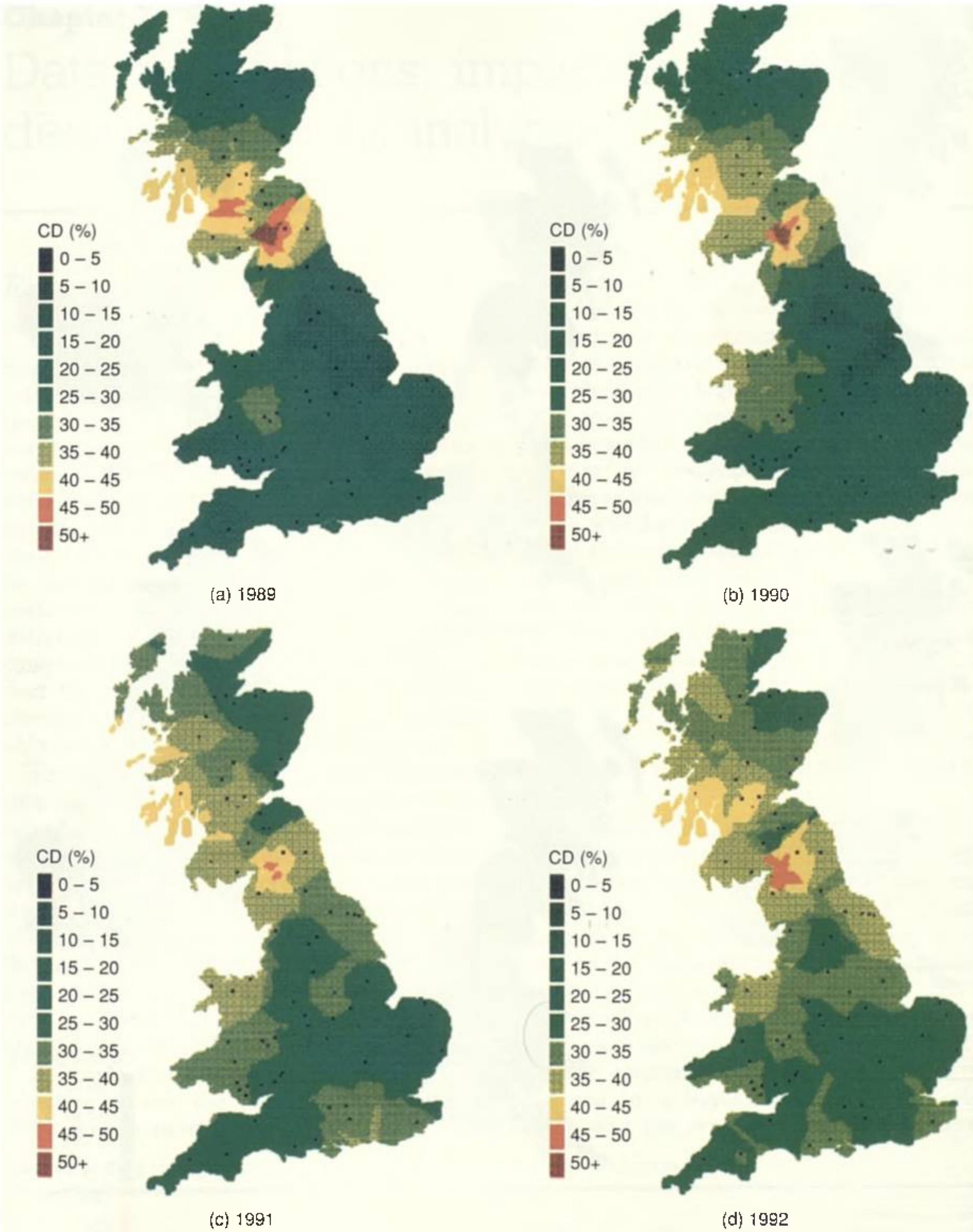


Plate 8(a)–(d) Scots pine crown density index 1989 to 1992. High scores indicate greater transparency; surfaces are interpolated as moving averages of three nearest sites within a maximum radius of 250 km, with inverse quadratic weighting for distance.

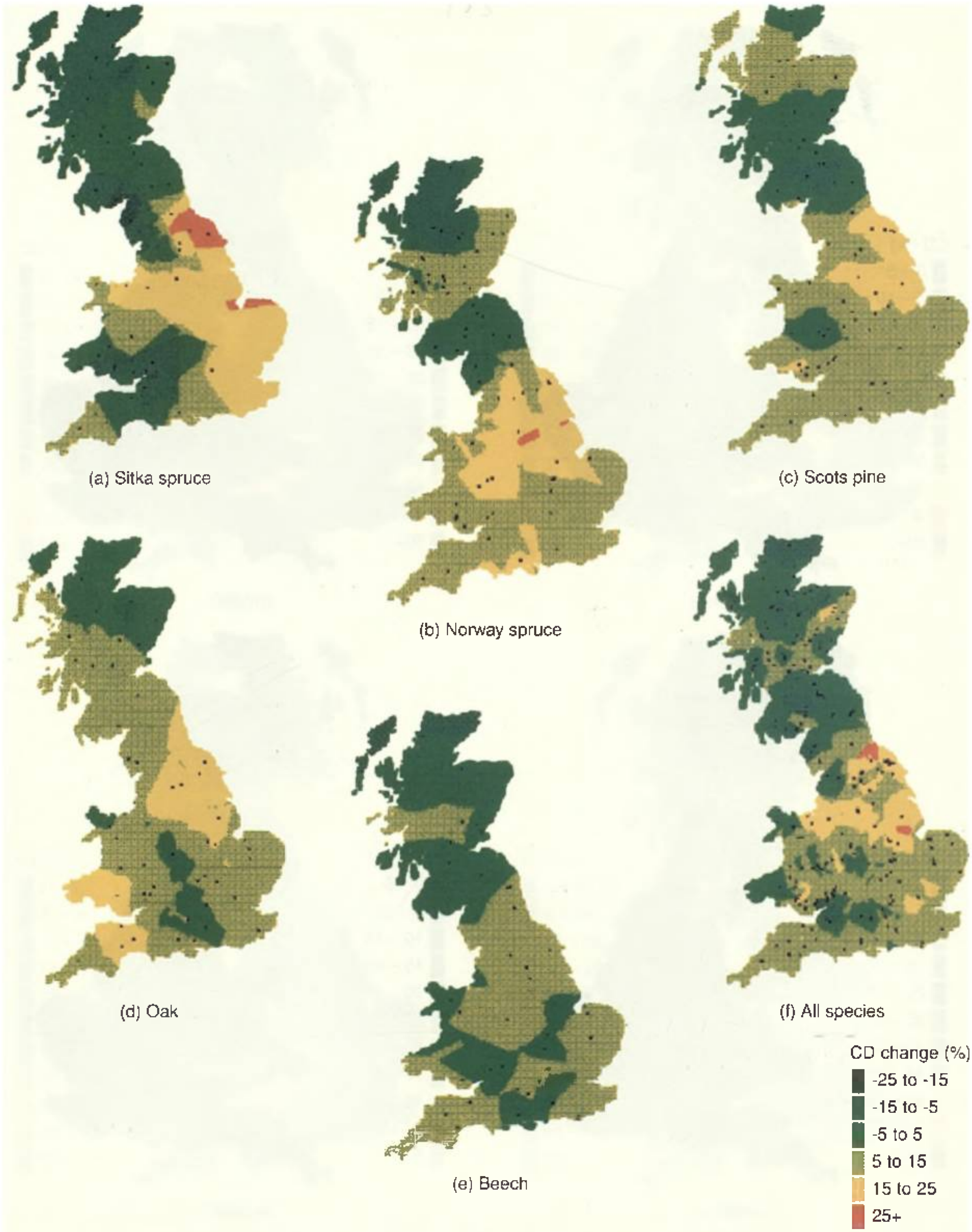


Plate 9(a)–(f) Overall changes in crown density (cd8992) between 1989 and 1992. Positive changes indicate increasing transparency; surfaces are interpolated as moving averages of three nearest sites within a maximum radius of 250 km, with inverse quadratic weighting for distance.

Chapter 3

Data distributions: implications for survey design and data analyses

Environmental and pollution strata

Site representation of environmental and pollution gradients, and data distribution of forest condition information, have consequences for survey design and data analyses. The 1992 national survey of all five species comprised 8856 trees at 369 sites (24 trees per site). A sample size of about 80 sites for each species in their normal areas of occurrence is believed to be necessary for meaningful spatial and temporal analyses (Innes and Boswell, 1991a). Although the 1992 complement of sites came close to this ideal, it can be seen from Table 3.1 that the numbers available for investigating change between 1989 and 1992 are considerably fewer for beech, oak and Sitka spruce.

From the time of the first survey Binns and co-workers (1985) recognised a long-term commitment to monitoring *change*, and that representation of British forests would be better served by a stratified survey than by the more widely used grid-based systematic surveys. The first survey, therefore, took the form of a 2^3 factorial experiment (eight 'treatments') with high and low levels of sulphur deposition, altitude and rainfall as factors and six regions, treated as blocks, to provide replication.

A simple test was conducted to determine whether or not the present distribution of 8992 change sites would satisfy the requirements of a future hypothetical 2^3 factorial design. Using the GIS, annual PET, ozone and total sulphur deposition maps were reclassified into two categories representing high and low values only (high values being for annual PET, ozone exceedance hours, and total sulphur deposition of > 620 mm yr^{-1}, > 100 h and > 2 g m^{-2} yr^{-1} respectively). The proportion of land cover available to each of the eight 'treatments' was derived by simple Boolean overlay of the three reclassified maps (Table 3.2). It can be seen that the eight classes are very unevenly represented in terms of land cover with the greater proportion of Great Britain being classified as 'high' ozone, 'high' PET and 'low' sulphur deposition in the south and 'low' levels for all three factors in the north. The particularly under-represented sixth class consisted of two small adjoining areas in west and mid-Wales.

Using similar map overlay processes, the numbers of 5 km squares represented by 8992 change sites were determined for each category. Table 3.2 shows that there is no representation of the sixth class for beech or the seventh for Sitka spruce, and no degrees of freedom in seven other classes (one each for beech and oak, two for Sitka spruce and three for Norway spruce). Nevertheless, 31 out of 40 possible species/class permutations were represented in a hypothetical factorial design, which was not originally intended to be the

Table 3.1 Site representation in 1992 and sites available for 8992 change indices.

Species	*Beech*	*Oak*	*Norway spruce*	*Sitka spruce*	*Scots pine*
Number of sites in 1992	62	78	78	74	82
Number of sites existing for both 1989 and 1992	36	53	72	55	76

specific use of the survey. Given the considerably greater number of sites for the 1992 survey, the indications are that at least partial factorial representation should be possible for other 'treatments', providing these are restricted to two level designs which consist of high and low classes only.

In reality, selection of strata should be species dependent and practical considerations will constrain studies to those pollution and background environmental factors thought to be most important. The future availability of 1 km^2 critical loads and exceedances based on specific receptors (Downing *et al.*, 1993), and possibly other digitised surfaces relating to physical geography, will permit more precise GIS based selections of sites according to particular specifications for control and environmental strata.

The stated objectives for 'permanent' (level II) and 'special forest ecosystem' (level III) sites are to provide further information and opportunities for verification of damage mechanism hypotheses (ICP Forests, 1992). Carefully considered locations for level I and II sites could also provide considerable opportunities for calibrating data and spatial models associated with level I analyses. For example, it appears desirable to cooperate with existing meteorological, deposition and environmental monitoring networks, and to monitor as many of the five species as possible at each level I or II site. This would minimise unnecessary duplications of effort and instrumentation for maximum return of information. At sites where more than one species is represented, opportunities to make cross-species comparisons of responses to environmental stimuli may also be of considerable interest.

Representation of environmental and pollution gradients in 8992 change sites

Frequency histograms (Figures 3.1 – 3.4) indicate the distribution of sites across environmental and pollution strata. Those presented here are for the 8992 change sites, which also broadly reflect distributions in the present full complement of survey sites.

Table 3.2 Land cover and 8992 site representation of classes ('treatments') for a 2^3 factorial design.

					Number of 5 km grid squares represented by 8992 change sites				
Class No.	*Sulphur*	*Ozone*	*Annual PET*	*Land surface (%)*	*Beech*	*Oak*	*Norway spruce*	*Sitka spruce*	*Scots pine*
1	high	high	high	9	9	8	11	5	17
2	high	high	low	13	3	7	11	9	9
3	high	low	high	8	1	5	1	1	3
4	high	low	low	7	2	2	11	5	6
5	low	high	high	28	11	11	6	13	15
6	low	high	low	1	-	1	1	1	2
7	low	low	high	3	2	3	1	-	3
8	low	low	low	31	8	12	25	21	21
			Totals	**100**	**36**	**49**	**67**	**55**	**76**

Note: The number of 5 km grid squares represented by 8992 change sites is less than the number of sites indicated in Table 3.1 when more than one site falls within a grid square.

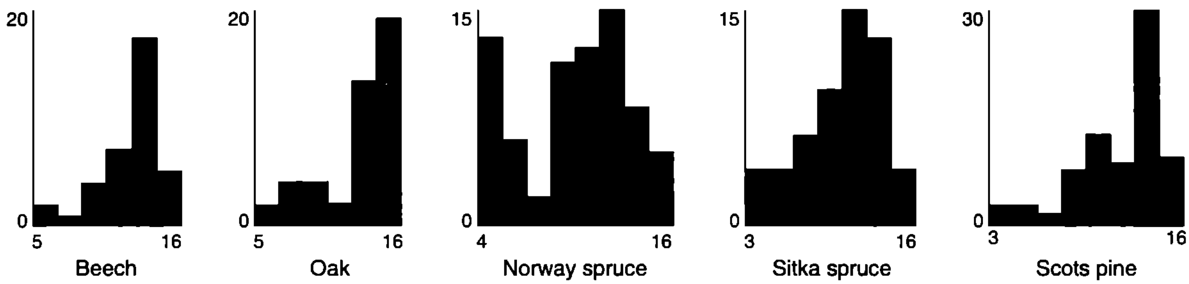


Figure 3.1 Site distributions against annual potential evapotranspiration: x = annual PET, classes 3 to 16 correspond to a range 500-650 mm yr^{-1}; y = number of sites.

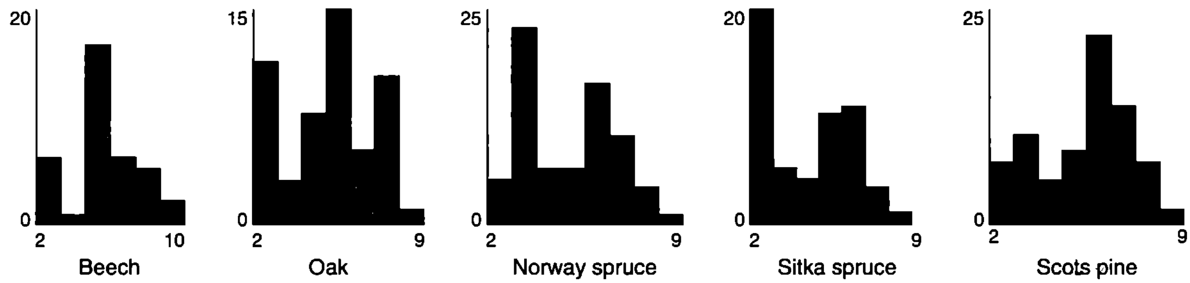


Figure 3.2 Site distributions against ozone: x = hours in which 60 ppb ozone is exceeded, classes 2 to 10 correspond to a range 0-200 hours; y = number of sites.

The PET distribution for beech (Figure 3.1) reflects its naturally southerly occurrence and its unsuitability for very wet and exposed sites. Oak, for reasons of production is normally found at low elevations, but is more tolerant than beech of persistently wet conditions. Scots pine is similarly distributed, in terms of PET, to beech and oak because it grows best on drier sites at low elevations (Savill, 1991). Norway spruce, which is able to tolerate moderately waterlogged sites, is well represented in areas of low PET, these being wet and elevated sites (Savill, 1991); although it is not evident why the distribution of Sitka spruce should differ in this respect.

Because ozone exceedances are more frequent in southern Britain, where summer anticyclones and light winds are particularly conducive to ozone production (Bower *et al.*, 1990), one might expect histograms for ozone exceedance (Figure 3.2), to reflect those for PET. However, northerly locations for some beech and oak sites in regions of lower ozone exposure, and the presence of spruce in other high exceedance, but low PET regions (such as the Cambrian Mountains, Snowdonia and the Pennines), resulted in the overall range of ozone exceedance exposures being better represented than might otherwise be expected.

Taking high total annual deposition of sulphur to be levels in excess of 2.0 g m^{-2} yr^{-1} (categories greater than 3 in Figure 3.3), it can be seen that although high and low deposition sites were well represented for conifers, they were less adequately represented for beech and oak.

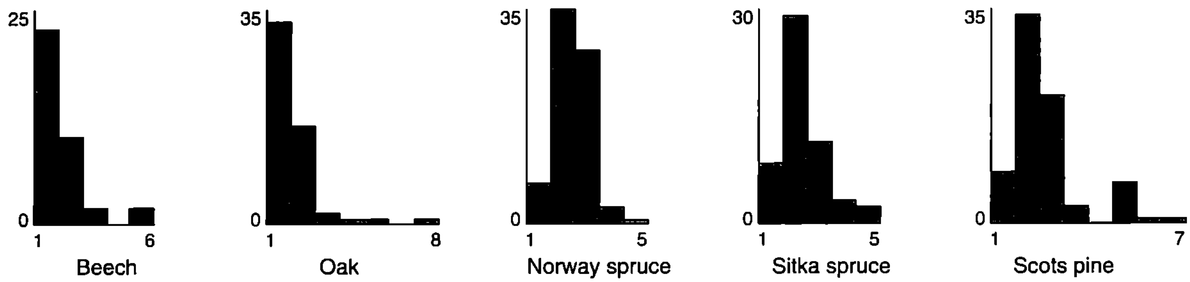


Figure 3.3 Site distributions against total sulphur deposition: x = deposition, classes 1 to 8 correspond to range 0-7 g $m^{-2}yr^{-1}$; y = number of sites.

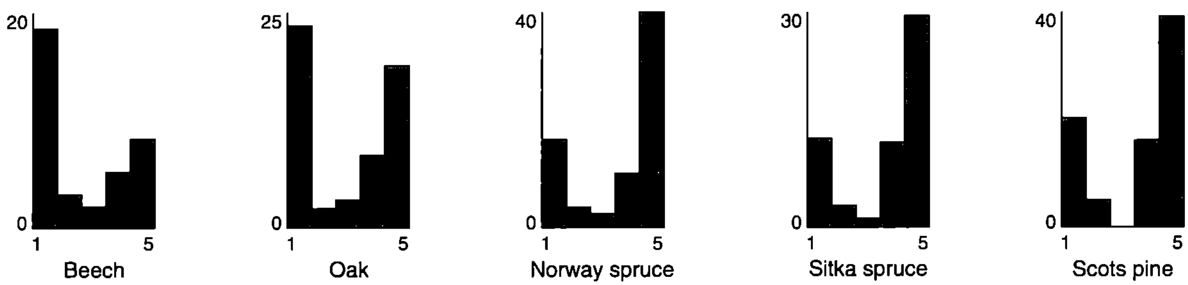


Figure 3.4 Site distributions against exceedance of critical loads of acidity for soils: x = exceedance, classes 1 to 5 correspond to a range 0 to >2.0 keq $ha^{-1}yr^{-1}$; y = number of sites.

Acid exceedances of critical loads (Figure 3.4), were best represented in the extreme classes 1 and 5 (corresponding to exceedances of 0.0-0.2 keq $ha^{-1}yr^{-1}$ and >2.0 keq $ha^{-1}yr^{-1}$ respectively). The rarer 'high exceedance' representation for beech may be explained by its predominance on well-buffered calcareous soils. Although many of the distributions were uneven, overall the spectra of environmental and pollution gradients of interest were adequately represented for the purposes of investigating changes in forest condition.

Distributions of 8992 change indices

The normality of distributions for 8992 change indices have implications for both statistical analyses, and for the diagnostic usefulness of indices. Indices for changes in crown density approached normality (Figure 3.5), and effectively distributed sites across a range representing increasing density (negative values) to increasing transparency (positive values).

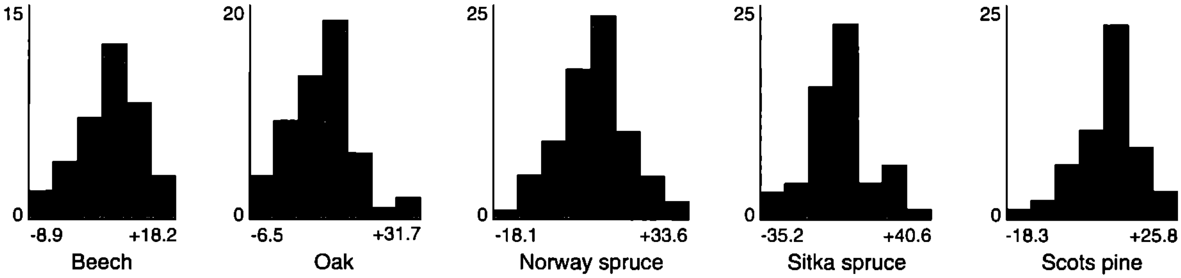


Figure 3.5 Change in crown density cd8992: *x* = less (reduction) to greater (increased) percentage transparency; *y* = number of sites.

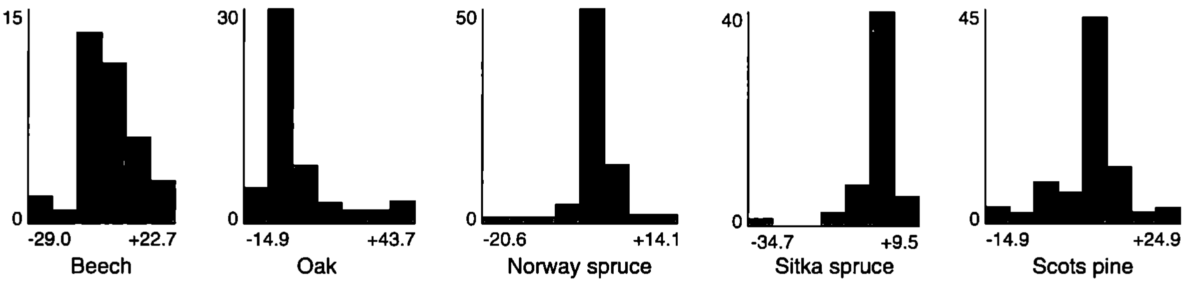


Figure 3.6 Change in overall foliage discoloration di8992: *x* = increasingly positive change (less to greater percentage discoloured foliage); *y* = number of sites.

