



Forestry Commission

Decline in Sitka Spruce on the South Wales Coalfield

Edited by M.P. Coutts



Technical Paper

9

FORESTRY COMMISSION TECHNICAL PAPER 9

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First published 1995

ISBN 0-85538-332-1
FDC 174.7:181.3:425:453:(429)

Acknowledgements

The authors of these chapters acknowledge the help of Tony Price and Dave Thomas, who carried out, in all weathers, most of the field work on which the investigations were based. Substantial editorial help from Jenny Claridge is also gratefully acknowledged.

KEYWORDS: Aphids, Conifers, Forest decline, Hydrology,
Nutrition, Pathogens, Pollution, Water relations

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Preface

Problems concerning the poor growth of conifers in parts of South Wales have been recognised since the 1930s and several attempts have been made to find the underlying causes. Growth problems received more attention when some of the Sitka spruce which had been established on the Pennant Sandstone of the coalfield area between 1955 and 1975, and which had made acceptable growth for a number of years, was found to be in a condition of greatly reduced growth and poor crown health. In many cases the tops of the trees were bent. Conservator Wales asked Research Division to investigate this 'bent top', as the condition was called. Research was started in 1984 with the principal aim of gaining a greater understanding of the problem. It soon became clear that we were presented with a condition akin to certain examples of forest decline in Europe, with trees subject to a variety of stresses. A multidisciplinary approach was therefore needed and workers in a number of institutes were invited to help in a collaborative venture. The chapters in this Technical Paper describe the work carried out between 1984 and 1991.

Summary

This Technical Paper describes a collaborative effort to explain the reduced growth at time of canopy closure or later of Sitka spruce on parts of the South Wales coalfield. Stem analysis showed that growth had declined steeply over a period of about four years. Decline was associated with thin crowns and with bending of the tops of some of the trees.

The climate is characterised by high rainfall and relatively warm winters, and late frosts are common. Atmospheric pollution by sulphur dioxide (SO₂) and nitrogen dioxide (NO₂) was measured and found to be too low to cause direct damage to the trees, but large quantities of sulphur were found in the needles. Poor growth was found on all of the three main soil types (peaty ironpan, peaty gley and deep peat), but growth was generally poorest on the wetter sites. Detailed information on soil hydrology is presented.

Mineral nutrition was found to have a bearing on the growth problem. The amount of readily mineralisable nitrogen was low in the peats, and concentrations of nitrogen and potassium in the foliage of the trees were positively correlated with growth. A fertiliser experiment in which NPK was applied to 20-year-old trees improved growth and reduced crown dieback. No clear-cut evidence was found for trace element deficiency or for toxic levels of heavy metals in the soil solution. Direct damage to needles, with subsequent crown dieback, was caused by the green spruce aphid and by two needle fungi, *Lophodermium piceae* and *Rhizosphaera kalkhoffii*.

As with most instances of forest decline which have been recorded in Europe and elsewhere, several factors and their interactions are involved. However, when nutritional problems have been corrected, the trees are better able to cope with other adverse conditions; there is scope for improving tree health and growth on the coalfield by the application of fertilisers.

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Front cover Main picture: Sitka spruce in decline on the South Wales coalfield showing yellowing of foliage and dieback of branches. Inset: twig from a declining tree with unexplained browning of needles.

Chapter 1

History and symptoms of decline in Sitka spruce on the South Wales coalfield

M.P. Coutts and N.P. Danby

History

Poor growth of trees in the coalfield area of South Wales has been recognised for many years. Day and Sanzen-Baker (1938) investigated poor growth of established crops on freely drained soils on some of the valley slopes. They attributed the slow growth of conifers mainly to the poor soils on the Pennant Sandstone. The area was known to be polluted by sulphur dioxide (SO₂) but growth was good on the better soils in polluted areas and it was considered that pollution was much less important than soil fertility. Sitka spruce (*Picea sitchensis* Bong. Carr.) suffered from defoliation by the green spruce aphid (*Elatobium abietinum* Walker), and young plantations were often damaged by early and late frosts, although these types of damage are common elsewhere in Britain.