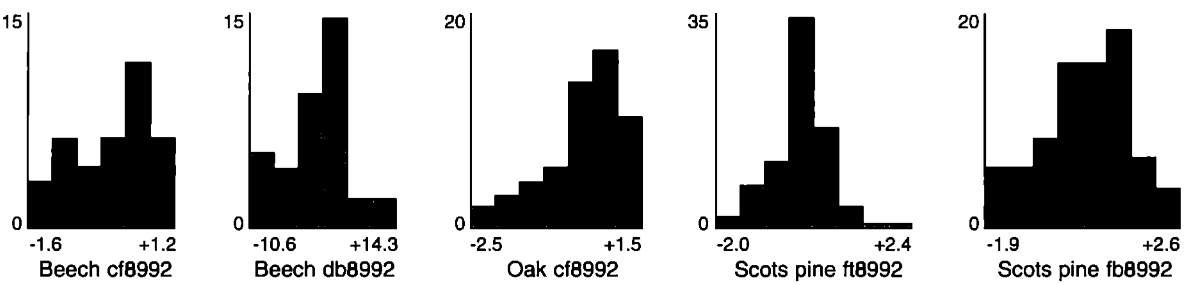


Figure 3.7 Other change indices of interest; crown form (cf8992) and dieback (db8992) in beech; crown form in oak (cf8992); upper and lower crown flowering in Scots pine (ft8992 and fb8992): *x* = increasingly positive change in 8992 indices; *y* = number of sites.

In contrast, change in overall discoloration (Figure 3.6) was neither normally distributed, nor particularly useful for identifying differences between sites. The modal values correspond to sites in which there had been no change in overall discoloration between 1989 and 1992, and corroborate other reports of the general rarity of foliage discoloration in Great Britain (Innes, 1993a). Although not presented here, the widely used individual indices for yellowing and browning (ICP Forests, 1992) were found to be similarly poor at discriminating between sites.

Distributions for indices representing changes in crown form in beech and oak, dieback in beech and flowering in Scots pine (Figure 3.7) are presented here because results from multivariate analyses (reported in Chapter 4) suggest their relationships with environmental factors. Allowing for the irregularity of distributions for crown form indices in beech and oak (partly explained by the categorical basis for their assessment), these, together with dieback in oak and flowering in Scots pine, showed greater diagnostic potential than assessments of discoloration.

Normality of distributions and minimum sample sizes for crown density change indices

Summary statistics (Table 3.3) suggest that distributions of site mean expressions for changes in crown density between 1989 and 1992 (cd8992) are sufficiently normal for analysis by parametric statistics. The standardised values for skewness (symmetry) and kurtosis (gradient of the sides with respect to an ideal Gaussian curve), with the exception of a minor departure for Scots pine, are within the range (-2.0 to +2.0) that indicates that distributions do not significantly depart from normality.

The question of sample adequacy is only addressed in relation to the totality of site means for cd8992. Results in Table 3.3, therefore, should not be used to infer adequacy of samples for other spatial or temporal investigations. The method by Philip (1983) indicates the minimum sample required for deviation of the mean of another random sample (from the hypothetical total population) to be less or equal to that of the sample used. Although only approximations (because of the need to use transformed means; see Table 3.3, footnote b) values calculated after Philip (1983) are very similar to actual sample sizes.

In the more likely event that sample accuracies should be required within a given range (for example ± 2.5 per cent being equivalent to one 5 per cent increment of the crown density index), it can be seen that, because of the greater distribution of Sitka spruce values, a much larger sample would be required for statistically confident representation of the overall Sitka spruce population.

For the purposes of statistical analyses reported here, distributions of cd8992 were considered to be near normal (accepting a slight departure for Scots pine). Allowing for the fact that Sitka spruce might have been under-represented, sample sizes were also believed to be adequate.

Table 3.3 Summary statistics and required sample sizes for crown density change indices (cd8992).

Species	*Beech*	*Norway spruce*	*Oak*	*Scots pine*	*Sitka spruce*
Sample size	36	72	53	78	55
Average	5.8	8.4	9.8	7.5	0.7
Variance	36.3	90.0	60.7	60.4	211.7
Standard deviation	6.0	9.5	7.8	7.7	14.6
Standard error	1.00	1.12	1.07	0.88	1.96
Minimum	-8.9	-18.1	-6.5	-18.3	-35.2
Maximum	18.2	33.6	31.7	25.8	40.6
Range	27.1	51.7	38.2	44.1	75.8
Standardised skewness	-0.55	0.10	1.26	-1.46	0.52
Standardised kurtosis	0.02	1.18	1.53	2.10	1.22
Coefficient of variation	16.7	13.2	14.7	10.0	26.5
Required sample size (method/level)					
Snedecor and Cochran (± 2.5 % cd8992)[a]	23	58	39	39	135
Snedecor and Cochran (± 1.0 % cd8992)[a]	145	360	243	242	847
Philip ($p = 0.10$)[b]	53	46	62	39	52
Philip ($p = 0.05$)[b]	68	60	79	50	68

[a] After Snedecor and Cochran (1980) where $n = 4s^2/L^2$; n = sample size, s^2 = variance, L = allowable error at $p = 0.05$.
[b] After Philip (1983) $n = \text{cov}^2 \times t^2/E\%$; n = sample size, cov = coefficient of variation, $E\%$ = per cent ratio of the confidence interval to the mean. The $E\%$ ratio only has meaning when values of x are either all positive or all negative. Means were therefore adjusted according to hypothetical distributions in which the minimum value was zero; $t_{(0.10)}1.29$; $t_{(0.05)}1.66$.

Individual tree crown density data

The crown density index is one of the most widely used indices of tree condition and is the single most important indicator of forest condition in the Community surveys (Anon., 1992, 1993). The term is misleading, as it relates to 5 per cent classes of crown 'transparency' (Innes, 1993a) in comparison to a standard 'fully-foliaged' tree. Therefore trees recorded as '0' have no reduction in foliage, those scored '5' have 5 per cent defoliation and so forth (Innes, 1990).

The histograms for 1992 individual tree crown density data (Appendix 1) are all slightly positively skewed in comparison to the superimposed equivalent normal distributions. In spite of the very different basis for coniferous and broadleaved indices (one being a cumulative measure of needles produced over several years, the other representing a 'snapshot' of the entire foliage complement produced in a single growing season), the five distributions are similar in most respects with modal classes for conifers ranging from 15 per cent to 25 per cent, and those for beech and oak being 25 and 30 per cent respectively. Only the spruces, however, are well represented in the '0' defoliation category.

Box and whisker plots (Tukey, 1977) for the five species (Appendix 2) show considerable variation in crown densities both within and between sites. Sitka and Norway spruce are the most variable with interquartile ranges within-sites of between 5 and over 40 per cent, and site median crown densities ranging from 0 per cent to nearly 60 per cent crown 'transparency'. Oak is intermediate in terms of its intra- and inter-site variability in crown density. Scots pine is comparatively consistent, with the notable exception of one, possibly storm damaged, site with a median crown density of 87 per cent. Beech crown density was the least variable with site interquartile ranges typically of only 10 to 20 per cent and all site median values fell within a range of 12 to 40 per cent.

The general impression is that crown density is extremely variable and, as is apparent from the spatial and temporal changes described below, is also a highly dynamic phenomenon. Because trees shed leaves in response to a wide range of stresses, it is very difficult to establish whether any part of this overall variation is uniquely attributable to pollution.

Spatial variation and implications for interpolation

Maps of crown density (discussed on pages 14–15) were interpolated from point data using weighted moving averages. Values for unvisited points (pixcels) were calculated to generate complete crown density 'surfaces' on the basis of the inverse quadratic weighted averages for the three nearest sites, within a window of maximum radius of 250 km. This weighting places greatest emphasis on values for closely neighbouring sites, and is based on the rationale that neighbouring sites are more likely to be similar than distant sites. Although intuitively acceptable, such weighting may not necessarily reflect the distribution of more localised influences on crown condition. The use of a large radius 'window' allowed interpolations (and extrapolations) to be made for remote areas of low sampling density. Maps were produced as 'potential surfaces' in preference to contoured ones; the latter would assume that gradients of crown density exist between neighbouring sites.

The assumption that neighbouring sites are similar raises many questions such as the degree and direction of variability (thus affecting the size and shape of the window to be used for interpolation), whether weightings should consider effects other than distance, and the errors associated with interpolated values (Burrough, 1992). Consideration was therefore given to the use of the geostatistical technique known as 'kriging'. This is based on 'regionalised variable theory', and recognises that spatial variations in certain regionalised variables are sometimes more efficiently described using stochastic (probability) surfaces, than by models based on smooth mathematical functions. The first stage of kriging involves the calculation of a semi-variance function. This describes the variation between sites with distance. The optimum weights for kriging interpolation are determined from models fitted to a semivariogram of semivariance plotted against distance (lag) between sites (Burrough 1987, 1992).

Curves were fitted to semivariograms using the isotropic 'spherical model' provided with Canodraw software (Smilauer, 1992). These allowed visual assessments to be made of the potential suitability of kriging for mapping indices of change in forest condition. Indices assessed were crown density (cd8992), crown form in beech and oak (cf8992), crown dieback in beech (db8992) and upper and lower crown flowering in Scots pine (ft8992 and fb8992). Spatially dependent variation was detectable in all the above, except for fb8992 which consisted of completely structureless noise, or 'nugget' variance. Distinct ranges for spatial dependence (after which variation became structureless) were detectable for cd8992 in oak, Scots pine and Sitka spruce, and for ft8992 in Scots pine. Linear trends without any obvious range limits were identifiable for cd8992 in beech and Norway spruce, for cf8992 in beech and oak, and for db8992 in beech. Distributions obtained for semivariograms of cd8992 indices in beech, oak and Sitka spruce broadly resembled those reported for 1988 records of crown density in those species (Innes and Boswell, 1989).

In cases where 'nugget' variation predominated over that due to lag effects, which was true of semivariograms for many of the above indices, this considerably reduces the advantage of using kriging over moving average based interpolation (Burrough, 1992). The results do, however, indicate that due to the considerable spatial independence of crown condition data, spatial interpolations are unsatisfactory and may be misleading. If possible, it would be desirable to incorporate some means of indicating the validity of interpolation into the GIS model, for example similar to the 'blank grid square' technique used by Innes and Boswell (1988, 1989). Neural network techniques have also been successfully applied to spatial generalisation of defoliation indices (Kohl and Jensen, 1993). The present form of the GIS, however, is not amenable to such manipulation. Because maps for crown density and changes in crown density are not based on stochastic models, they should only be used for general comparisons of regional changes with time, and not for purposes of spatial prediction.

Temporal and regional variations in crown density variation

Box and whisker plots for site mean crown density data show similar patterns of variation with time for beech, oak, Norway spruce and Scots pine (Appendix 3). These indicate a general trend of decreasing transparency between 1988 and 1989, and are believed to represent both the continuing recovery from 1987 storm damage, and the favourable growing conditions of a mild and wet 1988 summer (Innes and Boswell, 1989). A general increase in defoliation followed between 1989 and 1992, although beech appeared to improve slightly in 1992. Crown densities for Sitka spruce, however, remained remarkably consistent between 1988 and 1992; the overlapping 'notches' of all yearly distributions indicated that the median of any one year is not significantly different from those of any of the other four.

Several notable environmental phenomena occurred during the 1989 to 1992 period. In 1989 there were severe outbreaks of *Elatobium abietinum*, and a summer drought. Gale force winds in January and February of 1990 resulted in the loss of trees in the south of Britain. Further damage was recorded as a result of frosts in April and May. A late summer drought and elevated ozone levels were also recorded for 1990. In 1991 mechanical damage to Norway spruce in north-east England was recorded as a result of heavy snows and strong winds during December 1990. This was followed by damage due to severe frost in late May of 1991. Further mechanical damage in 1992 was attributed to the combined action of snow and wind, and also loss of needles in spruce trees by the abrasive effects of high winds on exposed sites. The general decline of crown condition throughout this period, however, was widely believed to be due to drought stress (Innes and Boswell, 1990, 1991a, 1991b; Redfern *et al.*, 1992).

The spatial dynamics of changes between years are reflected in Plates 4, 5, 6, 7 and 8. In beech declining condition (increasing transparency) between 1989 and 1990 is marked by the regions of yellow/green and yellow in Plate 4(b) (corresponding to 35-45 per cent defoliation) appearing over Scotland and other western parts of Great Britain. This trend continued over the whole of Britain in 1991, then showed a marked recovery in the worst affected areas of Wales and central and southern England in 1992 (Plates 4(a) and 4(b)).

A more dynamic situation is recorded for oak in Plates 5(a) and 5(b) with a marked change from 30-35 to 40-50+ per cent categories in North Wales between 1989 and 1990. While oak in North Wales appeared to recover over the remaining two years, the considerable decline over the rest of Britain, with centres for most notable declines in central Scotland and East Anglia, is apparent from Plates 5(c) and 5(d).

The increase in crown transparency for Norway spruce (Plate 6) appeared to be a more gradual and uniform process over the whole of Great Britain with few noticeable regional variations. The appearance of a red 45-50 per cent defoliation area centred over Lincolnshire in 1992, where there is no formal survey of Norway spruce condition, raises the question of the validity of interpolation between distant sites. Although the decline of Norway spruce in Lincolnshire was verified on the ground, considerable caution should be exercised in interpreting small regional variations.

The relatively static overall distribution of crown condition for Sitka spruce between 1988 and 1989 indicated in Appendix 3, belies the considerable and dynamic regional variations shown in Plate 7. Reductions in crown density are largely attributed to *Elatobium abietinum* infestations and droughts in 1989 and 1990. The apparent detioration over North Yorkshire between 1991 and 1992 may have been due to further wind and snow damage, this area being particularly affected during the winter of 1990 (Innes and Boswell, 1991b).

The regional pattern for Scots pine, like Norway spruce, reflects a gradual increase in crown transparency between 1989 and 1992, without any marked dynamic year-to-year regional variation. An area centred over the North Pennines and Southern Uplands, which is well represented by survey sites, was notable for its persistently high transparency scores (Plate 8).

Overall changes between 1989 and 1992, which were the subject of the multivariate analyses described in Chapter 4, are mapped for crown density (cd8992) in Plate 9. Areas of yellow/green, yellow and red indicate progressively greater declines in crown density; light green is equivalent to no, or very little, change; the two darker greens approximate to regions in which crown density has improved. Even allowing for the limitations of interpolation techniques, the main focus of decline for all species appears to lie over much of the industrial centre of England extending northwards from Birmingham over Manchester, the South Pennines and North Yorkshire Moors. Although there are no established grounds for comparing foliage shedding responses of different species, crown densities change values for all species were combined in a sixth map (Plate 9(f)), to determine the overall spatial pattern of improvement and decline.

In visual comparisons with pollution and meteorological maps (Plates 1, 2 and 3), Plate 9(f) most closely mirrored spatial distributions for total and dry deposition of sulphur. Regressions indicated that cd8992 was significantly associated with interpolated values for pollution and meteorological variables. The regression of cd8992 in Norway spruce on total sulphur deposition was highly significant at a level of $p<0.001$ (Appendix 4). However, the existence of a similarly strong relationship between cd8992 and rainfall (Appendix 4) precludes any interpretation of possible causal relationships.

Chapter 4

Analyses

Four categories of data were analysed:

1. Individual tree data for 1992 (evaluated for distribution patterns only).
2. Site indices for the individual years 1989 to 1992.
3. Derived indices describing between-year changes in crown condition.
4. Indices for overall longer-term 1989 to 1992 change in forest condition.

Data for categories 1, 2 and 4 were initially examined using Spearman rank-order (non-parametric) and Pearson product moment (parametric) correlation matrices, against all available environmental and pollution data. These included individual monthly expressions for departure from meteorological norms or, in the case of longer-term change, averages of these.

Although further investigations were conducted using step-wise regression, best subsets regression, multiple regressions and principle components analyses, interpretation of results were compromised by difficulties of autocorrelation associated with the repeated measures nature of data for categories 2 and 3. These were, therefore, abandoned in favour of the investigation of the overall longer-term changes in forest condition between 1989 and 1992. The following account refers to the analysis of *the indices for longer-term change between 1989 and 1992 only.*

Correlation matrices

Although certain variables were known to depart from normality, very similar correlations were obtained by both parametric and non-parametric means. Pearson product moment correlations are summarised with respect to crown condition 8992 change data in Appendix 5. These allowed comparison of the explanatory values of various forms of meteorological data, particularly in determining which of the following monthly expressions should be used in multivariate analyses: 1951 to 1980 means, 1988 to 1992 departures from monthly norms or soil moisture deficits. The general trends of interest were as follows:

- While strong correlations were obtained for change in crown density (cd8992) with environmental variables for conifers, this relationship was much weaker for broadleaves; the equivalent indices for crown form and dieback in beech and oak (cf8992 and db8992) appeared to reflect environmental variation more strongly than cd8992.
- Other indices which were strongly correlated with several environmental variables included those for masting in beech (ma8992); upper and lower crown flowering and crown shoot death in Scots pine (ft8992, fb8992 and cr8992 respectively); insect damage in all species except, surprisingly, oak (id8992); average number of years of needle growth present (na8992) in both spruces; fungal damage (fd8992) in oak.
- Associations between discoloration indices and environmental factors, especially for yellowing (ye8992 in broadleaves, yc8992 and yo8992 in conifers) were weak, with the exception of browning of current and old foliage (bc8992 and bo8992) in Norway spruce.
- In every case where significant correlations (r>0.2,<-0.2) existed between a crown condition index and a pollution variable, there

were also correlations of equivalent strength between the condition index and other environmental variables. Additionally, strong correlations exist between the pollution and environmental variables in question, typically in the range of absolute $r \geq 0.5$-0.9, indicating the presence of multicollinearity between explanatory variables. The only exceptions were associations between wet and cloud deposition of sulphur and fungal damage in beech (fd8992); these were later found to be due to a data anomaly in which all except three sites possessed the same value.

Multicollinearity among explanatory variables

It can be seen from Table 4.1 that some of the principal environmental and pollution variables used in multivariate analyses are highly correlated. As would normally be expected, there are strong correlations between annual expressions for meteorological variation (anPET, anppt and antmp) and monthly soil moisture deficits (SMDs).

However, SMDs were also found to be significantly correlated (r>0.2, <-0.2) with ozone (highly so at >0.5), cloud and dry deposition of sulphur and acid exceedances of critical loads for soils. No causal relationships may be inferred from results where response data are correlated with similarly intercorrelated pollution and environmental variables. Such multicollinear relationships in regression analyses also produce inflated variances for regression coefficients. These are consequently unstable and unsuitable for either interpretation or predictive modelling.

Principal component analysis (PCA) was considered as a possible alternative to regression analyses. However, similarly to the findings of Innes and Boswell (1988) in their report for PCA treatment of 1987 data, PCA of 8992 change data for crown density and foliage discoloration in Norway spruce also failed to identify any single important explanatory variables, or to provide composite indices which were more effective than the original crown indices in explaining environmental or pollution variation.

Canonical ordination based procedures were eventually selected for their abilities to constrain ordinations to environmental and pollution axes, for the provision of facilities to detect multicollinearity, and for additional intra-set correlation output unaffected by multicollinearity (ter Braak, 1987).

Table 4.1 Pearson product moment correlations for principal environmental and pollution variables: absolute r values for shaded bars: ≥0.3, <0.5; ≥0.5, <0.8; ≥0.8.

	anPET	anppt	antmp	ozone	Scld	Sdry	Stot	Swet	exceed	marSMD	junSMD	julSMD
anppt	-0.79											
antmp	0.99	-0.78										
ozone	0.77	-0.50	0.77									
Scld	-0.24	0.18	-0.24	0.15								
Sdry	0.24	-0.23	0.21	0.18	0.13							
Stot	0.27	-0.15	0.25	0.32	0.26	0.83						
Swet	-0.03	0.23	-0.03	0.22	0.43	0.18	0.55					
exceed	-0.22	0.36	-0.24	-0.02	0.47	0.07	0.21	0.40				
marSMD	0.78	-0.87	0.77	0.52	-0.35	0.28	0.16	-0.28	-0.42			
junSMD	0.81	-0.84	0.81	0.52	-0.35	0.30	0.19	-0.29	-0.40	0.93		
julSMD	0.78	-0.85	0.77	0.50	-0.25	0.35	0.26	-0.21	-0.34	0.90	0.96	
augSMD	0.79	-0.86	0.79	0.55	-0.24	0.34	0.22	-0.25	-0.37	0.92	0.96	0.96

Notes: anPET, antmp, anppt are annual means for 1951-1980 for potential evapotranspiration, rainfall and temperature respectively; ozone is hours of 60 ppb exceedance; Scld, Sdry, Stot and Swet are cloud, dry, total and wet deposition of sulphur; exceed is exceedance of critical loads for acidity of soils; marSMD, junSMD, julSMD and augSMD are mean monthly soil moisture deficits for March, June, July and August for the period October 1988 to September 1991.

Canonical analyses

Canonical analyses, in contrast to other techniques of ordination, such as principal component and correspondence analysis (CA), allow multivariate and *direct* gradient analysis of response data with respect to a set of explanatory variables (ter Braak and Prentice, 1988). The major limitation to indirect techniques, such as PCA and CA, is that environmental variables may be poorly related to ordination axes which only represent orthogonal directions in response data. They may, however, be strongly associated with other 'residual' and unknown directions of composite variation in response variables (ter Braak and Prentice, 1988). Direct gradient analysis combines both steps into one by regressing site scores on environmental scores at each iterative step of the ordination. The resulting axes are, therefore, constrained to be linear combinations of environmental variables (ter Braak, 1986, 1992; ter Braak and Prentice, 1988).

Innes and Whittaker (1993), applying detrended correspondence analyses (DCA) and detrended canonical correspondence analyses (DCCA) to Sitka and Norway spruce forest condition data, concluded that these techniques failed to demonstrate any convincing relationships between crown condition and many of the environmental variables used. Although widely favoured by many ecologists, the use of detrending algorithms in correspondence analyses remains controversial for their arbitrarity and sometimes poor performance, with skewed data distributions and the destruction of ecologically meaningful patterns (Pielou, 1984; Palmer 1993).

All condition change data were first analysed by canonical correspondence analysis (CCA) using version 3.1 of the CANOCO computer programme (ter Braak, 1992). However, the small eigenvalues obtained from ordination of crown density and discoloration data, ranging from 0.008 (for Scots pine) to 0.013 for oak and beech, indicated that unimodal distributions assumed for CCA may not be suitable for the analysis of forest condition data. Although in many circumstances it is acceptable to analyse the same data set by both linear and non-linear methods, Gaussian models tend to break down in circumstances where environmental gradients are short. Analyses were, therefore, repeated using the redundancy analysis facility provided by CANOCO. Redundancy analysis (RDA), also known as reduced-rank regression, is the canonical form of PCA and applies a linear model of ordination (ter Braak, 1987). Eigenvalues obtained for RDAs were in the order of 7 to 14 times greater than those for comparable CCA of condition change data; thus indicating that 'change' distributions were more effectively described by linear models than Gaussian ones. This is possibly a result of the 'shorter' environmental gradients one might expect of cultivated forest crops (which are usually planted only where they will be most productive), in comparison with natural or semi-natural plant communities which may be exposed to wider ranging and more extreme environmental stimuli.

Due to the use of different units and scales to express species and environmental variables, data were standardised to zero mean and unit variance, and RDAs conducted on correlation matrices (Pielou, 1984; ter Braak 1987, 1992).

Two types of RDA were employed. The first were exploratory analyses in which pollution data were included with environmental variables. These were followed by 'partial' RDAs conducted to determine variation uniquely attributable to pollution. In partial RDAs the effects of non-pollution environmental variables were eliminated before performing 'partial constrained ordinations' with respect to pollution variables. The process of partial RDA is possibly over-rigorous. All variation explainable by co-variables (namely age of stand, slope and the two monthly SMD variables most highly correlated with variation in crown condition data) is extracted regardless of whether or not that variation may have a real relationship with explanatory (pollution) variables. The overall result is, within the limitations of data quality, to test for that residual variation in response data which is *uniquely* attributable to pollution variables. Because they are constrained to be linear combinations of pollution variables, the axes produced as a result of a partial RDA of crown condition data are referred to as 'pollution' axes.

The statistical significance of relationships was assessed using a Monte Carlo permutation test. This involves the random permutation of sample response data with respect to environmental data. If, for instance, after 99 permutations, four random permutations produce eigenvalues greater than that originally calculated for the real data, the Monte Carlo significance (p-value) would be (4+1)/(99+1) = 0.05 (ter Braak, 1992).

Data for redundancy analyses

All site mean crown condition 8992 change data were included in exploratory analyses. Pollution data analysed were dry, wet and cloud deposition of sulphur, ozone (number of hours at which 60 ppb were exceeded between April and September) and acid exceedance of critical loads for soils. Although exceedances for soils are modelled on sulphur deposition data, they do not duplicate other sulphur data which represent atmospheric loads. Total sulphur deposition, however, was omitted as this was simply the sum of those wet, dry and cloud components already included.

Other 'environmental' data used were stand age, mean annual PET, site slope, and the two early growing season (spring) and mid-growing season (summer) soil moisture deficit (SMD) expressions which were most highly correlated with crown condition in each species. Mean annual PET was included to determine its potential usefulness as a general, easily available and inexpensive composite meteorological expression with particular biological meaning for plant growth. It was excluded from partial RDAs because of correlation with (and duplication of) SMD data.

Selection of SMD data was partly based on the results of correlation analyses (Appendix 5), and also on a requirement to keep variance inflation factors (VIFs) within acceptable limits (ter Braak, 1992). Preliminary analyses included many intercorrelated meteorological variables and other expressions which, although implicit in other explanatory data, did not themselves confer any direct environmental meaning (for example easterliness, northerliness and altitude). These resulted in the production of VIFs in excess of 10000, when values greater than 20 are normally regarded as being unacceptably high. By reducing the number of explanatory variables to the 10 most important environmental and pollution variables, it was possible to keep most VIFs below a maximum value of 10.

Partial RDAs, apart from the exclusion of annual PET noted above, used the same explanatory variables. Non-pollution environmental variables, however, were attributed covariable status for the purpose of testing residual variation against pollution.

Results and discussion: redundancy analyses of 8992 indices for change in forest condition

The ordination diagrams used for exploratory analyses (Figures 4.1 to 4.5) are correlation biplots in which environmental axes are symmetrically scaled to unit length and increment (ter Braak, 1992). In linear ordinations it is more usual to represent both environmental and response variables by arrows; the length of arrows (or vectors) being proportional to their standard deviations and the cosines of their angular separations corresponding to correlation coefficients (Corsten and Gabriel, 1976; ter Braak, 1987). Here, however, 8992 response variables are plotted as points for purposes of clarity. The heads of arrows and positions of points indicate the direction of maximum variation in value of the corresponding variable. Variables with arrows pointing in roughly the same direction are positively correlated, those pointing in opposite directions being negatively correlated, while perpendicular arrows indicate zero or low correlations. The longer the arrow, the greater the importance of the variable and also the confidence of the inferred correlation (ter Braak, 1987; ter Braak and Prentice, 1988). The same form of interpretation is attached to relationships between variables and the two principal axes.

In exploratory analyses (Table 4.2) the eigenvalues for the first environmental axis (horizontal) of each ordination range from 0.091 for oak and 0.147 for beech, indicating that for each species the first axis typically accounts for approximately 9 to 15 per cent of all variation in response data. Eigenvalues for the second axes (vertical) were also sufficiently high to merit attention and, on average, described a further 5 per cent of the variation in response variables. From the probability values produced by Monte Carlo permutation tests, presented in Table 4.2, it can be seen that the first environmental axes were most significantly related to variation in crown condition change indices in Norway spruce and Scots pine ($p<0.01$), and that the models describing overall variation in response data were also highly significant ($p<0.01$) for all species except oak. The result for oak is in itself valuable, suggesting either that procedures for monitoring oak (which has suffered widespread decline during the period of interest) are inadequate or that some other element of environmental influence has not been taken into account.

It should be understood that because canonical coefficients are optimised to fit environmental axes as well as species axes, their statistical properties are slightly different to those of regression coefficients. Because they possess larger variances than regression coefficients, the Student's t-test, although having exploratory value, should not be applied too rigorously. As a general guide, the critical value for a t-test at $p \leq 0.05$ and $p \leq 0.01$ is *c.* 2.1 and 2.9 respectively if n-q-1>18; where n is the number of samples and q is the number of environmental variables including any covariables. Variables possessing t-values of less than 2.1 contribute very little to the fit of crown condition data (ter Braak and Looman, 1987). The critical features of RDA based ordinations are as follows:

- The process of RDA is similar to PCA (principle component analysis). The main difference between the two processes is that in RDA axes are *directly* constrained to be linear combinations of environmental variables.
- In partial RDA all variation explainable by co-variables is first removed from the model. The subsequent ordination is then performed on the residual variation only.
- In Figures 4.1 to 4.5 the relationships between response variables (points) and explanatory variables (arrows) may be summarised as follows:
  - Those lying in the same direction are positively correlated.
  - Those placed in opposite positions are negatively correlated.
  - Variables with perpendicular position relationships have zero or weak correlations.

Table 4.2 Summary statistics for first two axes of exploratory redundancy analyses.

Species	*Eigenvalues* Axis 1	*Eigenvalues* Axis 2	*Response variable and environment correlations* Axis 1	Axis 2	*Cumulative percentage variances: dependent variables* Axis 1	Axis 2	*Cumulative percentage variances: dependent and environmental relationships* Axis 1	Axis 2	*Significance (p) for first axis*	*Significance (p) for overall model*
Beech	0.147	0.069	0.783	0.717	14.7	21.6	36.9	54.3	0.05	<0.01
Norway spruce	0.100	0.052	0.721	0.637	10.0	15.2	42.3	64.4	<0.01	<0.01
Oak	0.091	0.058	0.719	0.664	9.1	14.9	37.4	61.3	0.22	0.09
Scots pine	0.113	0.046	0.762	0.586	11.3	15.9	48.0	67.8	<0.01	<0.01
Sitka spruce	0.093	0.053	0.665	0.630	9.3	14.6	38.2	60.0	0.06	<0.01

- Arrows and points placed further from the origin of the axes are attributed greater importance and statistical confidence.

Beech

The environmental variables that appear to exert the greatest influence on the first axis in Figure 4.1 are ozone, annual PET and SMD in March and June (i.e. the arrows representing these variables lie closest to the horizontal axis). Results of statistical analyses (Table 4.3), confirm the influence of ozone, annual PET and SMD in June, and also indicate that critical load exceedance (t=-2.77, r=0.336) is significantly related to the first axis. Although seemingly significant (t>2.1) low inter-set correlations for dry and wet deposition of sulphur and stand age (0.145, -0.091 and 0.155) indicate that they contribute relatively little to the second axis. The general direction of relationships, without inferring causal links, associate increasing declines in forest condition with greater SMD, PET, sulphur deposition and exposure to ozone. These agree with other reports concerning the role of drought (Innes, 1992c; Stribley, 1993) and the possible involvement of ozone (Power, 1994) in beech decline.

Figure 4.1 suggests that the important crown condition variables in relation to the first axis and associated environmental variables are for changes in dieback (db8992), crown form (cf8992), premature leaf loss (pl8992) and, in directly opposite orientation to ozone, masting (ma8992) (i.e. the points representing these variables lie furthest from the origin). Crown density (cd8992) and foliage discoloration indices (bn8992, yc8992 and di8992) contributed very little to the overall ordination.

Results of partial redundancy analyses to determine unique effects of pollution are summarised in Table 4.4. Although pollution axes accounted for 28.8 per cent of the residual variation in change in crown density (cd8992) after fitting effects due to non-pollution environmental covariables, this was only significant at p=0.08. Further examination of the individual components of the partial ordination (Table 4.5) suggest the strongest associations with respect to cd8992 were with ozone (t=2.55, r=0.317) and then with dry deposition of sulphur, Sdry (t=2.17, r=0.314). A high inter-set correlation, but contrastingly low t-value, were obtained for cd8992 and occult deposition of sulphur, Scld (t=-0.913, r=0.882). Accepting the limitations of t-testing canonical coefficients, relationships between cd8992 and ozone and Sdry were significant at p=0.05.

Combining cd8992 with indices for change in discoloration and with other indices only introduced greater variation. This consequently reduced eigenvalues for environmental axes, without any improvement in statistical confidence (p=0.08 and 0.09 for first axis, Table 4.4, runs 2 and 3).

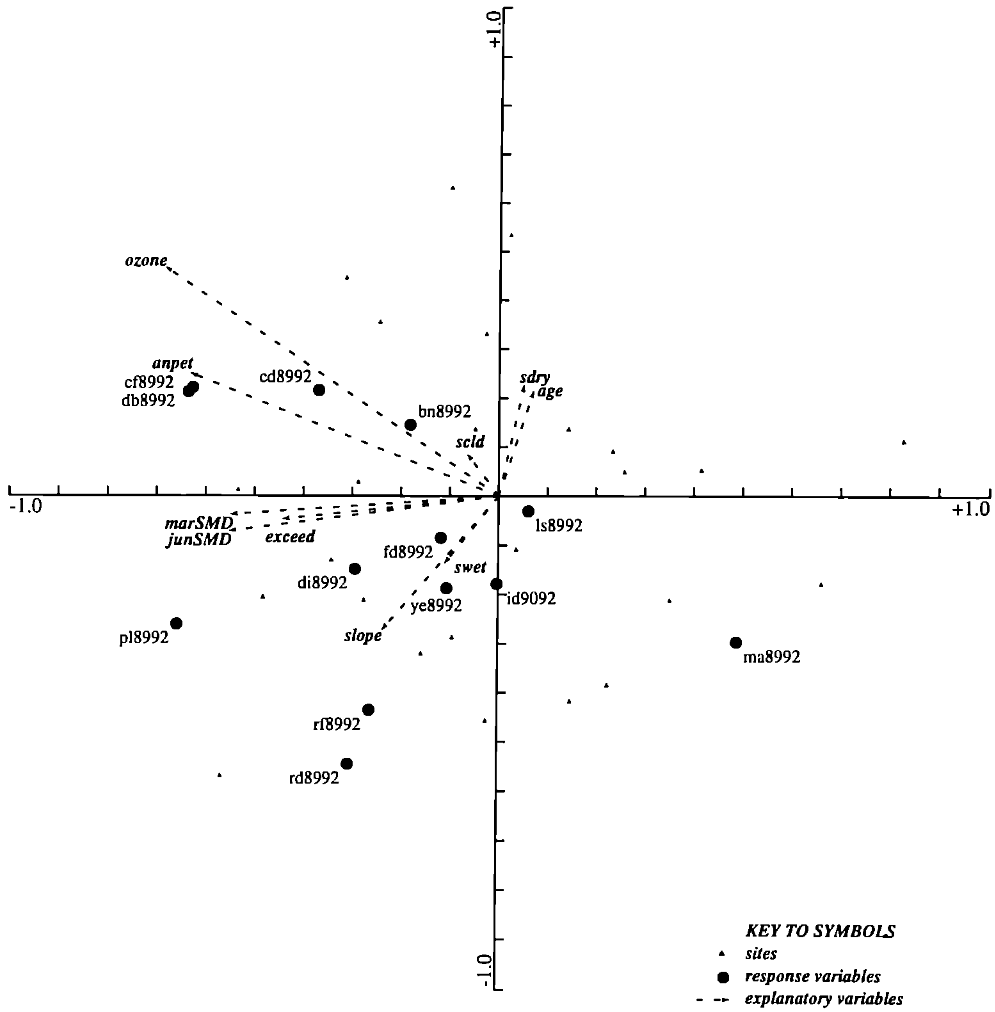


Figure 4.1 Ordination diagram for exploratory redundancy analysis of beech: Eigenvalues first (horizontal) axis = 0.147, second (vertical) axis = 0.069; Monte Carlo significance tests (p) first axis <0.05, overall model <0.01.

Table 4.3 Canonical coefficients, t-values and inter-set correlations for exploratory analysis of beech data (Figure 4.1).

Variable	*Canonical coefficients*		*t-values*		*Inter-set correlations*	
	Axis 1	*Axis 2*	*Axis 1*	*Axis 2*	*Axis 1*	*Axis 2*
ozone	-1.234	0.679	-3.38 **	1.52	-0.528	0.330
Scld	0.300	0.349	0.97	0.92	-0.044	0.054
Sdry	0.254	0.615	1.37	2.71 *	0.053	0.145
Swet	-0.255	-0.764	-0.93	-2.27 *	-0.082	-0.091
exceed	-0.630	-0.333	-2.77 *	-1.20	-0.336	-0.034
age	0.118	0.574	0.65	2.61 *	0.037	0.155
slope	-0.008	-0.239	-0.04	-0.94	-0.181	-0.188
anPET	1.254	0.749	2.41 *	1.18	-0.486	0.176
marSMD	0.474	-0.672	0.89	-1.03	-0.419	-0.026
junSMD	-1.664	-0.439	-2.92 **	-0.63	-0.422	-0.049

Statistically significant t-values are indicated; * t>2.1, $p \leq 0.05$, ** t>2.9, $p \leq 0.01$.

Table 4.4 Summary statistics for partial redundancy analyses of beech data.

Run	Variable(s)	Eigenvalues Axis 1	Eigenvalues Axis 2	Dependent variable and environment correlations Axis 1	Dependent variable and environment correlations Axis 2	Cumulative percentage variances: dependent variables Axis 1	Cumulative percentage variances: dependent variables Axis 2	Cumulative percentage variances: dependent and environmental relationships Axis 1	Cumulative percentage variances: dependent and environmental relationships Axis 2	Significance (p) for first axis	Significance (p) for overall model
1	cd8992	0.273	0.676	0.537	-	28.8	-	100.0	0.0	0.08	-
2	cd8992 and disc	0.075	0.041	0.523	0.343	8.7	13.4	55.7	86.0	0.08	0.46
3	all indices	0.087	0.049	0.807	0.653	10.2	15.9	41.0	64.0	0.09	0.02
4	cf8992	0.238	0.484	0.575	-	33.0	-	100.0	0.0	0.08	-
5	db8992	0.402	0.360	0.727	-	52.8	-	100.0	0.0	<0.01	-
6	cf8992 and db8992	0.277	0.044	0.696	0.505	37.3	43.2	86.3	100.0	<0.01	<0.01
7	pl8992	0.185	0.564	0.497	-	24.7	-	100.0	0.0	0.17	-

Note: disc refers to the use of all indices for change in discoloration in run 2.

The two other indices which appeared to be related with pollution axes were change in dieback db8992, and crown form cf8992 (runs 4, 5 and 6 in Table 4.4); although only significant at p=0.08 for cf8992. The strongest associations between individual components were for cf8992 with ozone (t=2.683, r=0.507) and db8992 with all pollution variables ($r \approx 0.5$), with the exception of wet deposition of sulphate (Swet). The dieback index bears strongest association with exceedance (t=2.83, r=0.568). As might be expected, statistics for the partial analysis of combined cf8992 and db8992 indices exhibit hybrid qualities of the individual indices (Table 4.5).

Oak

Comparatively low significance levels for the first axis (p<0.09) and the overall model (p<0.22) suggest that response variables poorly reflect environmental variation at oak sites. Figure 4.2 indicates that annual PET, ozone and SMD in March and July have the greatest influence on the first axis. The canonical coefficients, t-values and environmental correlations in Table 4.6, however, in spite of the apparent loading of pollution data on the first and second axes in the biplot, suggest that virtually all variation in response data is attributable to the two SMD indices and to annual PET. The similar orientations of dieback db8992, PET and SMD vectors of Figure 4.2 agree with the view that increases in dieback probably resulted from summer droughts in 1989 and 1990 (Innes, 1993a).

Table 4.5 Canonical coefficients, t-values and inter-set correlations for partial redundancy analyses of beech data.

Variable	Statistic	ozone	Scld	Sdry	Swet	exceed
cd8992	canonical coefficient	1.179	-0.542	0.759	0.391	-0.346
	t-value	2.550 *	-0.913	2.169 *	0.750	-0.884
	inter-set correlation	0.317	0.882	0.314	0.183	0.040
cf8992	canonical coefficient	1.123	-0.447	0.017	-0.019	0.519
	t-value	2.683 *	-0.831	0.055	-0.039	1.463
	inter-set correlation	0.507	0.105	-0.067	0.071	0.358
db8992	canonical coefficient	0.406	0.846	0.128	-0.560	0.666
	t-value	1.461	2.372 *	0.608	-1.785	2.860 *
	inter-set correlation	0.489	0.508	0.508	0.242	0.568
cf8992 and db8992	canonical coefficient	0.705	-0.426	0.096	-0.399	0.661
	t-value	2.324 *	1.095	0.419	-1.167	2.574 *
	inter-set correlation	0.558	0.389	0.004	0.195	0.544

Statistically significant t-values are indicated; * = t>2.1 $p \leq 0.05$.

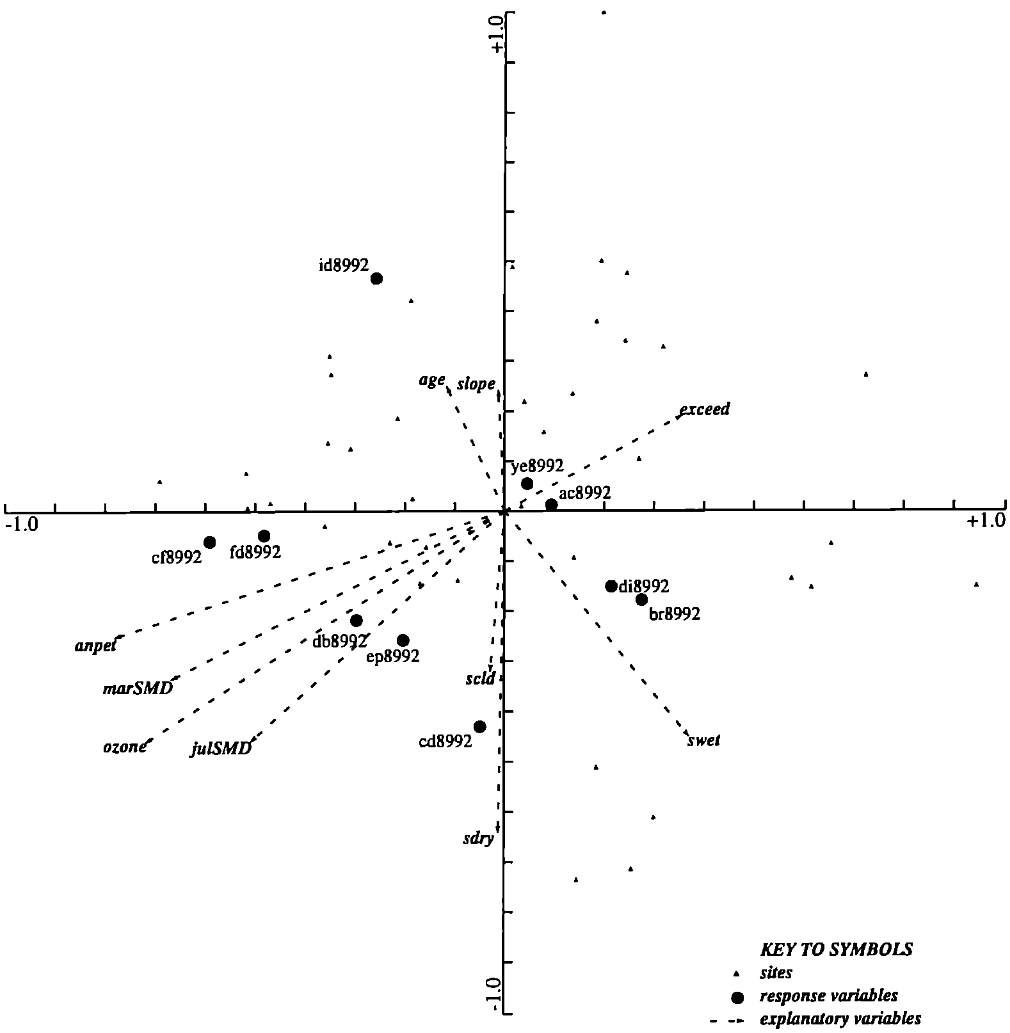


Figure 4.2 Ordination diagram for exploratory redundancy analysis of oak: Eigenvalues first (horizontal) axis = 0.091, second (vertical) axis = 0.058; Monte Carlo significance tests *(p)* first axis=0.22, overall model=0.09.

Table 4.6 Canonical coefficients, *t*-values and inter-set correlations for exploratory analysis of oak data (Figure 4.2).

	Canonical coefficients		*t-values*		*Inter-set correlations*	
Variable	*Axis 1*	*Axis 2*	*Axis 1*	*Axis 2*	*Axis 1*	*Axis 2*
ozone	-0.317	-0.578	-0.98	-1.54	-0.508	-0.301
Scld	-0.161	-0.186	-0.67	-0.66	-0.020	-0.205
Sdry	-0.014	-0.270	-0.08	-1.28	-0.001	-0.406
Swet	0.340	-0.429	1.69	-1.84	0.260	-0.294
exceed	0.098	0.253	0.51	1.12	0.247	0.122
age	-0.142	0.182	-0.92	1.01	-0.080	0.159
slope	-0.364	0.136	-1.69	0.54	-0.010	0.153
anPET	-0.506	1.020	-1.17	2.03	-0.552	-0.166
marSMD	-1.000	0.173	-2.18 *	0.32	-0.473	-0.218
julSMD	0.904	-1.147	2.26 *	-2.46 *	-0.360	-0.298

Statistically significant *t*-values are indicated: * $t > 2.1 \equiv p \leq 0.05$.