In 1968 an investigation called the Pennant Project was started by the Forestry Commission's Ecologist, J.M.B. Brown. Stem analysis revealed that a sustained reduction in height growth had occurred in 1963 in Sitka spruce crops 12 to 20 years old, growing at 280 m elevation (Brown, 1970). Wind exposure, a sequence of wet springs and a possible increase in air pollution were suggested causes.

Jones (1972) investigated the causes of poor growth of Sitka spruce during the establishment phase in Margam Forest. Growth was satisfactory for the first 2 years after planting but thinning of foliage and slow growth occurred during the subsequent 2 years. General observations led to the conclusion that two main stresses were involved: periodic drought and air pollution.

Broad and Brown (1972) recognised phosphorus deficiency on peats and peaty gley soils. They

found that the growth of Sitka spruce was correlated with concentrations of phosphorus and nitrogen in the needles. However, they concluded that other factors must also be involved in poor growth. Broad and Mayhead (1973) made estimates of yield class for Sitka spruce and other species on freely drained upland brown earths and intergrade soils in five forest blocks. The yield class of Sitka spruce ranged from 12 to 17 with the poorest growth in the more polluted areas.

Mayhead *et al.* (1974) investigated stands more than 20 years old on the better drained soils (upland brown earth, intergrade and ironpan) of the coalfield and found that on some sites Sitka spruce achieved only yield class 8-10. They found that owing to establishment problems, some areas had been repeatedly beaten up resulting in lower crop ages than would be expected from the original planting dates, and this gave a pessimistic assessment of yield class for about 11% of the area. However, growth was poorer than on comparable looking sites elsewhere.

Foliar analysis indicated no important deficiency of major nutrients on slope soils apart from slight phosphorus deficiency in some areas, but this was not considered sufficient to justify top dressing. However, the interpretation of nutrient concentrations in the foliage would have been based on comparisons with young crops, for which limiting concentrations of major nutrients were known, and values for young crops may not apply to older trees (see Chapter 6).

A lichen survey carried out in 1972-1973 indicated only moderate pollution and it was concluded that SO₂ levels were too low in most parts of the forest region to have much *direct* effect on tree growth. An assessment of

windiness using meteorological records and tatter flags suggested that wind was one factor which might be reducing growth. Mumbly Head (see Figure 2.1) has an average of 44 gales per year and is one of the stormiest meteorological stations in the country. Measurements of tatter flags made in 1969-1971 indicated that parts of the coalfield were as windy or windier than some of the exposed sites in Scotland. The climate of the coastal strip in South Wales is among the warmest in Britain and warm winters are known to favour the green spruce aphid (see Chapter 10). However, the report by Mayhead *et al.*, like the others, was inconclusive about causes of lower rates of production than expected, although their studies were largely confined to slope soils and were not accompanied by precise measures of pollution at the sampling points.

The higher plateau area of the coalfield, at elevations above 400 m, was planted mainly between 1955 and 1975. In 1982 the Conservator Wales asked the Forestry Commission Research Division to investigate declining vigour of Sitka spruce on the plateau. Stands ranging from 20 to 30 years old, which had shown acceptable growth for some years, were observed to have reduced needle length and thin crowns. Many trees showed bending of the leading shoot, the well-known 'bent top' condition of unthrifty Sitka spruce. A survey of the area of forest affected was carried out by S. Mead in 1982. Growth and tree health were found to be satisfactory on the valley slopes of the coalfield but on the plateau an area of about 9000 ha had poor growth and an additional 5000 ha of plantations were considered to be marginally affected.

Growth on the plateau is patchy, with yield classes in the range 4-20; areas of better growth are sometimes separated by no more than 15 m from areas in decline. Furthermore, within the poor crops individual trees vary enormously. Some are dead or dying whereas adjacent trees bear several generations of needles and look relatively healthy. The work described in this Technical Paper is restricted to crops on the plateau area.