Table 4.7 Summary statistics for partial redundancy analyses of oak data

Run	Variable(s)	Eigenvalues Axis 1	Eigenvalues Axis 2	Dependent variable and environment correlations Axis 1	Dependent variable and environment correlations Axis 2	Cumulative percentage variances: dependent variables Axis 1	Cumulative percentage variances: dependent variables Axis 2	Cumulative percentage variances: dependent and environmental relationships Axis 1	Cumulative percentage variances: dependent and environmental relationships Axis 2	Significance (p) for first axis	Significance (p) for overall model
1	cd8992	0.135	0.738	0.393	-	15.5	-	100.0	0.0	0.15	-
2	cd8992 and disc	0.048	0.013	0.396	0.241	5.3	6.7	76.0	96.4	0.64	0.84
3	all indices	0.035	0.027	0.490	0.514	4.0	7.2	41.0	73.3	0.68	0.51
4	cf8992	0.147	0.585	0.448	-	20.1	-	100.0	0.0	0.07	-
5	db8992	0.063	0.841	0.265	-	7.0	-	100.0	0.0	0.66	-
6	cf8992 and db8992	0.079	0.026	0.450	0.247	9.7	12.9	75.1	-	0.19	0.22

Note: disc refers to the use of all indices for change in discoloration in run 2.

Partial redundancy analyses with respect to pollution data and certain key 'change' indices produced similarly poor relationships (Table 4.7). Of these, only change in crown form (cf8992) displayed a tenuous correlation with pollution axes at p=0.07 (run 6). Given the overall deficiency of the model, there can be little confidence in the weakly implied relationship between cf8992 and ozone (Table 4.8). The general inadequacy of the model may be partly attributed to the different responses of the two species of oaks and their hybrids, which are not distinguished in the survey (Innes, 1993a).

Norway spruce

The variables appearing to exert the greatest influence on the first axis of the exploratory ordination for Norway spruce (Figure 4.3) are March and August SMD, closely followed by dry deposition of sulphur (Sdry) and mean annual PET. Their influences are confirmed by their high inter-set correlations with the first axis ($r \approx 0.5$ in Table 4.9). The similar ordination of the index for change in crown density (cd8992) suggests its covariation with SMD, PET and Sdry. The first axis and the overall model are significant at $p<0.01$.

Among partial redundancy analyses, only residual variation in crown density (cd8992) was found to be significantly related to a pollution axis; in this case pollution explained nearly one-quarter of residual variation in cd8992 at a significance level of $p<0.01$ (see run 1 in Table 4.10). Statistics for the components of the first and only pollution axis (because the partial RDA was with respect to one response variable) suggest that greater increases in crown transparency are particularly associated with increasing wet and dry deposition of sulphur (in Table 4.11 Sdry, t=2.053, r=0.354; Swet t=2.484, r=0.381). Allowing for limitations placed upon inference from modelled data, the weakness of the relationship between cd8992 and critical load exceedance (exceed) suggests that airborne levels of sulphur, thus implying foliage effects, should not be discounted. This contrasts with the more widely accepted view that regional declines may be

Table 4.8 Canonical coefficients, t-values and inter-set correlations for partial redundancy analyses of change in crown form (1989 to 1992) in oak.

Statistic	ozone	Scld	Sdry	Swet	exceed
canonical coefficient	0.938	0.299	-0.305	-0.701	-0.360
t-value	2.232 *	0.658	-0.826	-1.720	-0.936
inter-set correlation	0.261	0.084	-0.172	-0.182	-0.178

Statistically significant t-values are indicated; * = $t > 2.1$ $p \le 0.05$; ** ≡ $t > 2.9$ $p \le 0.01$.

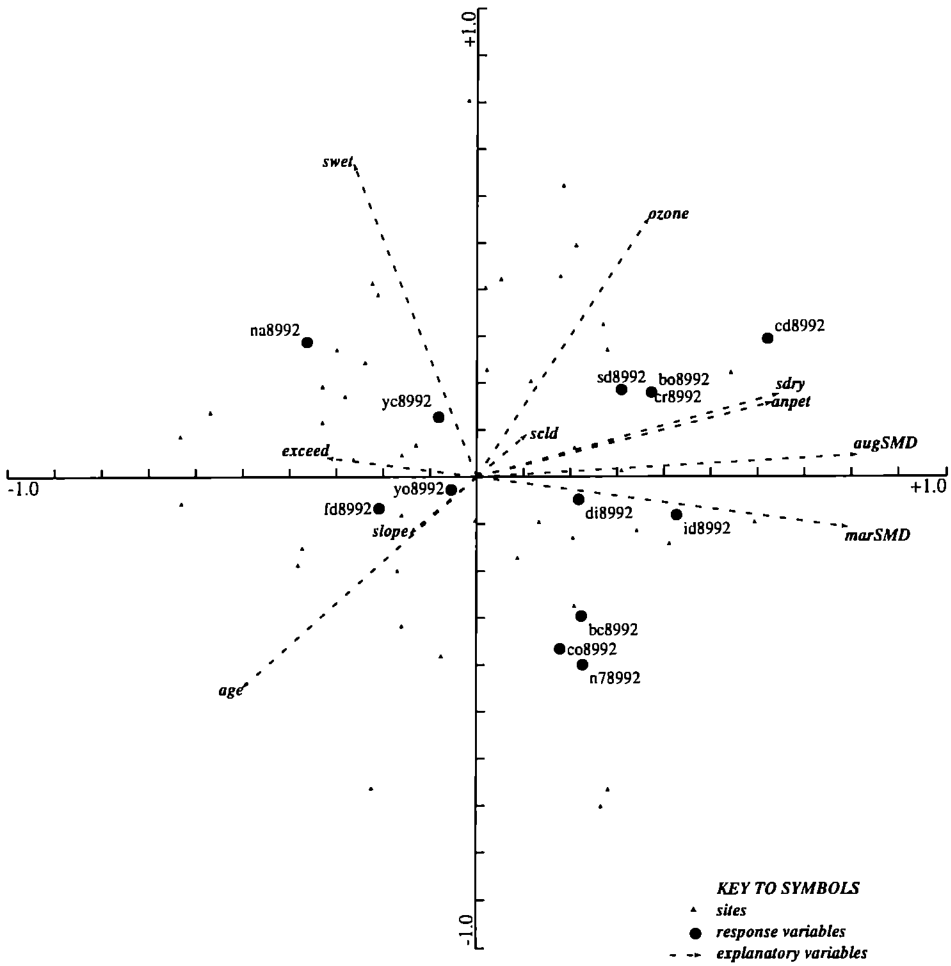


Figure 4.3 Ordination diagram for exploratory redundancy analysis of Norway spruce: Eigenvalues first (horizontal) axis = 0.100, second (vertical) axis = 0.052; Monte Carlo significance tests *(p)* first axis <0.01, overall model <0.01.

Table 4.9 Canonical coefficients, *t*-values and inter-set correlations for exploratory analysis of Norway spruce data (Figure 4.3).

Variable	*Canonical coefficients*		*t-values*		*Inter-set correlations*	
	Axis 1	*Axis 2*	*Axis 1*	*Axis 2*	*Axis 1*	*Axis 2*
ozone	-0.395	1.011	-1.67	3.39 **	0.260	0.345
Scld	0.258	-0.367	1.42	-1.60	0.071	0.052
Sdry	0.209	0.061	1.28	0.30	0.456	0.109
Swet	-0.097	0.479	-0.63	2.47 *	-0.188	0.417
exceed	0.185	-0.187	1.04	-0.83	-0.222	0.026
age	-0.476	-0.364	-3.76 **	-2.27 *	-0.353	-0.280
slope	-0.016	0.009	-0.10	0.05	-0.096	-0.071
anPET	0.300	-0.692	0.98	-1.79	0.445	0.098
marSMD	0.520	-0.771	1.46	-1.72	0.564	-0.067
augSMD	0.237	0.690	0.62	1.42	0.577	0.029

Statistically significant *t*-values are indicated: * $t > 2.1 \equiv p \leq 0.05$; ** $t > 2.9 \equiv p \leq 0.01$.

Table 4.10 Summary statistics for partial redundancy analyses of Norway spruce data.

Run	Variable(s)	Eigenvalues Axis 1	Eigenvalues Axis 2	Dependent variable and environment correlations Axis 1	Dependent variable and environment correlations Axis 2	Cumulative percentage variances: dependent variables Axis 1	Cumulative percentage variances: dependent variables Axis 2	Cumulative percentage variances: dependent and environmental relationships Axis 1	Cumulative percentage variances: dependent and environmental relationships Axis 2	Significance (p) for first axis	Significance (p) for overall model
1	cd8992	0.149	0.474	0.488	-	23.8	-	100.0	0.0	<0.01	-
2	cd8992 and disc	0.035	0.029	0.527	0.386	3.9	7.2	38.7	70.6	0.56	0.11
3	all indices	0.040	0.018	0.541	0.369	4.5	6.6	45.1	65.9	0.18	0.07

Note: disc refers to the use of all indices for change in discoloration in run 2.

Table 4.11 Canonical coefficients, *t*-values and inter-set correlations for partial redundancy analyses of change in crown density (1989 to 1992) in Norway spruce.

Statistic	*ozone*	*Scld*	*Sdry*	*Swet*	*exceed*
canonical coefficient	-0.237	0.351	0.618	0.706	0.096
t-value	-0.706	1.121	2.053	2.484 *	0.298
inter-set correlation	0.116	0.240	0.354	0.381	0.180

Statistically significant *t*-values are indicated; * $t>2.1 \equiv p \leq 0.05$.

attributed to soil-mediated effects (Freer-Smith and Benham, 1994). The use of composite indices for crown condition (runs 2 and 3, Table 4.10) only introduced greater variation without providing any further explanations concerning possible relationships with pollution variables.

Sitka spruce

Although the overall ordination for Sitka spruce was significant ($p<0.01$) the first axis described less than 10 per cent of variation in response data and was only weakly significant at $p=0.06$. Soil moisture deficit in March contributed most to the first axis (Figure 4.4 and Table 4.12), and with July SMD, exceedance and wet deposition of sulphur also contributed much to the ordination of the second axis. The position of many indices close to the origin, such as those for changes in browning of old foliage (bo8992), yellowing of current foliage (yc8992), crown shoot death (cr8992), suggest their weak relationships with environmental variables.

In partial RDAs (Table 4.13) residual variation in overall discoloration (di8992) and yellowing of old foliage (yo8992) were significantly related to the first pollution axes at $p=0.06$ and $p=0.07$ respectively. Partial RDA of combined discoloration indices bc8992, yo8992 and di8992 produced stronger relationships between response data and the model ($p=0.02$ and $p<0.01$ for the first axis and overall model respectively). Statistics for the components of the first axes for both the di8992 and the combined bc8992, yo8992 and di8992 runs indicate that variation is mainly attributable to exceedances of critical loads for soils (Table 4.14). However, due to the poor distribution of discoloration data, and the overall rarity of foliage discoloration, very little confidence can be attached to interpreting relationships which involve discoloration indices. Despite apparent covariation with Sdry in Figure 4.4 residual variation for cd8992 was not even remotely associated with pollution axes (run 1 in Table 4.13).

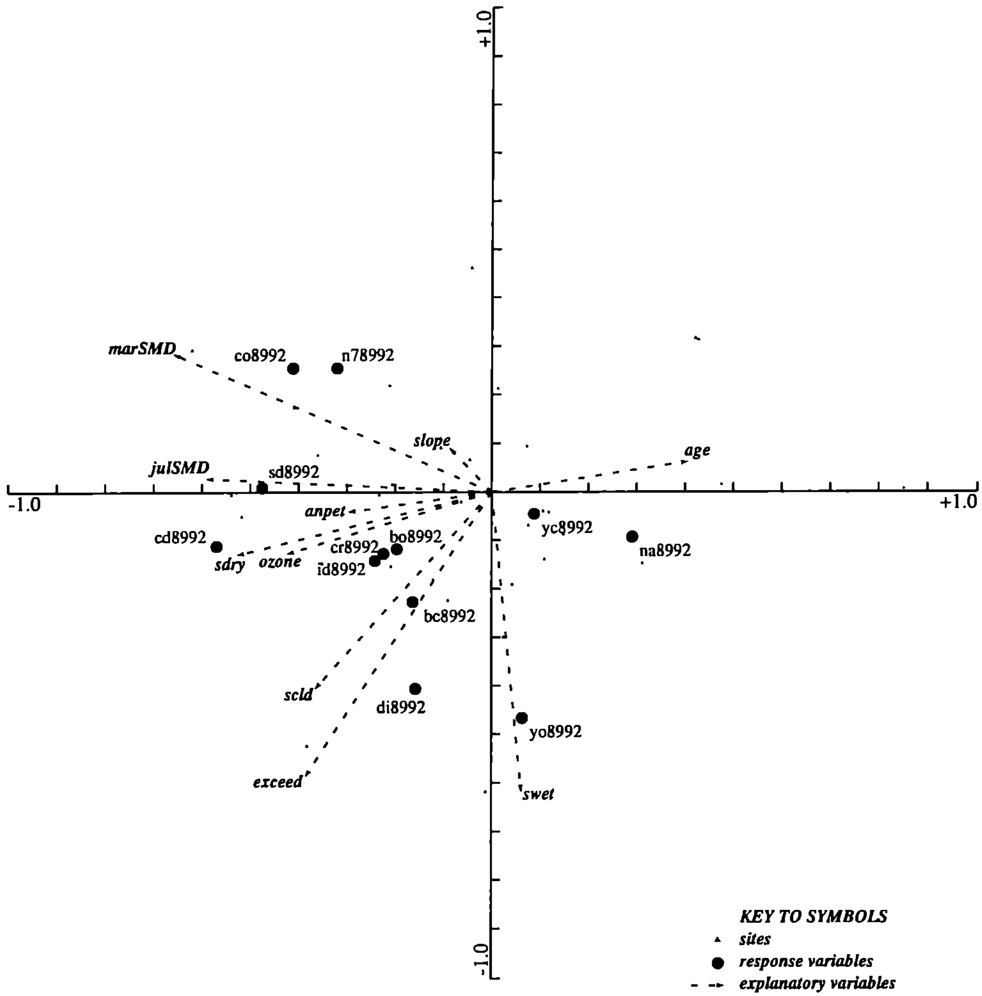


Figure 4.4 Ordination diagram for exploratory redundancy analysis of Sitka spruce: Eigenvalues first (horizontal) axis = 0.093, second (vertical) axis = 0.053; Monte Carlo significance tests *(p)* first axis = 0.06, overall model < 0.01.

Table 4.12 Canonical coefficients, *t*-values and inter-set correlations for exploratory analysis of Sitka spruce data (Figure 4.4).

Variable	*Canonical coefficients*		*t-values*		*Inter-set correlations*	
	Axis 1	*Axis 2*	*Axis 1*	*Axis 2*	*Axis 1*	*Axis 2*
ozone	-0.003	0.384	-0.01	1.03	-0.274	-0.078
Scld	-0.158	-0.204	-0.66	-0.78	-0.238	-0.249
Sdry	-0.322	0.101	-1.57	0.45	-0.342	-0.081
Swet	0.173	-0.413	0.82	-1.78	0.041	-0.381
exceed	-0.419	-0.611	-1.92	-2.55 *	-0.251	-0.362
age	0.346	-0.109	1.95	-0.56	0.262	0.038
slope	0.085	0.393	0.45	1.88	-0.053	0.052
anPET	0.303	-0.405	0.80	-0.98	-0.189	-0.025
marSMD	-0.923	1.332	-2.00	2.63 *	-0.431	0.176
julSMD	0.059	-1.307	0.12	-2.46 *	-0.384	0.017

Statistically significant *t*-values are indicated; * $t>2.1 \equiv p \leq 0.05$.

Table 4.13 Summary statistics for partial redundancy analyses of Sitka spruce data.

Run	Variable(s)	Eigenvalues Axis 1	Eigenvalues Axis 2	Dependent variable and environment correlations Axis 1	Dependent variable and environment correlations Axis 2	Cumulative percentage variances: dependent variables Axis 1	Cumulative percentage variances: dependent variables Axis 2	Cumulative percentage variances: dependent and environmental relationships Axis 1	Cumulative percentage variances: dependent and environmental relationships Axis 2	Significance (p) for first axis	Significance (p) for overall model
1	cd8992	0.083	0.593	0.350	-	12.3	-	100.0	-	0.30	-
2	cd8992 and disc	0.078	0.023	0.518	0.422	8.8	11.4	67.5	87.5	0.05	0.10
3	all indices	0.054	0.034	0.543	0.513	6.1	9.9	47.6	77.5	0.12	0.07
4	di8992	0.196	0.788	0.446	-	19.9	-	100.0	0.0	0.06	-
5	cd8992 and di8992	0.118	0.022	0.501	0.245	14.2	16.8	84.4	-	0.06	0.07
6	yo8992	0.150	0.642	0.435	-	18.9	-	100.0	-	0.07	-
7	bc8992, yo8992, di8992	0.115	0.042	0.504	0.389	12.8	17.4	70.5	96.2	0.02	0.01

Note: disc refers to the use of all indices for change in discoloration in run 2.

Scots pine

As in other exploratory ordinations, vectors for SMD, PET, ozone and dry deposition of sulphur tend to explain most of the variation in response data, and their relative proximities within the biplot (Figure 4.5) suggest that they relate to similar patterns in data. It can be seen from the coefficients and *t*-values in Table 4.15 that soil moisture deficit in August (augSMD), ozone and dry deposition of sulphur (Sdry) contribute most to the first axes. Although on the basis of *t*-statistics alone the major components of the second axis appear to be augSMD and slope (t=2.82 and t=3.11 respectively), contrastingly low inter-set correlations (r=-0.104 and r=0.293 respectively) indicate rather weaker relationships with the second axis.

From the positions of response indices, it can be seen that the ordination particularly describes variation in change indices for insect damage (id8992), crown density (cd8992), flowering in the upper and lower crown (ft8992 and fb8992 respectively), the extent and location of shoot death (sd8992 and cr8992 respectively). Heavier flowering in Scots pine is usually associated with reductions in crown density (Innes, 1993).

Results for partial RDAs in Table 4.16 indicate that most of the variation in response data, with the exception of the flowering indices, was readily explained by the SMD, slope and stand age covariables. The strongest association with a pollution axis was for 21.1 per cent of residual variation in 'top flowering' (ft8992) at a significance level of p=0.02. Closer examination suggests that this relationship is largely attributable to the ozone component of the pollution axis.

Table 4.14 Canonical coefficients, *t*-values and inter-set correlations for first axis of partial redundancy analyses of discoloration in Sitka spruce.

Variable(s)	Statistic	ozone	Scld	Sdry	Swet	exceed
di8992	canonical coefficient	0.509	-0.274	0.029	-0.309	-0.967
	t-value	1.166	-0.730	0.081	-0.833	-2.522 *
	inter-set correlation	-0.052	-0.237	-0.096	-0.211	-0.403
bc8992, yo8992	canonical coefficient	0.399	-0.076	-0.140	-0.372	-0.971
and di8992	*t*-value	1.072	-0.237	-0.455	-1.173	-2.962 **
	inter-set correlation	-0.097	-0.222	-0.170	-0.279	-0.461

Statistically significant *t*-values are indicated: * $t > 2.1 \equiv p \leq 0.05$; ** $t > 2.9 \equiv p \leq 0.01$.

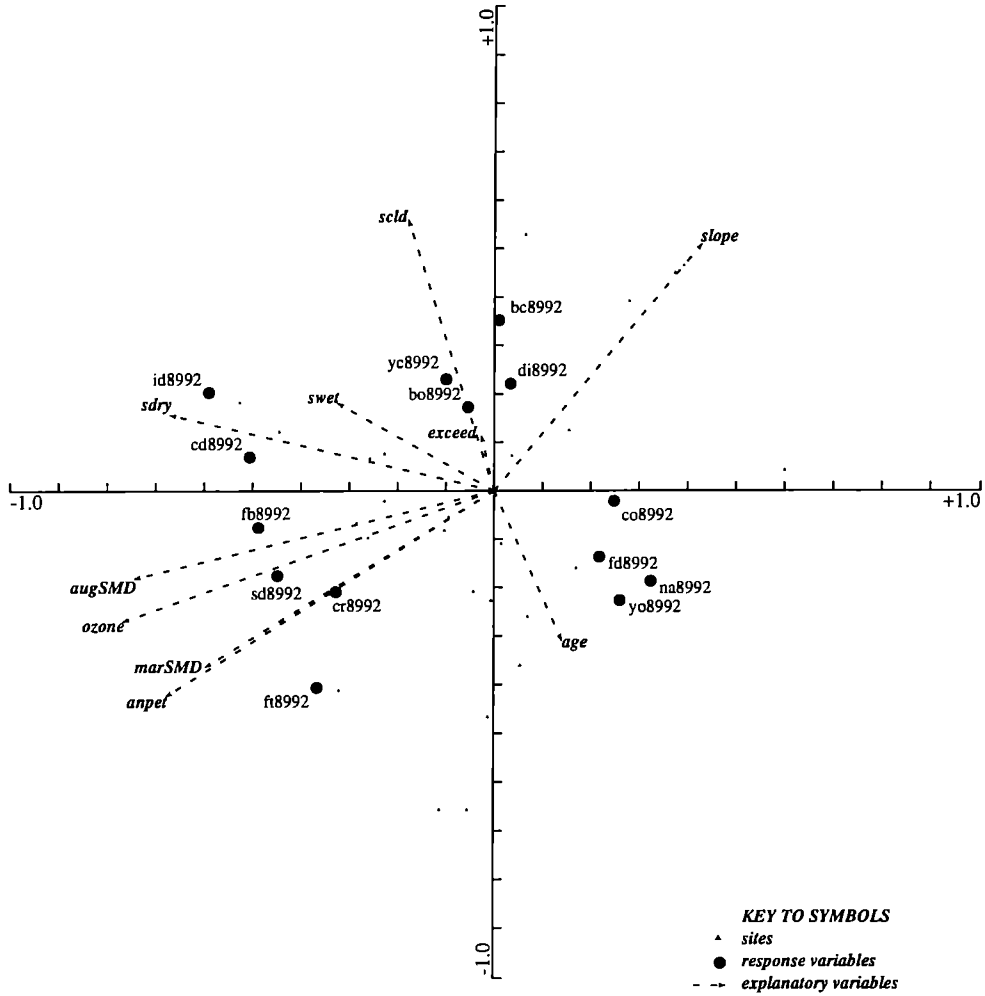


Figure 4.5 Ordination diagram for exploratory redundancy analysis of Scots pine: Eigenvalues first (horizontal) axis = 0.113, second (vertical) axis = 0.046; Monte Carlo significance tests *(p)* first axis <0.01, overall model <0.01.

Table 4.15 Canonical coefficients, *t*-values and inter-set correlations for exploratory analysis of Scots pine data (Figure 4.5).

Variable	*Canonical coefficients* *Axis 1*	*Axis 2*	*t-values* *Axis 1*	*Axis 2*	*Inter-set correlations* *Axis 1*	*Axis 2*
ozone	-0.531	-0.299	-2.58 *	-0.89	-0.577	-0.156
Scld	-0.164	0.448	-1.03	1.73	-0.134	0.321
Sdry	-0.381	0.268	-3.10 **	1.34	-0.503	0.091
Swet	-0.025	-0.140	-0.17	-0.58	-0.239	0.102
exceed	0.058	-0.076	0.47	-0.38	-0.014	0.051
age	0.165	-0.313	1.52	-1.78	0.103	-0.176
slope	0.195	0.686	1.44	3.11 **	0.321	0.293
anPET	0.170	-0.644	0.64	-1.48	-0.511	-0.245
marSMD	0.216	-0.562	0.75	-1.19	-0.447	-0.214
augSMD	-0.610	1.396	-2.01	2.82 *	-0.559	-0.104

Statistically significant *t*-values are indicated: * $t>2.1 \equiv p \leq 0.05$; ** $t>2.9 \equiv p \leq 0.01$.

Table 4.16 Summary statistics for partial redundancy analyses of Scots pine data.

Run	Variable(s)	Eigenvalues Axis 1	Eigenvalues Axis 2	Dependent variable and environment correlations Axis 1	Dependent variable and environment correlations Axis 2	Cumulative percentage variances: dependent variables Axis 1	Cumulative percentage variances: dependent variables Axis 2	Cumulative percentage variances: dependent and environmental relationships Axis 1	Cumulative percentage variances: dependent and environmental relationships Axis 2	Significance (p) for first axis	Significance (p) for overall model
1	cd8992	0.060	0.709	0.279	-	7.8	-	100.0	0.0	0.44	-
2	cd8992 and disc	0.033	0.024	0.421	0.280	3.6	6.3	49.2	84.9	0.51	0.37
3	all indices	0.051	0.027	0.633	0.539	5.8	8.9	50.3	76.6	0.02	-
4	fb8992	0.127	0.714	0.388	-	15.1	-	100.0	0.0	0.07	-
5	ft8992	0.179	0.670	0.460	-	21.1	-	100.0	0.0	0.02	-
6	fb8992 and ft8992	0.131	0.022	0.425	0.431	15.5	18.1	85.7	-	0.04	0.03

Note: disc refers to the use of all indices for change in discoloration in run 2.

Redundancy analyses: general discussion

Although it was apparent from the exploratory analyses that much of the variation in 8992 response data could be attributed to the effects of water stress, as indicated by the strength of relationships with soil moisture deficit and potential evapotranspiration data, many of the ordinations placed equal emphases on modelled pollution data. The most notable general contributions by a pollution variable in exploratory analyses were for ozone; this being the variable most highly correlated with first axes in beech and Scots pine (r=-0.528 and -0.577 respectively), and the second most highly correlated in oak (r=-0.508). The possible effects of ozone during the period of study are noted elsewhere. The Forestry Commission reported depressions in the growth of Norway spruce and beech during 1989 and 1990 in the 'ambient-air' treatments of open-top chamber experiments, and related these to elevated ozone levels during 1989 and 1990 (Durrant *et al.*, 1992). The effect of the 1989 drought, however, should not be underestimated. A wide range of tree species exhibited signs of drought stress, particularly in southern Britain, and it is also possible that high ozone concentrations during the drought may have resulted in additional stress (Innes *et al.*, 1989).

It is not appropriate to infer causal relationships from monitoring programmes without experimental controls; Schulze and Freer-Smith (1991) commented that '...observational field studies can only reject, and not prove, hypotheses...'. They do, however, provide opportunities to generalise variation and examine patterns of co-variation from which hypotheses may be generated. A hypothesis that mainly attributed decline to drought effects, possibly even single drought events, but allowed that trees growing in polluted areas were physiologically more vulnerable to water stress, would not be inconsistent with the findings reported here. There is considerable evidence that trees which tolerate the independent stresses of pollution and drought will exhibit signs of decline under circumstances of combined water and pollution stress. Interactions between drought and pollution

Table 4.17 Canonical coefficients, *t*-values and inter-set correlations for partial redundancy analyses of change in top flowering (1989 to 1992) in Scots pine.

Statistic	*ozone*	*Scld*	*Sdry*	*Swet*	*exceed*
canonical coefficient	1.326	-0.167	0.344	-0.138	-0.105
t-value	3.752 **	-0.507	1.240	-0.414	-0.379
inter-set correlation	0.453	0.119	0.141	0.181	0.113

Statistically significant *t*-values are indicated: ** $t>2.9 \equiv p\leq0.01$.

have been demonstrated for many species including Norway spruce (Macrez and Hubac, 1988; Pierre and Queiroz, 1988), beech (Taylor and Dobson, 1989; Taylor and Davies, 1990) and birch (*Betula* spp.) (Neighbour *et al.*, 1988). In spruces the interaction between pollution and water stress is widely believed to be mediated by pollution disturbance of stomatal control, thereby affecting water regulation and photosynthesis (Cornic, 1987; Dobson *et al.*, 1990; Maier-Maierker and Koch, 1991; Wallin and Skarby, 1992).

Although canonical analyses provide a valuable means for determining unique influences, certain limitations concerning data should be recorded. Firstly, because crown densities were not adjusted for mechanical damage, the possibility exists that sulphur deposition, being greatest at high and exposed elevations, may have reflected increased crown transparency due to the effects of wind and snow. Secondly, apart from possible inaccuracies associated with modelled data, deposition models are known to reflect many other aspects of meteorological variation.

In contrast, accepting the limitations noted above, it should be understood that the prior extraction of covariation in partial RDAs (to determine effects uniquely attributable to pollution), heavily favours explanation of variation due to non-pollution factors. It can be said, therefore, that within the limitations of available data, significant relationships between 8992 change data and pollution variables became apparent under rigorously tested circumstances. The principal significant relationships were between dieback in beech and ozone exceedance, crown density in Norway spruce and sulphur deposition, and flowering in Scots pine and ozone exceedance. It was also interesting to note that composite variables provided no additional information, and that inclusion of further condition indices in ordinations were usually more confusing than helpful.

Chapter 5

Conclusions and recommendations

A GIS has been established which allows analysis and presentation of the UK data on forest condition along with appropriate environmental data, including sulphur inputs, ozone episodes and soil critical load exceedance. There may be further opportunities to improve GIS specification, for example with inclusion of critical loads for specific receptors, soil and topographic information and facilities for producing maps based upon geostatistical techniques.

Investigations concerning the adequacy of the present survey provided useful information towards a partial fulfilment of the secondary objectives; namely how effectively parameters recorded in the present survey reflect crown condition, and the possible implications for intensive monitoring. In the absence of a clear understanding of decline processes, the present survey is sufficiently adaptable to provide at least partial factorial representation for simple combinations of environmental strata. Assuming that the objective of surveys is to monitor processes of decline and recovery, provision should be made for sufficient representation for investigating medium term changes; Innes and Boswell (1991a) suggested sample sizes of about 80 sites for each species for adequate spatial and temporal representation of forest condition.

From the results of redundancy analyses, environmental influences of principal interest appear to be soil moisture deficit, ozone and sulphur deposition. Future surveys may also stratify for exceedances of critical loads for acidity of soils when these are available for specific receptors. Although these considerations may be applied to selection of intensively monitored sites, selections should also be guided by practical requirements to maximise the returns of information for the considerable resource and instrumentation requirements of Level II sites.

Although redundancy analyses indicated that variations in crown condition may be attributable to both soil water and pollution effects, it is not possible to translate crown condition indices (particularly crown density) to more objective indicators of production and vigour, for example annual volume increment. It would, therefore, appear reasonable to supplement survey information with quantifiable (and economically meaningful) dendrochronological/ecological assessments of regional and temporal distributions of past patterns in growth performance. These would provide a historical means for comparing growth with discrete climatological events and regional variations in pollution deposition.

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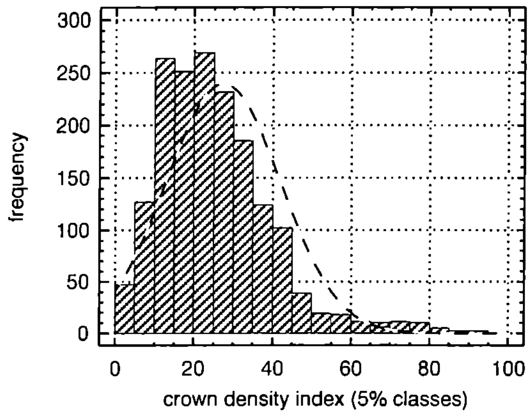
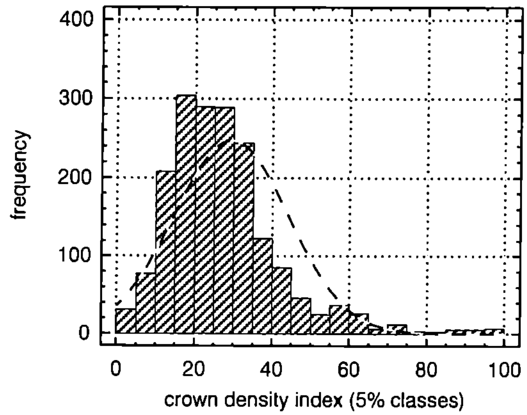
Appendix 1

Frequency distributions for crown density (1992 individual tree data)

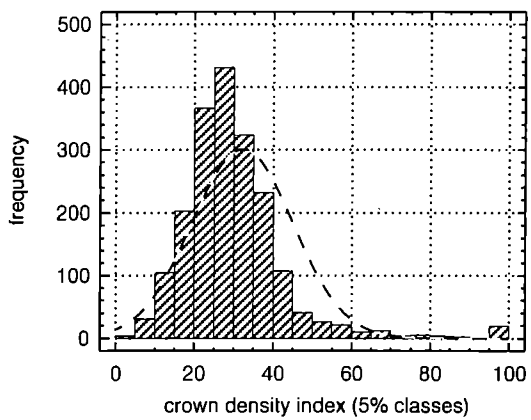
Sitka spruce (mean=27; sd=15)



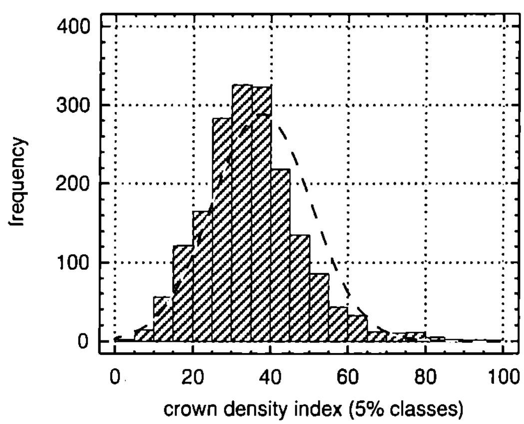
Norway spruce (mean=29; sd=15)



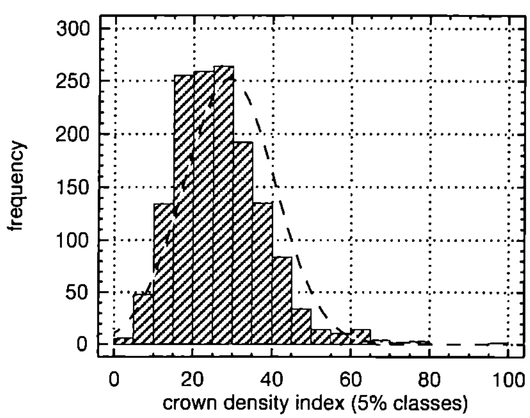
Scots pine (mean=32; sd=13)



Oak (mean=38; sd=13)



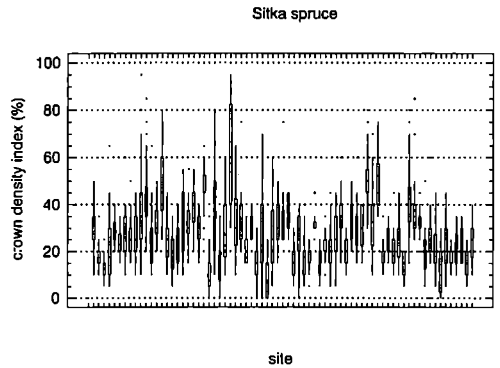
Beech (mean=29; sd=12)

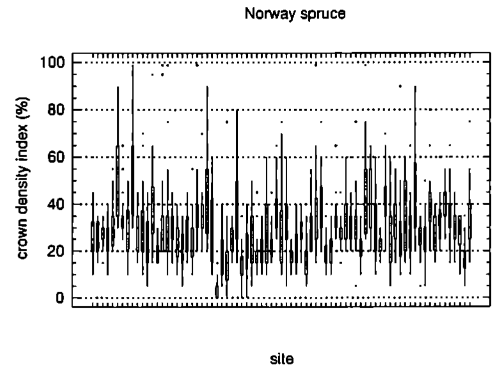


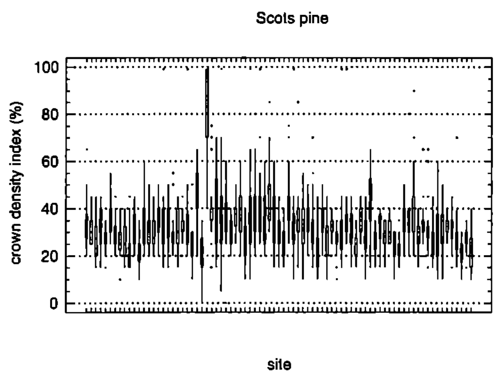
Appendix 2

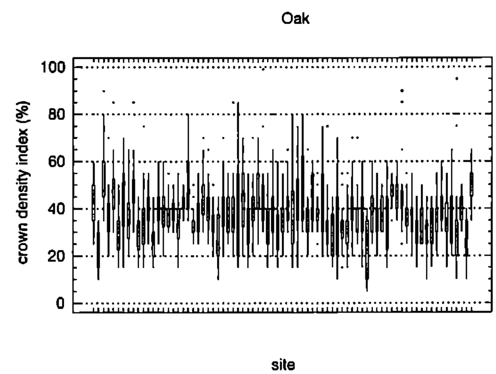
Box and whisker distributions of site variation in crown density

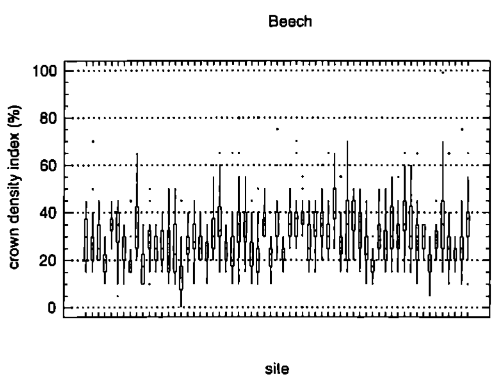
Note: boxes cover interquartile ranges, whiskers extend to the normal limits of distributions, the line bisecting the box is the median, and outliers are plotted as individual points.









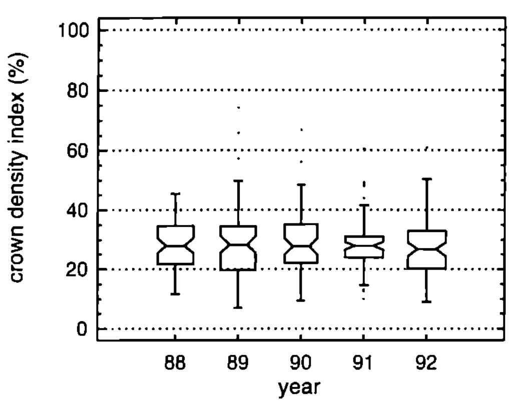


Appendix 3

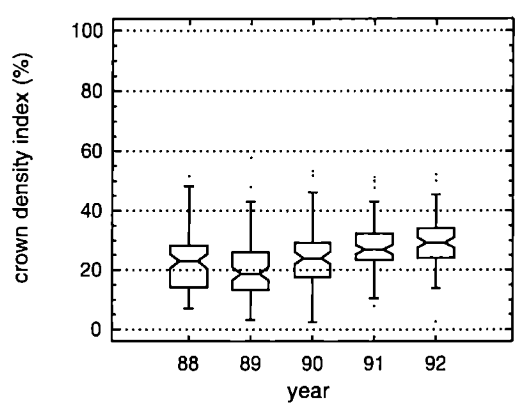
Box and whisker distributions showing yearly variation in site mean crown density

Note: boxes cover interquartile ranges, whiskers extend to the normal limits of distributions, the line bisecting the box is the median, the notches in the sides of boxes indicate 95 per cent confidence limits for the median.

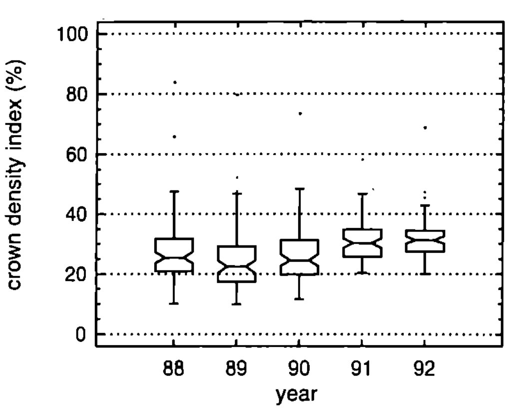
Sitka spruce



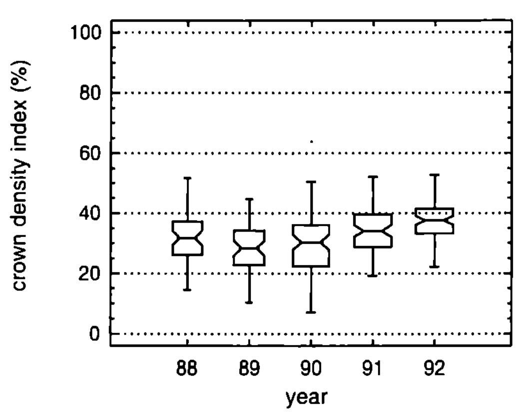
Norway spruce



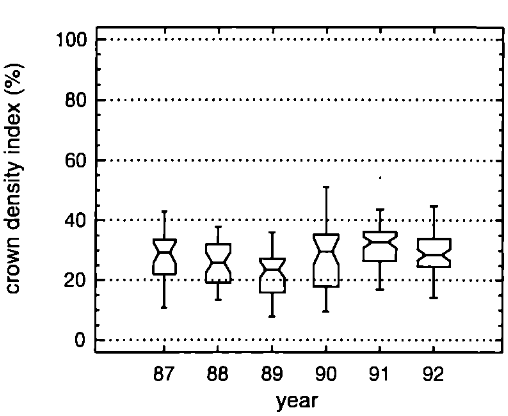
Scots pine



Oak



Beech

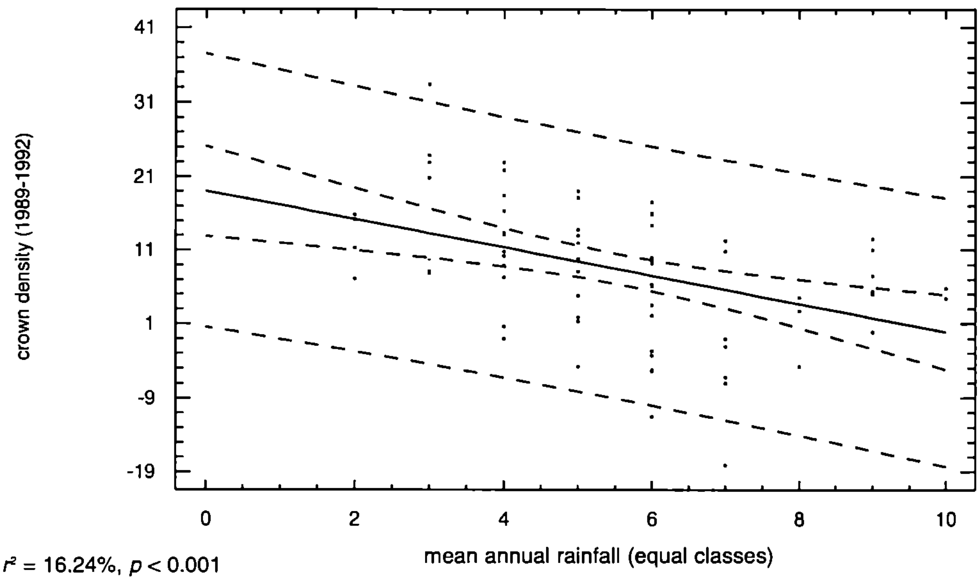


Appendix 4

Regressions of change in crown density (cd8992) in Norway spruce on mean annual rainfall and total sulphate deposition

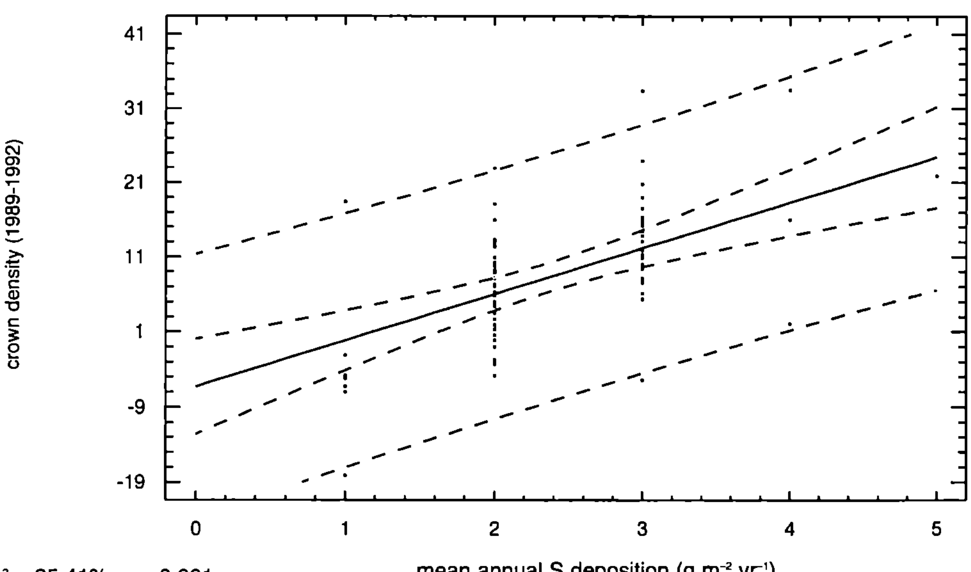
Note: the inner pair of broken lines (those immediately adjacent to the regression curve) indicate 95 per cent confidence limits for the regression curve; the outer pair show 95 per cent confidence limits for data.

Regression of CD change (1989-1992) on mean annual rainfall



$r^2 = 16.24\%$, $p < 0.001$

Regression of CD change (1989-1992) on sulphur deposition



$r^2 = 25.41\%$, $p < 0.001$

Appendix 5

(a) Pearson product moment correlations for beech site indices for forest condition against environmental variables.