Symptoms

Decline has not been defined in a quantitative sense, the term simply indicates the condition of crops in which acceptable growth has been succeeded by reduced growth over a sustained period (see Chapter 4). Reduced growth on the

coalfield is associated with various visible symptoms in addition to a progressive reduction in leader length. On the poor sites the canopy is thin. This is partly due to the loss of needles and partly because fewer and smaller needles are produced than normal. In addition, the shoots produce fewer branches than normal, which is consistent with the known relationship between shoot length and the number of lateral branch buds produced (Cannell and Bowler, 1978).

The colour of the needles varies greatly between sites, between individual trees and from time to time. In the poorer crops yellowish-green colours of the type associated with nutrient deficiency are common and sometimes suggest a combination of nitrogen (N) and potassium (K) deficiencies described by Taylor (1991). The bright yellow colour caused by magnesium (Mg) deficiency does not occur. Light yellow flecks on otherwise green needles are common in good and poor crops. They resemble those described on Norway spruce (*Picea abies* H. Karst.) in Germany and attributed by Lang and Holdenrieder (1985) to damage by photo-oxidants. Comparable flecks on *Picea* species were thought by Liedeker and Klein (1989) to be caused by chronic stress prior to forest decline. In South Wales they may be caused by sea salt because, after sea spray had been carried into the forest by a south-westerly gale, numerous flecks appeared on wind-exposed current year foliage. Flecked needles often survive for several years, have been found in healthy crops in other parts of Britain, and may not be associated with decline.

Infection by the green spruce aphid and by certain endophytic fungi are described by Carter and by Smith and Magan (see Chapters 10 and 11), respectively. Yellowing is found in individual needles killed by aphids and black bars are commonly found on needles killed by *Lophodermium piceae*. An unexplained browning of needles also occurs on declining trees. This may be caused partly by late frosts; it is not the well-known death of emerging shoots but damage to older needles which only becomes evident later. On branches marked for repeated observation it was found to increase during the autumn. A rather similar browning has been observed on sites in Scotland where acute K deficiency has been induced by the application of other major nutrients. Acute K deficiency may also be observed in Sitka spruce on peaty gleys which have high water-tables in the growing season.

Dieback of shoots occurs, especially in the lower crown, on trees in decline. Shoot death is probably not caused by any direct effects of the coalfield conditions on the cambium. Death caused by loss of needles appears more likely, with a consequent inability of buds on the weaker shoots to flush in the spring. A similar dieback of shoots has been demonstrated on potted trees after defoliation with scissors. In extreme cases of decline in crops on the coalfield, dieback results in death of the whole tree.

Trees in decline produce epicormic shoots from the main stem and from branches. These shoots initially look green and healthy and may form a replacement crown. After a few years the epicormics also begin to decline in the same way as the original branches. Epicormic shoots appear in response to defoliation. They can be induced by removing the foliage experimentally and are probably stimulated to grow by the release of suppressed buds from apical dominance.

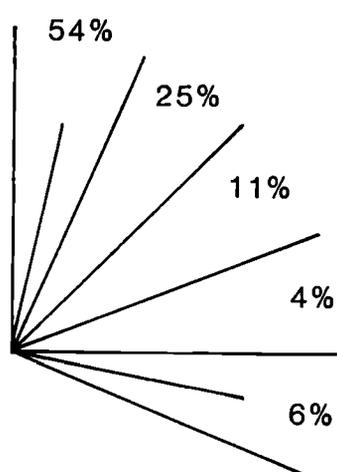


Figure 1.1 Percentage of Sitka spruce trees with leading shoots growing at different angles in a 26-year-old stand in a severe stage of decline.

Bent top is produced by growth of the leader at an angle to the vertical (Figure 1.1), or by death of the apical bud with subsequent growth of a lateral branch which fails to straighten up. The direction of the bent leaders is not confined to that of the prevailing wind, but occurs in all compass directions. Although bent top is a conspicuous feature of poor crops in the coalfield, counts have shown that only a proportion of the trees are affected, for example, on a site where most of the trees were in a state of decline half of them had vertical leaders. Loss of fine roots may well be involved in causing bent top because elsewhere this symptom commonly occurs on trees which are

'pumping' prior to windthrow, i.e. in situations where the root system has been disturbed. Bent top is evidently not a primary response to poor conditions, but is secondary, and associated with declining vigour. The investigations have therefore concentrated on factors affecting growth rather than bent top *per se*.