Absolute *r* values for shaded bars: $r \geq 0.3, < 0.5$, $r \geq 0.5, < 0.8$, $r \geq 0.8$. See Chapter 4 for variable codes.

	CD8992	BN8992	YE8992	CF8992	DI8992	DB8992	FD8992	ID8992	LS8992	MA8992	PL8992	RD8992	RF8992
BN8992	0.2												
YE8992	-0.1	-0.1											
CF8992	0.3	0.3	0.4										
DI8992	0.1	0.6	0.6	0.5									
DB8992	0.3	0.3	0.0	0.7	0.2								
FD8992	-0.2	-0.1	0.3	0.2	0.0	0.0							
ID9092	0.4	0.0	-0.1	0.0	0.1	0.3	-0.4						
LS8992	0.1	0.3	-0.2	0.1	0.2	0.0	0.0	0.2					
MA8992	0.0	-0.1	-0.1	-0.3	-0.1	-0.3	-0.1	0.4	0.0				
PL8992	-0.2	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	0.1			
RD8992	-0.1	0.1	0.3	0.3	0.3	0.2	0.1	0.1	-0.1	0.0	0.1		
RF8992	-0.2	0.1	0.3	0.3	0.2	0.3	0.1	0.0	-0.1	0.0	0.1	0.9	
AGE92	0.0	0.2	0.0	0.0	0.3	0.0	-0.2	-0.1	0.0	0.1	0.1	-0.2	-0.2
THIN92	0.2	-0.1	0.2	0.0	0.1	-0.3	-0.1	0.1	0.1	0.2	-0.1	0.1	-0.2
ALT	0.0	0.3	0.0	0.4	0.1	0.5	0.0	-0.2	0.0	-0.3	0.2	0.0	0.2
SLOP	0.0	0.4	0.0	-0.1	0.3	-0.1	0.0	0.0	0.1	-0.1	0.2	0.2	0.1
E	0.3	0.0	-0.1	0.2	0.1	0.3	-0.1	0.5	0.2	0.2	-0.3	-0.1	0.0
N	-0.2	-0.1	-0.1	-0.7	-0.1	-0.6	-0.1	0.0	0.0	0.4	0.2	-0.1	-0.1
ozone	0.3	0.3	-0.1	0.5	0.1	0.5	-0.1	0.0	0.0	-0.5	-0.3	0.0	0.0
Scld	0.0	0.3	-0.2	-0.1	0.0	0.1	-0.5	0.1	-0.1	-0.1	0.1	0.1	0.1
Sdry	0.3	-0.2	0.0	0.1	-0.1	0.2	-0.1	0.5	0.1	0.1	0.1	-0.1	-0.1
Stot	0.3	-0.2	0.0	0.0	-0.1	0.1	-0.2	0.5	0.1	0.0	0.1	-0.1	-0.1
Swet	0.1	0.2	-0.1	0.0	0.1	0.1	-0.5	0.3	0.1	0.0	0.0	0.2	0.2
CL	-0.1	0.1	-0.1	0.3	0.0	0.3	0.3	-0.3	0.0	-0.2	0.1	0.4	0.3
CLmod	0.0	0.2	-0.1	0.2	0.0	0.3	0.2	-0.2	-0.1	-0.2	0.2	0.3	0.2
exceed	0.0	0.2	-0.1	0.2	0.0	0.3	-0.1	0.0	0.0	-0.3	0.2	0.3	0.2
anPET	0.2	0.1	-0.1	0.6	0.1	0.6	0.1	0.1	0.2	-0.3	-0.2	0.1	0.1
anppt	-0.2	0.0	0.1	-0.4	-0.1	-0.5	0.0	-0.4	-0.2	-0.1	0.1	0.0	-0.1
antmp	0.1	0.0	0.0	0.6	0.1	0.6	0.1	0.1	0.1	-0.3	-0.1	0.0	0.1
SepR	-0.3	-0.2	0.2	-0.4	0.0	-0.5	0.1	-0.3	-0.3	0.3	0.2	0.2	0.0
OctR	-0.2	-0.1	-0.1	-0.5	-0.2	-0.5	-0.1	-0.3	-0.2	-0.1	0.1	0.0	0.0
NovR	-0.1	-0.1	0.1	-0.5	-0.1	-0.4	-0.1	0.1	-0.1	0.4	0.2	0.1	0.0
DecR	0.0	0.2	0.1	0.0	0.2	0.2	-0.4	0.4	0.0	0.1	0.2	0.1	0.1
JanR	-0.4	-0.1	0.2	-0.3	-0.1	-0.5	0.1	-0.5	-0.3	0.0	0.1	-0.1	-0.1
FebR	-0.3	0.0	-0.1	-0.6	-0.2	-0.6	0.0	-0.5	-0.2	0.1	0.0	-0.1	-0.2
MarR	-0.4	0.0	0.0	-0.6	-0.2	-0.6	0.0	-0.3	-0.2	0.2	0.1	0.0	-0.1
AprR	0.0	0.1	0.0	0.3	0.1	0.2	0.2	-0.3	-0.1	-0.3	-0.2	-0.1	-0.1
MayR	-0.2	-0.1	0.1	-0.6	-0.1	-0.5	0.0	0.1	-0.1	0.5	0.2	0.0	0.0
JunR	-0.1	-0.2	-0.1	-0.1	-0.3	-0.1	0.2	-0.3	-0.4	0.1	-0.2	0.1	0.2
JulR	0.2	0.0	0.2	0.6	0.3	0.4	0.1	0.2	0.1	-0.2	-0.1	-0.1	0.0
AugR	-0.3	-0.1	0.1	-0.4	-0.1	-0.5	0.1	-0.5	-0.3	-0.1	0.1	0.1	0.0

SepT	0.3	0.0	0.0	0.6	0.0	0.5	0.2	0.0	0.0	-0.3	-0.2	0.0	0.0
OctT	0.3	0.1	0.0	0.5	0.2	0.5	0.0	0.3	0.2	-0.2	-0.2	-0.1	-0.1
NovT	-0.1	0.2	-0.3	-0.5	0.0	-0.4	0.0	-0.2	0.1	0.0	-0.1	0.0	0.0
DecT	0.2	0.2	-0.1	0.1	0.2	0.3	-0.1	0.4	0.4	0.1	-0.2	-0.3	-0.2
JanT	0.0	0.0	-0.2	-0.4	-0.1	-0.3	0.0	0.2	0.2	0.4	-0.2	-0.4	-0.3
FebT	0.1	0.0	-0.2	-0.3	-0.1	-0.1	-0.3	0.4	0.2	0.3	0.1	-0.1	0.0
MarT	0.3	0.1	-0.1	0.4	0.2	0.4	-0.1	0.5	0.3	0.0	-0.1	-0.1	0.0
AprT	0.1	0.1	-0.1	-0.2	0.1	0.0	-0.2	0.3	0.1	0.1	-0.1	-0.1	0.0
MayT	0.2	-0.1	0.0	0.4	-0.1	0.3	0.3	-0.4	-0.3	-0.5	-0.2	0.1	0.1
JunT	0.2	0.0	-0.2	-0.1	-0.2	0.0	-0.2	0.1	0.0	0.0	0.2	0.3	0.1
JulT	0.2	0.1	0.0	0.4	0.1	0.3	0.0	0.1	0.2	-0.1	-0.1	0.0	0.0
AugT	0.4	0.0	-0.1	0.4	0.1	0.6	0.0	0.4	0.2	0.0	-0.2	-0.1	0.0
rjan5180	-0.2	0.0	0.0	-0.4	-0.2	-0.5	0.1	-0.4	-0.2	-0.1	0.1	0.1	0.0
rfeb5180	-0.2	0.0	0.0	-0.2	-0.2	-0.4	0.0	-0.5	-0.3	-0.2	0.1	0.0	0.0
rmar5180	-0.1	0.1	0.0	-0.4	0.0	-0.5	0.0	-0.3	-0.1	0.0	0.2	0.1	0.0
rapr5180	0.1	0.1	-0.1	-0.2	-0.2	-0.3	-0.1	-0.2	-0.2	0.0	0.1	0.1	-0.1
rmay5180	0.0	0.1	0.1	-0.3	-0.1	-0.4	0.1	-0.4	-0.1	-0.1	0.2	-0.1	-0.1
rjun5180	0.0	-0.1	0.2	-0.3	-0.1	-0.3	0.1	-0.5	-0.4	-0.1	0.2	0.0	0.0
rjul5180	-0.2	-0.1	0.1	-0.5	-0.1	-0.6	-0.1	-0.3	-0.2	0.1	0.2	0.0	-0.1
raug5180	-0.1	0.0	-0.1	-0.4	-0.2	-0.4	-0.2	-0.2	-0.2	0.0	0.4	0.1	0.0
rsep5180	-0.1	0.0	0.0	-0.4	-0.2	-0.4	0.1	-0.3	-0.2	-0.2	0.1	0.0	0.0
roct5180	-0.2	-0.1	-0.1	-0.5	-0.2	-0.6	0.0	-0.3	-0.1	0.0	0.2	-0.1	-0.2
rnov5180	-0.1	0.1	-0.1	-0.4	-0.2	-0.5	0.0	-0.4	0.0	-0.1	0.2	-0.1	-0.2
rdec5180	-0.1	-0.1	0.0	-0.3	-0.2	-0.5	0.1	-0.4	-0.2	-0.1	0.2	0.0	-0.1
tjan5180	0.0	0.0	0.1	0.5	0.3	0.5	0.2	0.2	0.3	-0.3	-0.1	0.1	0.1
tfeb5180	0.1	0.1	0.0	0.5	0.2	0.4	0.2	0.1	0.2	-0.3	-0.3	-0.1	-0.1
tmar5180	0.3	0.2	-0.2	0.3	0.1	0.4	0.0	0.2	0.1	-0.3	-0.4	0.0	0.0
tapr5180	0.2	0.1	-0.3	0.4	-0.1	0.4	0.1	-0.2	0.1	-0.4	-0.2	-0.2	-0.1
tmay5180	0.2	-0.1	0.2	0.6	0.0	0.6	0.1	0.0	-0.2	-0.4	-0.1	0.1	0.2
tjun5180	0.1	0.0	0.1	0.6	0.1	0.5	0.1	0.0	0.0	-0.2	-0.1	0.1	0.2
tjul5180	0.2	0.0	0.0	0.5	0.0	0.5	0.0	0.0	-0.1	-0.3	-0.2	-0.1	0.0
taug5180	0.2	0.0	0.0	0.5	0.0	0.4	-0.1	0.1	-0.1	-0.4	-0.3	0.0	0.0
tsep5180	0.2	0.2	-0.1	0.5	0.2	0.5	-0.1	0.3	0.2	-0.3	-0.3	0.0	0.1
toct5180	0.1	0.0	0.1	0.6	0.1	0.6	0.0	0.0	0.0	-0.3	-0.1	0.1	0.2
tnov5180	0.1	0.1	-0.3	0.2	-0.1	0.3	-0.1	0.0	0.1	-0.2	-0.3	-0.1	-0.1
tdec5180	0.1	0.1	-0.3	0.2	-0.1	0.3	-0.1	0.0	0.1	-0.2	-0.3	-0.1	-0.1
octSMD	0.1	-0.1	0.1	0.3	0.1	0.4	0.0	0.5	0.1	0.3	0.0	0.1	0.1
novSMD	0.1	-0.1	0.1	0.2	0.1	0.4	0.0	0.6	0.1	0.3	0.0	0.1	0.1
decSMD	-0.1	0.1	0.0	0.3	0.1	0.5	0.1	0.5	0.1	0.4	0.0	0.2	0.3
janSMD	-0.1	0.0	0.0	0.1	0.1	0.3	0.0	0.6	0.1	0.5	-0.1	0.3	0.3
febSMD	-0.1	-0.2	-0.1	0.1	-0.1	0.2	0.1	0.4	0.0	0.5	0.0	0.3	0.3
marSMD	0.2	0.0	0.1	0.5	0.2	0.5	0.1	0.3	0.2	-0.1	-0.2	0.1	0.1
aprSMD	0.0	-0.1	-0.1	-0.1	0.1	0.0	0.0	0.3	0.4	0.2	0.0	0.0	0.0
maySMD	0.2	-0.2	0.1	0.5	0.1	0.4	0.1	0.2	0.1	-0.1	-0.1	0.1	0.1
junSMD	0.2	-0.1	0.1	0.5	0.2	0.5	0.2	0.3	0.2	0.0	0.0	0.1	0.2
julSMD	0.2	-0.1	0.1	0.4	0.2	0.4	0.1	0.4	0.2	0.0	0.1	0.1	0.2
augSMD	0.2	-0.1	0.1	0.4	0.2	0.4	0.1	0.3	0.2	0.0	0.0	0.1	0.2
sepSMD	0.2	-0.1	0.0	0.3	0.1	0.4	0.0	0.4	0.3	0.0	-0.1	0.1	0.1

(b) Pearson product moment correlations for oak site indices for forest condition against environmental variables.

Absolute r values for shaded bars: $r \geq 0.3, < 0.5$, $r \geq 0.5, < 0.8$, $r \geq 0.8$. See Chapter 4 for key to variable codes.

	CD8992	BN8992	YE8992	DI8992	AC8992	CF8992	DB8992	EP8992	FD8992	ID8992
BN8992	-0.3									
YE8992	-0.3	0.1								
DI8992	0.0	0.7	0.7							
AC8992	-0.4	-0.1	0.2	0						
CF8992	0.2	0.0	0.0	0.0	-0.2					
DB8992	0.3	0.0	0.0	0.0	-0.3	0.2				
EP8992	0.2	-0.1	-0.1	-0.1	-0.3	0.1	0.4			
FD8992	0.1	0.1	0.1	0.1	-0.1	0.4	0.2	-0.1		
ID8992	0.2	0.0	0.2	0.1	-0.2	0.2	0.0	-0.1	0.3	
AGE92	0.0	-0.1	0.2	0.1	-0.1	0.0	-0.1	0.0	0.1	0.2
DBH88	-0.2	-0.4	0.5	0.1	0.2	0.2	0.3	0.1	0.2	-0.1
HT88	-0.2	-0.4	0.2	-0.1	0.2	0.2	0.3	0.0	0.0	-0.4
THIN92	-0.2	0.0	0.0	0.1	0.0	0.0	-0.3	0.0	0.0	0.3
ALT	-0.2	-0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.0	-0.3
SLOP	0.0	0.0	-0.1	-0.1	-0.3	-0.1	-0.1	-0.2	0.1	0.1
E	0.2	-0.1	-0.1	-0.1	0.2	0.3	0.2	0.0	0.3	0.0
N	-0.2	0.1	0.1	0.2	0.0	-0.5	-0.3	-0.3	-0.3	0.0
ozone	0.3	0.0	-0.1	-0.1	-0.1	0.4	0.3	0.3	0.4	0.0
Scld	0.1	0.0	0.0	0.0	-0.2	0.0	0.1	0.1	0.1	-0.2
Sdry	0.3	0.1	0.0	0.1	0.0	-0.1	0.2	0.2	0.1	-0.2
Stot	0.4	0.1	0.0	0.1	0.0	-0.1	0.2	0.1	0.1	-0.1
Swet	0.3	0.2	-0.2	0.1	-0.1	-0.3	0.0	0.1	-0.1	-0.2
CL	-0.1	0.0	-0.1	-0.1	0.0	-0.2	-0.2	-0.2	-0.1	0.1
CLmod	-0.2	-0.1	-0.1	-0.2	0.0	-0.3	-0.2	-0.2	-0.2	0.1
exceed	0.0	0.0	0.0	0.0	-0.1	-0.3	-0.2	-0.1	-0.1	0.1
anPET	0.2	-0.1	-0.1	-0.2	0.1	0.5	0.3	0.1	0.3	0.1
anppt	-0.1	0.1	0.0	0.0	-0.2	-0.4	-0.2	0.0	-0.4	-0.1
antmp	0.2	-0.1	-0.1	-0.2	0.0	0.5	0.3	0.1	0.3	0.1
SepR	-0.2	0.0	0.2	0.1	-0.1	-0.4	-0.1	-0.1	-0.3	0.2
OctR	-0.1	0.1	0.0	0.0	0.0	-0.2	-0.4	-0.3	-0.2	-0.1
NovR	-0.2	0.1	0.1	0.1	-0.1	-0.3	-0.1	-0.2	-0.1	0.0
DecR	0.1	0.2	0.0	0.2	-0.2	-0.1	0.2	-0.1	-0.2	-0.1
JanR	-0.3	0.1	0.1	0.1	0.0	-0.5	-0.2	-0.1	-0.3	0.1
FebR	-0.3	0.1	0.0	0.1	-0.1	-0.5	-0.3	-0.2	-0.3	0.1
MarR	-0.3	0.1	0.1	0.1	0.0	-0.5	-0.3	-0.2	-0.3	0.1
AprR	-0.1	0.0	0.0	-0.1	0.1	0.0	0.0	0.2	-0.1	0.2
MayR	-0.2	0.1	0.1	0.2	0.0	-0.4	-0.2	-0.2	-0.3	0.0
JunR	0.0	0.0	0.1	0.1	0.2	0.3	-0.2	-0.2	0.1	0.0
JulR	0.2	0.0	0.0	0.0	0.0	0.3	0.3	0.3	0.1	0.0
AugR	-0.2	0.1	0.1	0.0	-0.1	-0.4	-0.2	-0.1	-0.3	0.2
SepT	0.2	-0.1	0.0	-0.1	0.1	0.5	0.3	0.3	0.3	0.0
OctT	0.2	-0.2	-0.1	-0.2	0.1	0.4	0.2	0.3	0.3	0.0
NovT	0.0	0.0	-0.2	-0.1	-0.2	-0.2	-0.1	-0.1	0.0	0.1
DecT	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.2	-0.1

JanT	-0.2	0.0	0.0	0.0	0.1	-0.4	-0.2	-0.1	-0.1	0.0
FebT	0.2	0.2	-0.1	0.1	0.0	0.2	0.0	-0.2	0.1	-0.3
MarT	0.3	-0.1	-0.1	0.0	0.0	0.4	0.2	0.1	0.2	-0.2
AprT	0.0	-0.2	-0.2	-0.2	0.0	0.1	0.0	0.0	0.3	-0.1
MayT	0.1	-0.1	0.0	-0.1	0.1	0.4	0.1	0.1	0.2	0.0
JunT	0.5	0.0	-0.1	0.0	-0.2	0.1	0.2	-0.1	0.0	0.1
JulT	0.3	-0.2	-0.2	-0.2	0.0	0.5	0.2	0.1	0.3	0.0
AugT	0.3	-0.2	-0.2	-0.2	0.0	0.4	0.3	0.2	0.3	-0.1
rjan5180	-0.1	0.1	-0.1	0.0	-0.2	-0.4	-0.2	0.0	-0.4	-0.1
rfeb5180	-0.1	0.2	0.0	0.1	-0.2	-0.4	-0.2	0.1	-0.4	-0.1
rmar5180	-0.1	0.2	0.0	0.1	-0.1	-0.4	-0.2	0.1	-0.4	0.0
rapr5180	0.0	0.1	-0.1	0.0	-0.1	-0.3	0.0	0.1	-0.3	-0.1
rmay5180	-0.1	0.1	0.0	0.1	-0.1	-0.5	-0.1	0.1	-0.4	-0.2
rjun5180	-0.3	0.1	0.2	0.1	-0.1	-0.4	-0.2	0.1	-0.3	-0.1
rjul5180	-0.1	0.2	0.1	0.2	-0.1	-0.5	-0.2	0.0	-0.4	-0.1
raug5180	-0.2	0.1	0.1	0.1	-0.1	-0.5	-0.3	-0.2	-0.4	-0.1
rsep5180	-0.2	0.1	0.0	0.0	-0.1	-0.4	-0.2	0.0	-0.4	-0.1
roct5180	-0.1	0.2	0.0	0.1	-0.1	-0.5	-0.3	0.0	-0.4	0.0
rnov5180	-0.1	0.2	0.0	0.1	-0.2	-0.5	-0.2	0.0	-0.4	-0.1
rdec5180	-0.1	0.1	0.0	0.0	-0.2	-0.4	-0.2	0.1	-0.4	0.0
tjan5180	0.2	-0.2	-0.1	-0.2	0.0	0.5	0.3	0.0	0.3	0.2
tfeb5180	0.3	0.0	-0.1	-0.1	-0.1	0.4	0.4	0.1	0.3	0.1
tmar5180	0.2	0.0	-0.1	-0.1	0.0	0.4	0.3	0.0	0.4	0.1
tapr5180	0.2	-0.1	-0.1	-0.1	-0.1	0.5	0.3	0.1	0.4	0.2
tmay5180	0.3	-0.1	-0.1	-0.1	-0.1	0.4	0.5	0.4	0.3	-0.1
tjun5180	0.1	-0.2	0.0	-0.1	0.0	0.6	0.3	0.1	0.4	0.2
tjul5180	0.1	-0.1	-0.2	-0.2	0.0	0.4	0.2	0.2	0.3	0.0
taug5180	0.3	-0.1	-0.1	-0.1	0.0	0.4	0.2	0.2	0.3	0.0
tsep5180	0.2	-0.1	-0.1	-0.1	0.0	0.4	0.3	0.2	0.3	0.0
toct5180	0.2	-0.2	-0.1	-0.2	0.1	0.6	0.3	0.1	0.3	0.2
tnov5180	0.3	0.0	-0.2	-0.1	0.0	0.5	0.4	0.1	0.3	0.3
tdec5180	0.2	-0.1	-0.1	-0.1	0.0	0.5	0.2	0.0	0.3	0.2
octSMD	0.2	-0.2	-0.1	-0.1	0.1	0.3	0.3	0.1	0.2	-0.1
novSMD	0.1	-0.1	0.0	-0.1	0.1	0.2	0.2	0.1	0.2	-0.1
decSMD	0.1	-0.2	-0.1	-0.2	0.1	0.3	0.2	0.1	0.2	0.0
janSMD	0.1	-0.2	0.0	-0.1	0.1	0.2	0.2	0.1	0.2	0.0
febSMD	0.2	-0.1	-0.1	-0.2	0.1	0.2	0.2	0.1	0.1	-0.1
marSMD	0.2	-0.2	0.0	-0.1	0.1	0.5	0.3	0.2	0.3	0.0
aprSMD	0.2	0.0	-0.1	0.0	0.1	0.3	0.2	0.0	0.1	-0.1
maySMD	0.3	0.0	-0.1	-0.1	0.1	0.4	0.3	0.1	0.2	-0.1
junSMD	0.2	-0.1	0.0	-0.1	0.1	0.5	0.3	0.1	0.2	-0.1
julSMD	0.3	0.0	0.0	0.0	0.1	0.5	0.3	0.0	0.2	-0.1
augSMD	0.2	-0.1	-0.1	-0.1	0.1	0.5	0.3	0.1	0.2	-0.1
sepSMD	0.2	-0.1	-0.1	-0.1	0.1	0.4	0.3	0.1	0.2	-0.1

(c) Pearson product moment correlations for Norway spruce site indices for forest condition and environmental variables.

Absolute *r* values for shaded bars: $r \geq 0.3, < 0.5$, $r \geq 0.5, < 0.8$, $r \geq 0.8$. See Chapter 4 for key to variable codes.

	CD8992	BC8992	BO8992	YC8992	YO8992	DI8992	CO8992	CR9092	FD8992	ID8992	N78992	NA8992	SD8992
BC8992	0.0												
BO8992	0.2	0.4											
YC8992	0.0	0.0	0.1										
YO8992	-0.3	0.1	-0.1	-0.1									
DI8992	0.0	0.6	0.8	0.2	0.4								
CO8992	0.0	0.1	-0.1	-0.1	0.3	0.1							
CR9092	0.5	0.0	0.1	0.0	-0.1	0.0	0.0						
FD8992	-0.3	0.3	0.0	0.1	0.1	0.2	0.0	-0.3					
ID8992	0.2	0.3	0.4	-0.2	0.1	0.3	0.3	0.1	0.2				
N78992	0.1	0.1	-0.2	-0.2	0.0	-0.1	0.1	0.0	-0.1	0.2			
NA8992	-0.3	-0.2	0.0	0.2	0.1	0.0	-0.1	-0.1	0.2	-0.3	-0.9		
SD8992	0.5	0.0	0.0	0.1	-0.2	-0.1	-0.1	0.7	-0.4	-0.1	0.2	-0.2	
AGE92	-0.3	0.0	-0.3	-0.1	0.2	-0.1	0.1	-0.3	0.2	0.0	0.0	0.1	-0.3
DBH88	-0.2	0.0	-0.1	0.0	0.0	0.0	0.0	-0.3	0.2	0.0	0.0	0.1	-0.3
HT88	-0.2	0.0	-0.1	-0.1	0.0	-0.1	0.0	-0.3	0.3	0.1	0.0	0.0	-0.3
THIN92	-0.1	0.0	0.0	-0.1	-0.1	-0.1	0.0	-0.2	0.1	0.2	0.1	-0.2	-0.2
ALT	-0.1	0.0	0.2	0.2	0.0	0.2	0.0	0.0	0.3	0.2	-0.2	0.2	-0.1
ASP88	0.1	-0.2	-0.1	0.0	-0.1	-0.2	0.1	-0.1	-0.1	-0.1	0.2	-0.3	0.0
SLOP	-0.2	0.0	0.0	-0.1	0.0	0.0	0.2	0.1	0.2	0.1	-0.2	0.1	-0.1
E	0.4	0.2	0.2	-0.2	-0.1	0.2	0.2	0.1	0.0	0.6	0.3	-0.4	0.0
N	-0.4	0.0	-0.3	-0.2	0.2	-0.2	0.1	-0.2	0.1	-0.3	0.2	-0.1	-0.2
ozone	0.4	-0.1	0.3	0.2	-0.2	0.2	-0.1	0.1	0.0	0.3	-0.2	0.1	0.1
Scld	0.1	-0.1	0.2	0.0	0.0	0.1	0.0	0.0	0.2	0.2	-0.1	0.0	-0.1
Sdry	0.5	-0.1	0.2	-0.1	-0.1	0.1	0.1	0.2	-0.2	0.2	0.1	-0.3	0.2
Stot	0.5	-0.1	0.2	-0.1	-0.2	0.0	-0.1	0.3	0.0	0.2	-0.2	0.0	0.1
Swet	0.2	-0.2	0.0	0.0	-0.2	-0.1	-0.3	0.0	0.1	-0.2	-0.3	0.3	0.0
CL	-0.3	-0.1	-0.1	0.1	0.0	0.0	0.0	0.0	0.0	-0.2	-0.2	0.1	0.0
CLmod	-0.3	-0.1	0.0	0.1	0.1	0.0	0.1	0.0	0.1	-0.1	-0.2	0.2	0.0
exceed	-0.2	0.0	-0.1	0.0	0.1	0.0	0.0	-0.1	0.2	-0.1	-0.2	0.2	-0.1
anPET	0.5	0.2	0.3	0.0	-0.2	0.2	0.0	0.2	-0.1	0.4	0.1	-0.1	0.1
anppt	-0.4	-0.3	-0.3	0.1	0.1	-0.2	-0.2	-0.1	0.0	-0.6	-0.3	0.4	0.0
antmp	0.4	0.2	0.3	0.0	-0.2	0.2	0.0	0.1	-0.1	0.4	0.0	-0.1	0.1
SepR	-0.6	-0.1	-0.4	0.0	0.2	-0.2	0.1	-0.2	0.0	-0.4	0.1	0.1	0.0
OctR	-0.2	0.0	0.0	0.0	0.1	0.0	-0.1	-0.1	0.2	-0.2	-0.2	0.2	-0.2
NovR	-0.4	0.1	-0.2	-0.1	0.2	0.0	0.2	-0.2	0.2	0.0	0.3	-0.3	-0.2
DecR	-0.1	-0.4	-0.2	-0.1	-0.1	-0.3	-0.3	-0.2	-0.1	-0.3	-0.1	0.1	-0.1
JanR	-0.5	-0.1	-0.4	0.0	0.2	-0.2	-0.1	-0.2	0.0	-0.5	-0.1	0.2	0.0
FebR	-0.6	-0.1	-0.3	0.0	0.1	-0.2	0.0	-0.3	0.1	-0.5	-0.1	0.2	-0.2
MarR	-0.6	-0.1	-0.3	0.0	0.2	-0.2	0.0	-0.3	0.1	-0.5	-0.1	0.2	-0.2
AprR	-0.1	-0.3	-0.2	0.1	0.0	-0.2	-0.4	-0.1	-0.2	-0.5	-0.3	0.4	0.1
MayR	-0.4	0.0	-0.3	-0.1	0.2	-0.1	0.1	-0.2	0.2	-0.3	0.2	-0.1	-0.2
JunR	0.2	0.2	0.3	0.2	0.1	0.3	0.1	0.0	0.1	0.3	0.0	0.0	0.0
JulR	0.3	-0.2	0.0	0.0	-0.1	-0.1	-0.1	0.2	-0.3	-0.1	-0.1	0.1	0.3
AugR	-0.5	-0.2	-0.3	0.1	0.1	-0.2	-0.1	-0.2	0.1	-0.5	-0.2	0.3	-0.1

SepT	0.4	0.0	0.3	0.2	-0.2	0.2	-0.1	0.3	-0.2	0.3	-0.1	0.0	0.4
OctT	0.5	0.0	0.2	-0.1	-0.2	0.0	0.0	0.2	-0.2	0.3	0.0	-0.1	0.2
NovT	-0.2	0.2	0.0	-0.1	0.1	0.1	0.4	0.0	0.1	0.2	0.2	-0.3	-0.1
DecT	0.2	0.1	0.1	-0.3	-0.1	0.0	0.2	0.0	-0.1	0.4	0.4	-0.5	-0.1
JanT	-0.2	0.0	-0.2	-0.3	0.2	-0.1	0.3	-0.1	0.1	-0.1	0.3	-0.2	-0.2
FebT	0.3	0.2	0.3	-0.2	-0.1	0.2	0.2	0.0	0.2	0.5	0.2	-0.3	-0.3
MarT	0.6	0.1	0.3	-0.1	-0.2	0.1	0.0	0.2	0.0	0.5	0.1	-0.1	0.0
AprT	0.1	0.2	0.0	-0.2	0.0	0.1	0.2	0.1	0.0	0.4	0.4	-0.5	-0.1
MayT	0.4	0.0	0.3	0.3	-0.1	0.2	-0.2	0.2	-0.1	0.2	-0.2	0.2	0.3
JunT	0.3	0.1	0.2	0.2	-0.3	0.1	-0.1	0.2	0.0	0.3	-0.1	-0.1	0.2
JulT	0.4	0.0	0.2	0.1	-0.2	0.1	-0.1	0.3	-0.2	0.3	0.1	-0.2	0.3
AugT	0.5	0.1	0.3	-0.1	-0.1	0.1	0.1	0.3	-0.1	0.5	0.2	-0.3	0.2
rjan5180	-0.4	-0.2	-0.2	0.1	0.1	-0.2	-0.1	-0.1	0.0	-0.6	-0.3	0.4	0.0
rfeb5180	-0.3	-0.3	-0.3	0.2	0.1	-0.2	-0.2	-0.1	0.0	-0.6	-0.3	0.4	0.1
rmar5180	-0.4	-0.3	-0.3	0.1	0.1	-0.2	-0.2	-0.1	0.0	-0.6	-0.2	0.4	0.0
rapr5180	-0.2	-0.4	-0.1	0.2	0.0	-0.2	-0.3	-0.1	0.0	-0.5	-0.4	0.4	0.0
rmay5180	-0.3	-0.3	-0.2	0.2	0.1	-0.2	-0.1	-0.1	0.0	-0.6	-0.4	0.5	0.0
rjun5180	-0.4	-0.3	-0.3	0.1	0.2	-0.2	0.0	-0.1	0.0	-0.6	-0.3	0.4	0.0
rjul5180	-0.4	-0.2	-0.2	0.1	0.1	-0.2	-0.1	-0.1	0.0	-0.5	-0.2	0.3	-0.1
raug5180	-0.5	-0.2	-0.2	0.0	0.2	-0.1	-0.1	-0.2	0.2	-0.4	-0.3	0.4	-0.3
rsep5180	-0.4	-0.2	-0.2	0.1	0.1	-0.2	-0.2	-0.2	0.1	-0.6	-0.3	0.4	-0.1
roct5180	-0.5	-0.2	-0.3	0.0	0.1	-0.2	-0.2	-0.2	0.1	-0.6	-0.2	0.3	-0.1
rnov5180	-0.4	-0.3	-0.3	0.2	0.1	-0.2	-0.2	-0.1	0.0	-0.6	-0.3	0.4	0.0
rdec5180	-0.4	-0.3	-0.3	0.1	0.1	-0.2	-0.2	0.0	0.0	-0.6	-0.3	0.4	0.1
tjan5180	0.3	0.3	0.1	0.0	-0.2	0.0	-0.1	0.1	-0.1	0.3	0.1	-0.2	0.2
tfeb5180	0.3	0.2	0.2	0.1	-0.3	0.0	-0.2	0.1	-0.2	0.3	0.1	-0.2	0.1
tmar5180	0.3	0.1	0.3	-0.1	-0.2	0.1	0.0	0.2	-0.2	0.4	0.1	-0.2	0.2
tapr5180	0.3	0.2	0.3	0.1	-0.1	0.3	-0.2	0.0	0.1	0.4	0.0	0.0	0.0
tmay5180	0.5	0.0	0.2	0.0	-0.1	0.1	-0.1	0.2	-0.2	0.3	-0.1	0.0	0.2
tjun5180	0.3	0.2	0.3	0.1	-0.1	0.3	0.0	0.1	0.0	0.4	0.0	-0.1	0.0
tjul5180	0.5	0.0	0.2	0.0	-0.1	0.1	0.0	0.2	-0.2	0.3	0.0	-0.1	0.2
taug5180	0.6	0.0	0.2	0.0	-0.2	0.1	-0.1	0.2	-0.1	0.3	-0.1	0.0	0.2
tsep5180	0.5	0.1	0.2	0.0	-0.2	0.1	-0.1	0.2	-0.1	0.3	0.0	-0.1	0.2
toct5180	0.4	0.2	0.3	0.0	-0.1	0.2	0.0	0.1	0.0	0.5	0.2	-0.2	0.1
tnov5180	0.3	0.2	0.2	-0.1	-0.2	0.1	0.0	0.1	-0.1	0.4	0.1	-0.2	0.1
tdec5180	0.3	0.3	0.1	0.0	-0.2	0.1	0.0	0.0	0.0	0.4	0.2	-0.3	0.1
octSMD	0.4	0.1	0.1	-0.1	-0.1	0.1	0.2	0.2	-0.2	0.3	0.3	-0.3	0.1
novSMD	0.3	0.1	0.1	0.0	-0.1	0.1	0.2	0.2	-0.2	0.3	0.3	-0.3	0.2
decSMD	0.3	0.2	0.0	0.0	0.0	0.1	0.2	0.2	-0.1	0.3	0.4	-0.3	0.2
janSMD	0.3	0.3	0.1	0.0	0.0	0.1	0.3	0.2	-0.1	0.3	0.3	-0.3	0.2
febSMD	0.3	0.2	0.1	0.1	0.0	0.1	0.4	0.1	-0.1	0.2	0.1	-0.2	0.1
marSMD	0.5	0.2	0.2	0.0	-0.1	0.1	0.2	0.3	-0.2	0.4	0.2	-0.3	0.2
aprSMD	0.4	0.3	0.2	-0.2	-0.1	0.1	0.3	0.2	0.0	0.4	0.2	-0.2	0.0
maySMD	0.5	0.2	0.3	0.0	-0.2	0.2	0.1	0.3	-0.1	0.4	0.0	-0.1	0.2
junSMD	0.4	0.2	0.2	0.0	-0.1	0.1	0.1	0.3	-0.1	0.4	0.1	-0.1	0.2
julSMD	0.5	0.2	0.3	-0.1	-0.1	0.1	0.1	0.2	-0.1	0.5	0.1	-0.2	0.1
augSMD	0.5	0.2	0.3	-0.1	-0.1	0.1	0.1	0.3	-0.2	0.4	0.2	-0.2	0.2
sepSMD	0.5	0.2	0.2	-0.2	-0.1	0.1	0.1	0.3	-0.2	0.4	0.2	-0.3	0.1
slopN	0.1	0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.0	0.1	0.2	0.0	0.1	-0.1
slopW	0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.3	-0.1	0.3	-0.2	0.1

(d) Pearson product moment correlations for Sitka spruce site indices for forest condition against environmental variables.

Absolute *r* values for shaded bars: $r \geq 0.3, < 0.5$, $r \geq 0.5, < 0.8$, $r \geq 0.8$. See Chapter 4 for key to variable codes.

	CD8992	BC8992	BO8992	YC8992	YO8992	DI8992	CO8992	CR8992	FD8992	ID8992	N78992	NA8992	SD8992
BC8992	0.3												
BO8992	0.1	0.1											
YC8992	-0.2	0.0	0.0										
YO8992	0.0	0.1	0.0	0.2									
DI8992	0.0	0.1	0.8	0.2	0.5								
CO8992	0.3	0.2	0.0	-0.1	-0.1	-0.1							
CR8992	0.2	0.1	0.0	0.1	0.1	0.1	0.0						
FD8992	-0.3	0.1	0.0	0.0	0.1	0.1	-0.2	0.0					
ID8992	0.5	0.2	0.3	-0.1	-0.1	0.2	0.0	0.0	0.1				
N78992	0.4	-0.1	0.1	0.1	0.0	0.1	0.2	-0.1	-0.2	0.5			
NA8992	-0.5	0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.1	0.2	-0.5	-0.9		
SD8992	0.2	0.0	0.1	0.1	0.1	0.1	0.4	0.3	-0.4	-0.1	0.2	-0.1	
AGE92	-0.3	-0.2	0.1	-0.1	-0.1	0.0	-0.2	-0.1	0.2	-0.1	-0.1	0.1	-0.1
DBH88	0.3	0.1	0.0	0.1	0.0	0.0	-0.1	-0.2	0.2	0.6	0.6	-0.6	-0.2
HT88	0.1	0.3	0.1	0.0	0.4	0.2	0.0	0.0	0.2	0.1	0.1	-0.1	0.1
THIN92	0.2	-0.2	0.1	0.0	-0.1	0.0	0.1	0.0	-0.1	0.2	0.4	-0.2	0.0
ALT	0.1	0.1	-0.1	0.0	0.0	0.0	0.1	0.1	-0.1	0.0	-0.2	0.1	0.0
ASP88	0.0	-0.2	0.1	-0.1	0.2	0.1	-0.1	-0.1	-0.3	-0.1	0.0	-0.1	0.2
SLOP	0.1	0.1	0.0	-0.1	-0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
E	0.5	0.0	0.1	0.0	0.0	0.1	0.2	0.2	0.0	0.4	0.3	-0.3	0.1
N	-0.3	-0.2	-0.2	0.1	0.2	0.0	-0.2	-0.2	0.1	0.0	0.2	-0.3	-0.2
ozone	0.3	0.3	0.2	-0.1	-0.2	0.0	0.2	0.2	-0.1	0.1	-0.2	0.2	0.2
Scld	0.2	0.1	0.1	-0.1	0.1	0.2	0.1	0.2	-0.1	0.2	0.0	-0.1	0.1
Sdry	0.4	0.0	0.1	-0.2	0.1	0.1	0.3	0.1	-0.1	0.1	0.1	-0.1	0.2
Stot	0.3	0.2	0.1	-0.1	0.2	0.2	0.1	0.2	0.0	0.1	-0.1	0.0	0.0
Swet	0.1	0.2	0.1	0.0	0.2	0.2	-0.1	0.2	0.0	0.0	-0.3	0.1	-0.1
CL	-0.1	0.3	0.4	0.1	0.1	0.4	-0.1	-0.2	0.0	0.0	-0.2	0.2	0.1
CLmod	-0.1	0.3	0.3	0.1	0.2	0.4	-0.1	-0.1	0.0	-0.1	-0.2	0.1	0.1
exceed	0.1	0.3	0.2	-0.1	0.2	0.4	0.0	0.0	-0.1	0.1	0.0	-0.1	0.3
anPET	0.3	0.2	0.2	0.0	-0.2	0.0	0.1	0.1	0.0	0.1	0.0	0.2	0.1
anppt	-0.4	0.0	-0.1	-0.1	0.1	-0.1	-0.1	-0.1	0.0	-0.3	-0.2	0.1	-0.2
antmp	0.3	0.2	0.1	0.0	-0.2	0.0	0.1	0.1	0.0	0.1	-0.1	0.2	0.1
SepR	-0.5	-0.2	-0.1	0.1	0.1	-0.1	-0.2	-0.4	0.0	-0.3	0.1	-0.1	-0.1
OctR	-0.2	0.0	-0.1	0.2	0.2	0.0	-0.1	0.0	0.3	0.0	-0.2	0.2	-0.1
NovR	-0.2	-0.2	0.0	0.1	0.2	0.1	-0.1	-0.3	0.1	0.0	0.2	-0.3	-0.3
DecR	0.0	0.0	0.0	-0.2	0.0	0.0	-0.3	0.0	0.1	-0.1	-0.1	0.0	-0.2
JanR	-0.5	-0.2	-0.2	0.0	0.1	-0.2	-0.3	-0.3	0.1	-0.3	0.0	0.0	-0.2
FebR	-0.5	-0.2	-0.2	0.0	0.2	-0.1	-0.3	-0.3	0.2	-0.2	0.0	-0.1	-0.3
MarR	-0.4	-0.2	-0.2	0.1	0.2	-0.1	-0.3	-0.3	0.2	-0.2	0.0	-0.1	-0.3
AprR	-0.3	0.1	-0.2	-0.1	-0.1	-0.2	-0.3	0.0	0.1	-0.3	-0.2	0.3	0.0
MayR	-0.3	-0.2	-0.1	0.1	0.3	0.1	-0.2	-0.3	0.1	-0.1	0.2	-0.3	-0.3
JunR	0.1	0.1	0.1	0.3	0.0	0.2	0.1	0.2	0.1	0.1	-0.1	0.1	0.1
JulR	0.1	0.1	0.0	-0.2	-0.1	-0.1	0.1	0.2	-0.2	-0.2	-0.1	0.2	0.3
AugR	-0.5	-0.2	-0.2	0.0	0.1	-0.2	-0.3	-0.2	0.2	-0.4	-0.1	0.1	-0.2