Recent research

The earlier work described was mainly concerned with tree growth problems on the valley slopes and does not necessarily apply to the more recently afforested plateau area. The research described in this Technical Paper was initiated for two reasons. Firstly, the declining Sitka spruce crops are of immediate local concern. There is a need for reliable prognoses for the affected plantations on which production forecasts, silvicultural treatment and management decisions can be based. Secondly, the forests on the coalfield are the only sizeable area of declining Sitka spruce plantations in Britain, and offer an opportunity to learn about the species when it is subject to limiting levels of stress. Uncertainties about the causes of decline indicated that a multidisciplinary approach was required. This phase of research by the Forestry Commission was started in 1984 and workers in other institutes gradually became involved.

Acknowledgements

We are indebted to Mr D.B. Paterson for much useful discussion and for his helpful comments on the draft of this chapter.

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Chapter 2

Atmospheric pollution in forests of the South Wales coalfield

M.P. Coutts, J.A. Winter and T.W. Ashenden

Introduction

Atmospheric pollution in the South Wales coalfield may be more important than in many other rural areas of the United Kingdom because of proximity to industry on the coast and domestic coal burning in the valleys. Indeed, there has been concern about the poor growth of trees on the coalfield for over two decades. The possibility that high concentrations of pollution were responsible for poor tree performance was considered and a lichen survey conducted in 1972-73 in order to assess the quality of the air

(Mayhead *et al.*, 1974). The results of the survey indicated that sulphur dioxide (SO_2) concentrations were only moderate and seemed insufficient to have direct effects on tree growth. In 1983, a new effort to identify causes of the poor growth of Sitka spruce was started (Coutts and Danby, Chapter 1). It included the measurement of nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) on the plateau area of the coalfield, among Sitka spruce crops planted during the 1960s. This chapter presents results of those measurements and attempts to evaluate the role of pollution in forest decline in South Wales.