SepT	0.2	0.2	0.2	-0.1	-0.3	0.0	0.3	0.2	-0.2	0.0	-0.1	0.3	0.3
OctT	0.4	0.2	0.1	-0.2	-0.1	0.0	0.2	0.2	-0.2	0.2	0.0	0.0	0.2
NovT	-0.1	-0.2	0.1	0.1	0.0	0.1	0.1	-0.2	-0.1	0.2	0.3	-0.3	0.0
DecT	0.4	-0.1	0.1	-0.2	0.2	0.2	0.1	0.1	-0.1	0.4	0.4	-0.6	0.0
JanT	-0.1	-0.2	-0.1	0.0	0.3	0.1	-0.2	-0.1	0.1	0.2	0.3	-0.5	-0.2
FebT	0.4	0.0	0.1	0.0	0.2	0.3	0.1	0.2	0.0	0.5	0.1	-0.3	-0.1
MarT	0.6	0.2	0.1	-0.1	0.0	0.1	0.2	0.4	-0.1	0.3	0.0	-0.1	0.1
AprT	0.2	-0.2	0.2	0.0	0.1	0.3	0.3	-0.1	-0.2	0.2	0.4	-0.5	0.0
MayT	0.1	0.2	0.2	0.1	-0.2	0.0	0.2	0.2	-0.1	0.0	-0.3	0.4	0.3
JunT	0.2	0.1	0.1	0.0	-0.3	0.0	0.2	0.2	-0.1	0.1	-0.1	0.3	0.2
JulT	0.4	0.1	0.3	-0.1	-0.4	0.1	0.3	0.2	-0.3	0.1	0.0	0.1	0.3
AugT	0.5	0.1	0.2	-0.1	-0.2	0.1	0.4	0.3	-0.2	0.3	0.2	-0.1	0.3
rjan5180	-0.4	0.1	-0.1	0.0	0.1	-0.1	-0.2	-0.1	0.0	-0.3	-0.2	0.2	-0.1
rfeb5180	-0.3	0.2	-0.1	-0.1	0.0	-0.1	-0.1	0.0	-0.1	-0.3	-0.2	0.2	-0.1
rmar5180	-0.3	0.0	-0.1	-0.2	0.0	-0.1	-0.1	0.0	-0.1	-0.3	-0.1	0.1	-0.1
rapr5180	-0.2	0.1	0.0	-0.2	0.3	0.1	-0.1	0.1	-0.1	-0.3	-0.2	0.2	0.1
rmay5180	-0.2	-0.1	-0.1	-0.2	0.2	-0.1	-0.1	0.1	-0.1	-0.2	-0.2	0.1	0.0
rjun5180	-0.3	0.0	-0.1	-0.2	0.1	-0.1	-0.1	-0.1	-0.1	-0.3	-0.1	0.0	-0.1
rjul5180	-0.3	-0.1	-0.1	-0.1	0.2	-0.1	-0.1	-0.1	0.0	-0.2	-0.1	0.0	-0.2
raug5180	-0.4	0.0	-0.1	0.0	0.2	0.0	-0.2	-0.1	0.1	-0.2	-0.2	0.0	-0.3
rsep5180	-0.4	0.0	-0.2	-0.1	0.1	-0.1	-0.3	0.0	0.1	-0.3	-0.2	0.2	-0.3
roct5180	-0.4	0.0	-0.1	0.0	0.2	0.0	-0.2	-0.1	0.1	-0.2	-0.1	0.0	-0.2
rnov5180	-0.4	0.0	-0.2	-0.1	0.0	-0.2	-0.1	-0.1	0.0	-0.3	-0.3	0.2	-0.2
rdec5180	-0.4	0.0	-0.1	0.0	0.1	-0.1	0.0	-0.1	0.0	-0.3	-0.2	0.2	-0.1
tjan5180	0.1	0.0	0.0	0.2	-0.3	0.0	0.0	0.1	0.0	0.1	0.0	0.1	0.2
tfeb5180	0.2	0.1	0.1	0.0	-0.2	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1
tmar5180	0.2	0.1	0.1	0.0	-0.2	0.0	0.0	0.0	0.1	0.2	0.0	0.1	0.1
tapr5180	0.3	0.2	0.2	0.0	-0.4	0.0	0.1	0.1	0.1	0.3	0.0	0.1	0.0
tmay5180	0.3	0.1	0.1	0.0	-0.1	0.0	0.2	0.0	-0.2	0.0	0.0	0.2	0.3
tjun5180	0.2	0.2	0.2	0.0	-0.3	0.0	0.0	0.2	0.1	0.2	-0.1	0.3	0.0
tjul5180	0.4	0.2	0.1	-0.2	-0.1	0.0	0.2	0.1	-0.2	0.1	0.0	0.1	0.2
taug5180	0.4	0.1	0.1	-0.1	-0.1	0.0	0.2	0.0	-0.1	0.1	0.0	0.2	0.2
tsep5180	0.4	0.1	0.1	-0.1	-0.2	0.0	0.2	0.1	-0.1	0.1	0.0	0.1	0.2
toct5180	0.2	0.2	0.2	0.1	-0.3	0.1	0.1	0.0	0.0	0.1	0.0	0.2	0.1
tnov5180	0.2	0.1	0.2	0.1	-0.3	0.0	0.0	-0.1	0.0	0.2	0.1	0.1	0.0
tdec5180	0.1	0.2	0.2	0.2	-0.4	0.0	0.1	-0.1	0.0	0.2	0.0	0.2	0.1
octSMD	0.4	0.0	0.1	-0.2	-0.2	0.0	0.2	0.3	-0.1	0.3	0.3	-0.2	0.2
novSMD	0.4	-0.1	0.1	-0.2	-0.1	0.0	0.2	0.3	-0.1	0.3	0.3	-0.3	0.1
decSMD	0.2	-0.1	0.1	0.2	0.0	0.1	0.1	0.2	-0.1	0.2	0.4	-0.4	0.1
janSMD	0.3	-0.2	0.0	0.1	0.0	0.1	0.1	0.2	-0.1	0.2	0.5	-0.5	0.2
febSMD	0.2	0.1	0.1	-0.1	0.0	0.0	0.2	0.3	-0.1	0.1	0.2	-0.1	0.2
marSMD	0.4	0.0	0.2	0.0	-0.3	0.0	0.3	0.2	-0.2	0.2	0.2	-0.1	0.3
aprSMD	0.3	-0.2	0.0	0.0	-0.2	0.0	0.1	0.1	0.0	0.2	0.3	-0.2	0.1
maySMD	0.4	0.0	0.1	0.0	-0.2	0.0	0.2	0.2	-0.1	0.1	0.0	0.2	0.3
junSMD	0.4	0.0	0.1	0.0	-0.3	0.0	0.2	0.2	0.0	0.2	0.1	0.1	0.3
julSMD	0.5	0.0	0.1	0.0	-0.2	0.0	0.2	0.3	0.0	0.3	0.1	0.0	0.2
augSMD	0.5	0.0	0.2	0.0	-0.2	0.0	0.3	0.2	-0.1	0.2	0.1	0.0	0.3
sepSMD	0.5	0.0	0.2	0.0	-0.2	0.1	0.3	0.2	-0.1	0.3	0.2	-0.1	0.3
slopN	0.0	-0.1	0.0	-0.1	0.1	0.1	-0.1	0.2	-0.1	0.0	0.0	0.0	0.1
slopW	-0.1	-0.1	0.0	0.0	0.1	0.0	-0.2	-0.2	-0.1	0.0	-0.1	0.1	-0.1

(e) *Pearson product moment correlations for Scots pine site indices for forest condition against environmental variables.*

Absolute r values for shaded bars: $r \geq 0.3, < 0.5$, $r \geq 0.5, < 0.8$, $r \geq 0.8$. See Chapter 4 for key to variable codes.

	CD8992	BC8992	BO8992	YC8992	YO8992	DI8992	CO8992	CR9192	FD8992	FB8992	FT8992	ID8992	NA8992	SD8992
BC8992	0.0													
BO8992	0.2	0.2												
YC8992	0.0	0.3	0.0											
YO8992	-0.1	-0.1	0.1	0.0										
DI8992	0.0	0.5	0.4	0.4	0.7									
CO8992	-0.2	-0.1	0.1	0.1	0.1	0.1								
CR9192	0.2	-0.1	0.0	0.0	-0.1	0.0	-0.2							
FD8992	-0.1	0.0	0.0	-0.1	0.0	0.0	0.0	-0.1						
FB8992	0.1	-0.1	-0.1	0.0	-0.2	-0.2	-0.1	0.1	-0.1					
FT8992	0.1	-0.1	0.0	0.0	-0.1	-0.2	-0.2	0.0	0.0	0.8				
ID8992	0.4	0.2	0.1	0.2	-0.2	0.1	-0.3	0.3	-0.2	0.1	0.0			
NA8992	-0.5	-0.2	-0.2	0.1	0.1	-0.1	0.2	-0.2	0.0	-0.1	0.0	-0.3		
SD8992	0.5	0.0	0.2	0.0	-0.1	0.1	-0.1	0.3	0.0	0.3	0.2	0.3	-0.3	
AGE92	-0.1	-0.1	-0.1	0.0	0.1	-0.1	0.0	0.1	0.2	0.1	0.0	-0.1	0.0	0.0
DBH88	-0.1	-0.1	-0.2	-0.3	0.1	-0.2	0.1	0.0	0.1	0.0	-0.2	-0.1	0.1	-0.3
HT88	0.1	0.0	0.0	-0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.0	-0.1	0.0	0.1
THIN92	0.1	-0.1	0.0	0.0	0.1	0.1	0.2	0.0	0.1	-0.2	-0.2	0.1	0.0	0.1
ALT	-0.1	0.3	0.0	0.3	-0.3	0.0	-0.1	-0.1	-0.1	-0.2	-0.2	0.2	0.0	-0.1
ASP	0.2	0.2	0.0	-0.1	-0.2	-0.1	0.0	-0.1	0.0	0.0	0.0	0.0	-0.1	0.0
SLOP	-0.2	0.2	-0.1	0.2	-0.1	0.0	-0.1	-0.1	0.0	-0.3	-0.3	-0.2	0.2	-0.3
E	0.4	-0.1	-0.1	0.0	0.0	0.0	0.1	0.2	-0.1	0.2	0.1	0.2	-0.1	0.1
N	-0.3	0.1	0.2	0.0	0.2	0.2	0.2	-0.5	0.0	-0.4	-0.4	-0.4	0.0	-0.4
ozone	0.4	0.0	-0.1	0.1	-0.3	-0.2	-0.3	0.4	0.0	0.3	0.4	0.4	-0.1	0.4
Scld	0.1	0.3	0.0	0.1	-0.3	0.0	-0.3	-0.1	0.0	0.0	-0.1	0.2	-0.1	0.1
Sdry	0.3	0.1	0.1	0.1	-0.2	0.0	-0.1	0.1	-0.3	0.4	0.2	0.4	-0.2	0.2
Stot	0.3	0.1	0.1	0.2	-0.2	-0.1	-0.2	0.2	-0.3	0.3	0.2	0.4	-0.1	0.2
Swet	0.1	0.0	0.0	0.1	-0.3	-0.1	-0.3	0.2	-0.2	0.1	0.1	0.1	0.0	0.1
CL	0.1	0.3	0.2	0.2	0.1	0.3	0.1	-0.1	0.1	-0.2	0.0	0.0	0.2	0.2
CLmod	0.0	0.3	0.2	0.2	0.0	0.3	0.0	-0.1	0.1	-0.2	-0.1	0.0	0.2	0.2
exceed	0.0	0.1	0.1	0.1	0.0	0.1	-0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.1
anPET	0.3	-0.1	-0.2	0.0	-0.1	-0.1	-0.1	0.4	-0.1	0.4	0.4	0.4	0.0	0.3
anppt	-0.3	0.1	0.2	0.0	0.0	0.0	-0.1	-0.2	0.1	-0.3	-0.2	-0.3	0.1	-0.2
antmp	0.3	-0.1	-0.2	0.0	-0.1	-0.2	-0.1	0.4	0.0	0.4	0.4	0.3	0.0	0.3
SepR	-0.3	0.0	0.1	0.0	0.2	0.1	0.3	-0.4	0.1	-0.5	-0.4	-0.4	0.1	-0.2
OctR	-0.3	0.2	0.1	0.1	0.0	0.1	-0.2	-0.1	0.1	-0.2	-0.2	0.1	0.0	-0.2
NovR	-0.2	0.2	0.2	0.1	0.1	0.2	0.1	-0.4	-0.1	-0.2	-0.3	-0.1	0.0	-0.3
DecR	0.2	0.1	-0.1	-0.2	-0.1	-0.2	-0.4	0.1	-0.1	0.1	0.1	0.0	-0.2	-0.1
JanR	-0.3	0.0	0.1	-0.1	0.1	0.0	0.1	-0.4	0.0	-0.4	-0.3	-0.5	0.2	-0.3
FebR	-0.4	0.0	0.1	-0.1	0.1	0.1	0.1	-0.4	0.1	-0.5	-0.4	-0.5	0.2	-0.4
MarR	-0.4	0.1	0.1	-0.1	0.2	0.1	0.1	-0.4	0.1	-0.5	-0.4	-0.5	0.2	-0.4
AprR	-0.1	-0.3	-0.1	-0.2	0.0	-0.2	0.0	0.1	0.0	-0.1	0.1	-0.4	0.3	0.0
MayR	-0.3	0.1	0.1	-0.1	0.2	0.1	0.3	-0.5	-0.1	-0.3	-0.4	-0.4	0.1	-0.4
JunR	-0.1	0.0	-0.2	0.1	0.1	0.1	0.2	0.1	0.1	0.0	0.1	0.1	0.0	0.0
JulR	0.2	-0.2	-0.1	-0.1	-0.1	-0.2	-0.1	0.3	-0.1	0.4	0.3	0.2	0.0	0.3

AugR	-0.4	0.0	0.1	-0.1	0.1	0.0	0.1	-0.3	0.1	-0.5	-0.3	-0.4	0.2	-0.3
SepT	0.4	-0.1	-0.1	0.1	-0.1	-0.1	0.0	0.4	0.0	0.3	0.3	0.4	0.0	0.5
OctT	0.4	-0.2	-0.2	-0.1	-0.1	-0.1	-0.1	0.4	-0.1	0.4	0.4	0.2	-0.1	0.3
NovT	-0.1	0.0	0.1	0.0	0.1	0.2	0.1	-0.2	0.2	-0.4	-0.3	-0.1	-0.1	0.0
DecT	0.3	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.0	-0.2	0.3	0.1	0.1	-0.2	0.1
JanT	-0.2	-0.1	0.0	-0.2	0.1	0.0	0.3	-0.3	-0.1	-0.2	-0.3	-0.4	0.1	-0.3
FebT	0.1	0.2	0.0	0.1	-0.1	0.1	-0.2	0.0	-0.2	0.3	0.1	0.4	-0.2	-0.1
MarT	0.3	0.0	-0.1	0.0	-0.2	-0.1	-0.2	0.4	-0.1	0.5	0.3	0.4	-0.2	0.2
AprT	0.2	0.0	0.1	0.1	0.0	0.1	0.1	-0.2	-0.2	0.0	-0.2	0.2	-0.2	0.1
MayT	0.1	0.0	0.0	0.2	-0.1	0.0	-0.2	0.4	0.0	0.2	0.3	0.3	0.0	0.4
JunT	0.2	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.1	-0.1	-0.1	0.2	-0.3	0.1
JulT	0.5	-0.1	0.0	0.0	-0.1	0.0	0.0	0.4	0.0	0.2	0.3	0.4	-0.2	0.5
AugT	0.4	-0.2	-0.1	0.0	-0.1	-0.1	0.0	0.3	-0.1	0.4	0.3	0.3	-0.2	0.4
rjan5180	-0.4	0.1	0.1	0.0	0.0	0.0	-0.1	-0.2	0.2	-0.3	-0.2	-0.3	0.2	-0.2
rfeb5180	-0.3	0.1	0.1	0.0	-0.1	-0.1	-0.2	-0.1	0.1	-0.2	-0.2	-0.1	0.1	-0.1
rmar5180	-0.3	0.1	0.2	-0.1	0.0	0.0	-0.1	-0.2	0.1	-0.3	-0.2	-0.2	0.1	-0.1
rapr5180	-0.2	0.0	0.1	0.0	-0.1	-0.1	-0.2	-0.1	0.1	-0.1	-0.1	-0.1	0.1	-0.1
rmay5180	-0.3	0.1	0.1	0.0	-0.1	0.0	-0.1	-0.2	0.0	-0.1	-0.2	-0.1	0.1	-0.2
rjun5180	-0.3	0.1	0.1	0.0	-0.1	-0.1	0.0	-0.3	0.1	-0.2	-0.2	-0.3	0.2	-0.2
rjul5180	-0.3	0.2	0.2	0.1	-0.1	0.0	-0.1	-0.4	0.0	-0.3	-0.2	-0.2	0.1	-0.3
raug5180	-0.4	0.2	0.1	0.0	0.0	0.0	-0.2	-0.3	0.1	-0.3	-0.4	-0.2	0.1	-0.4
rsep5180	-0.4	0.1	0.1	0.0	0.0	0.0	-0.2	-0.2	0.1	-0.3	-0.2	-0.3	0.2	-0.3
roct5180	-0.4	0.1	0.1	0.0	0.0	0.0	0.0	-0.3	0.1	-0.4	-0.3	-0.4	0.2	-0.3
rnov5180	-0.3	0.1	0.2	0.0	0.1	0.0	-0.1	-0.2	0.1	-0.3	-0.2	-0.3	0.1	-0.2
rdec5180	-0.3	0.0	0.1	-0.1	0.0	-0.1	-0.1	-0.2	0.1	-0.3	-0.2	-0.3	0.2	-0.2
tjan5180	0.3	0.0	-0.1	-0.1	0.1	0.0	-0.1	0.3	0.0	0.2	0.3	0.2	-0.1	0.3
tfeb5180	0.3	0.0	-0.1	0.0	0.0	0.0	-0.1	0.3	-0.1	0.2	0.3	0.3	-0.1	0.3
tmar5180	0.3	0.0	-0.2	0.1	0.0	-0.1	-0.2	0.3	-0.1	0.2	0.3	0.2	0.0	0.2
tapr5180	0.1	-0.1	-0.2	0.0	0.0	-0.1	-0.1	0.3	0.1	0.2	0.3	0.2	0.1	0.1
tmay5180	0.4	-0.1	-0.1	0.1	-0.2	-0.2	-0.2	0.3	-0.2	0.5	0.5	0.3	-0.1	0.4
tjun5180	0.1	-0.1	-0.3	0.0	0.0	-0.1	0.0	0.4	-0.1	0.3	0.3	0.3	0.0	0.1
tjul5180	0.4	-0.2	-0.1	0.0	-0.1	-0.1	-0.1	0.3	-0.1	0.4	0.5	0.3	0.0	0.3
taug5180	0.4	-0.2	-0.1	0.0	-0.2	-0.1	-0.1	0.4	-0.1	0.4	0.4	0.3	-0.1	0.4
tsep5180	0.4	-0.2	-0.1	0.0	-0.1	-0.2	0.0	0.4	-0.1	0.3	0.3	0.3	0.0	0.3
toct5180	0.3	-0.1	-0.2	0.0	0.0	-0.1	-0.1	0.4	-0.1	0.3	0.3	0.3	-0.1	0.3
tnov5180	0.3	0.0	-0.1	0.0	-0.1	-0.1	-0.1	0.3	0.0	0.2	0.3	0.2	0.0	0.2
tdec5180	0.1	-0.1	-0.1	0.0	0.1	0.0	0.1	0.3	0.1	0.1	0.2	0.1	0.0	0.2
octSMD	0.3	-0.2	-0.2	-0.1	0.1	0.0	0.2	0.3	-0.1	0.4	0.3	0.1	-0.1	0.2
novSMD	0.3	-0.2	-0.2	-0.1	0.1	0.0	0.2	0.2	-0.2	0.3	0.2	0.1	-0.1	0.1
decSMD	0.2	-0.2	-0.2	-0.2	0.2	0.0	0.2	0.1	-0.1	0.3	0.2	-0.1	0.0	0.1
janSMD	0.3	-0.2	-0.1	-0.1	0.2	0.0	0.2	0.1	-0.2	0.3	0.2	0.0	0.0	0.1
febSMD	0.3	-0.1	0.0	0.0	0.1	0.0	0.0	0.1	-0.1	0.3	0.2	0.1	0.0	0.1
marSMD	0.4	-0.1	-0.1	0.0	0.0	0.0	0.1	0.4	-0.1	0.4	0.3	0.3	-0.1	0.3
aprSMD	0.3	0.0	0.0	0.0	0.1	0.1	0.1	0.3	0.0	0.2	0.0	0.3	-0.2	0.1
maySMD	0.4	-0.2	-0.1	0.1	0.0	0.0	0.0	0.5	0.0	0.4	0.3	0.4	-0.2	0.3
junSMD	0.3	-0.1	-0.1	0.0	0.1	0.0	0.0	0.5	-0.1	0.4	0.3	0.4	-0.1	0.3
julSMD	0.4	-0.1	-0.1	0.0	0.0	0.0	0.0	0.5	-0.1	0.4	0.3	0.4	-0.3	0.2
augSMD	0.5	-0.1	0.0	0.0	0.0	0.0	0.0	0.4	-0.1	0.4	0.2	0.4	-0.2	0.4
sepSMD	0.4	-0.1	-0.1	0.0	-0.1	0.0	0.0	0.4	-0.1	0.4	0.2	0.4	-0.3	0.3
slopN	0.2	0.1	0.2	-0.2	-0.1	0.0	-0.1	0.2	0.1	-0.3	-0.2	0.0	-0.1	-0.1
slopW	0.2	0.0	0.1	0.0	0.0	0.0	0.2	-0.1	0.0	0.1	0.2	0.0	-0.1	0.2

Glossary of abbreviations and terms

[1] If attached to the suffix 8992, for example cd8992, this refers to the change in the index recorded between 1989 and 1992.

ac[1]	An index for the abundance of acorn production at oak survey sites.
anPET	Annual mean potential evapotranspiration.
anppt	Annual mean temperature.
augSMD	Mean soil moisture deficit for the month of August.
bc[1]	An index for the extent of browning of needles produced during the current year.
bn[1]	An index for the extent of browning of foliage in broadleaves at survey sites.
bo[1]	An index for the extent of browning of needles produced by older growth in previous years.
CA	The technique of ordination known as correspondence analysis.
CCA	The canonical equivalent for the ordination process of correspondence analysis.
CCE	The Coordination Centre for Effects at Bilthoven.
cd[1]	An index of crown density based upon the crown *transparency* of trees at survey sites.
CEC	The Commission of the European Communities.
cf[1]	An index of crown form in broadleaves at forest condition survey sites.
CLAG	The United Kingdom Critical Loads Advisory Group.
CLRTAP	The 1985 Convention on Long-Range Transboundary Air Pollution.
co[1]	An index for the abundance of cone production at survey sites.
cov	Coefficient of variation.
cr[1]	An index for the location of shoot death in spruce and Scots pine.
db[1]	An index of the extent of dieback in broadleaves at survey sites.
DCA	The detrended form of correspondence analysis.
DCCA	The detrended and canonical form of correspondence analysis.
di	An index for overall discoloration of foliage at survey sites.
EC	The European Community.
EEC	The European Economic Community.
EMEP	The Cooperative Programme for the Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants.
ep[1]	An index for the abundance of epicormic branching at oak survey sites.
EU	The European Union.
fb[1]	An index for the extent of flowering in the lower crown of Scots pine.
fd[1]	An index for the extent of fungal damage at survey sites.
ft[1]	An index for the extent of flowering in the upper crown of Scots pine.
GIS	Geographical information system.
ICP Forests	The International Cooperative Programme on the Assessments and Monitoring of Air Pollution Effects on Forests.
id[1]	An index for the extent of insect damage at survey sites.
IDRISI	A widely used PC-based geographical information system.
IIASA	The International Institute for Applied Systems Analysis.

ITE	The Institute of Terrestrial Ecology.
julSMD	Mean soil moisture deficit for the month of July.
junSMD	Mean soil moisture deficit for the month of June.
ls[1]	An index for leaf size at beech survey sites.
ma[1]	An index for the abundance of beech mast at survey sites.
marSMD	Mean soil moisture deficit for the month of March.
MORECS	The Meteorological Office Rainfall and Evapotranspiration System.
MWRs	Monthly Weather Reports published by the Meteorological Office.
na[1]	Index for the mean number of years of needles held by conifers at survey sites.
NOx	Oxides of nitrogen.
PCA	The technique of ordination known as principal component analysis.
PET	Potential evapotranspiration.
pl[1]	An index for the premature loss of leaves at beech survey sites.
PORG	The United Kingdom Photochemical Oxidants Review Group.
ppb	Parts per billion.
rd[1]	An index for the degree of leaf rolling at beech survey sites.
RDA	The canonical form of principal component analysis known as redundancy analysis.
rf[1]	An index for the frequency of leaf rolling at beech survey sites.
RGAR	The United Kingdom Review Group on Acid Rain.
Scld	Cloud deposition of sulphur.
sd[1]	An index for the extent of shoot death in conifers.
Sdry	Dry deposition of sulphur.
SMD	Soil moisture deficit.
SPANS	A PC-based geographical information system.
Stot	Total deposition of sulphur.
Swet	Wet deposition of sulphur.
UN-ECE	The United Nations Economic Commission for Europe.
UTM	The Universal Transverse Mercator Coordinate System.
VIFs	Variance inflation factors.
yc[1]	An index for the extent of yellowing of needles produced during the current year.
ye[1]	An index for the extent of yellowing of foliage in broadleaves at survey sites.
yo[1]	An index for the extent of yellowing of needles produced by older growth in previous years.

Printed in the UK for HMSO
Dd 297429 11/95 C20 552 12521

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