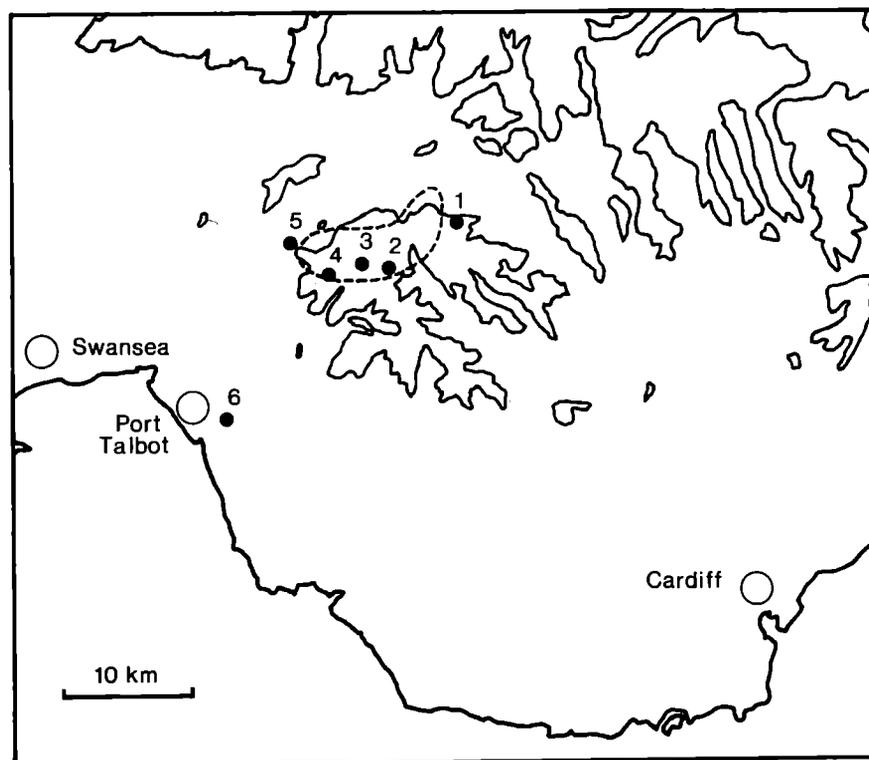


Figure 2.1 Part of South Wales showing the six numbered monitoring stations for SO_2 and NO_2 . The 350 m contour is shown and the dashed line encloses the area where the 20 experimental sites in Forestry Commission experiment Afan 1 are situated.

Table 2.1 Sites monitored for pollution in the South Wales coalfield and the mean SO₂ and NO₂ levels recorded at each monitor

Monitor number	Elevation (m)	Aspect	Sulphur dioxide ^a (nl l ⁻¹)	Nitrogen dioxide ^b (nl l ⁻¹)
1	430	NE	6.97 ± 0.92	4.40 ± 0.62
2	510	E	10.50 ± 1.55	5.26 ± 0.72
3	500	All ^c	11.63 ± 1.72	5.20 ± 0.66
4	490	W	11.05 ± 1.64	5.42 ± 0.72
5	140	W	9.28 ± 1.01	4.43 ± 0.65
6	350	N	14.03 ± 1.47	6.86 ± 0.51

^a Mean SO₂ concentrations from November 1983 to October 1987.

^b Mean monthly NO₂ concentration from 30 May 1986 to 30 March 1987.

^c Exposed hill top.

Methods

Six sites were monitored (Figure 2.1). Monitors 1 to 5 were in the area where the 20 sites used in Forestry Commission experiment Afan 1 were situated (Coutts *et al.*, Chapter 5). Monitor 6 was further south, in Margam Forest, where decline has occurred in some trees planted in the 1930s and 1940s. Each monitor was attached to a post at a height of 1.5 m. Details of elevation and aspect of the six sites are given in Table 2.1. It is notable that aspect was variable and elevation ranged from 140 to 510 m. The monitors were situated within the forest area and therefore received some shelter from the trees, but shelter effects would have been limited because the monitors were in clearings.

Sulphur dioxide was monitored by the lead dioxide method (DSIR, 1960). Monthly measurements were made and the monitors were exposed for 1 month before analysis. The monitoring period was from November 1983 to January 1989. Concentrations of SO₂ in the atmosphere were calculated on the basis that 1 unit of sulphation is equivalent to 4.3 nl l⁻¹ (Meade and Pasquill, 1958). Nitrogen dioxide was monitored by the diffusion tube method (see Ashenden and Bell, 1989). The diffusion tubes were attached to the posts just below the lead dioxide gauges, and were changed at intervals of

about 14 days. The monitoring period was from May 1986 to March 1987. Mean concentrations of NO₂ in the air over the exposure period were calculated using the formulae reported by Atkins *et al.*, 1978.

Results

Mean SO₂ concentrations for the six monitors for the 4 years 1984-1987 were as follows: 10.5, 11.3, 9.7 and 8.0 nl l⁻¹. Mean rates for the individual monitors are shown in Table 2.1. Gauge number 6, situated nearer to Port Talbot than the others, gave the highest sulphation rates. The general pattern of peaks and troughs from month to month for the different monitors was fairly well synchronised. Figure 2.2(a) shows mean monthly concentrations. Peak values of monthly means were recorded in February during 1984, 1985 and 1986, and in January 1987. The maximum monthly concentration recorded for the six monitors occurred in February 1986 (43 nl l⁻¹). Low rates of 3-4 nl l⁻¹ generally occurred in December (probably because industrial work stopped over the Christmas period) and during some of the summer months (the Port Talbot steelworks closes down for a period in July/August). The monthly mean values reported may be overestimates because the sites are windy and wind enhances sulphation rate (Lawrence, 1962). However, the integration of

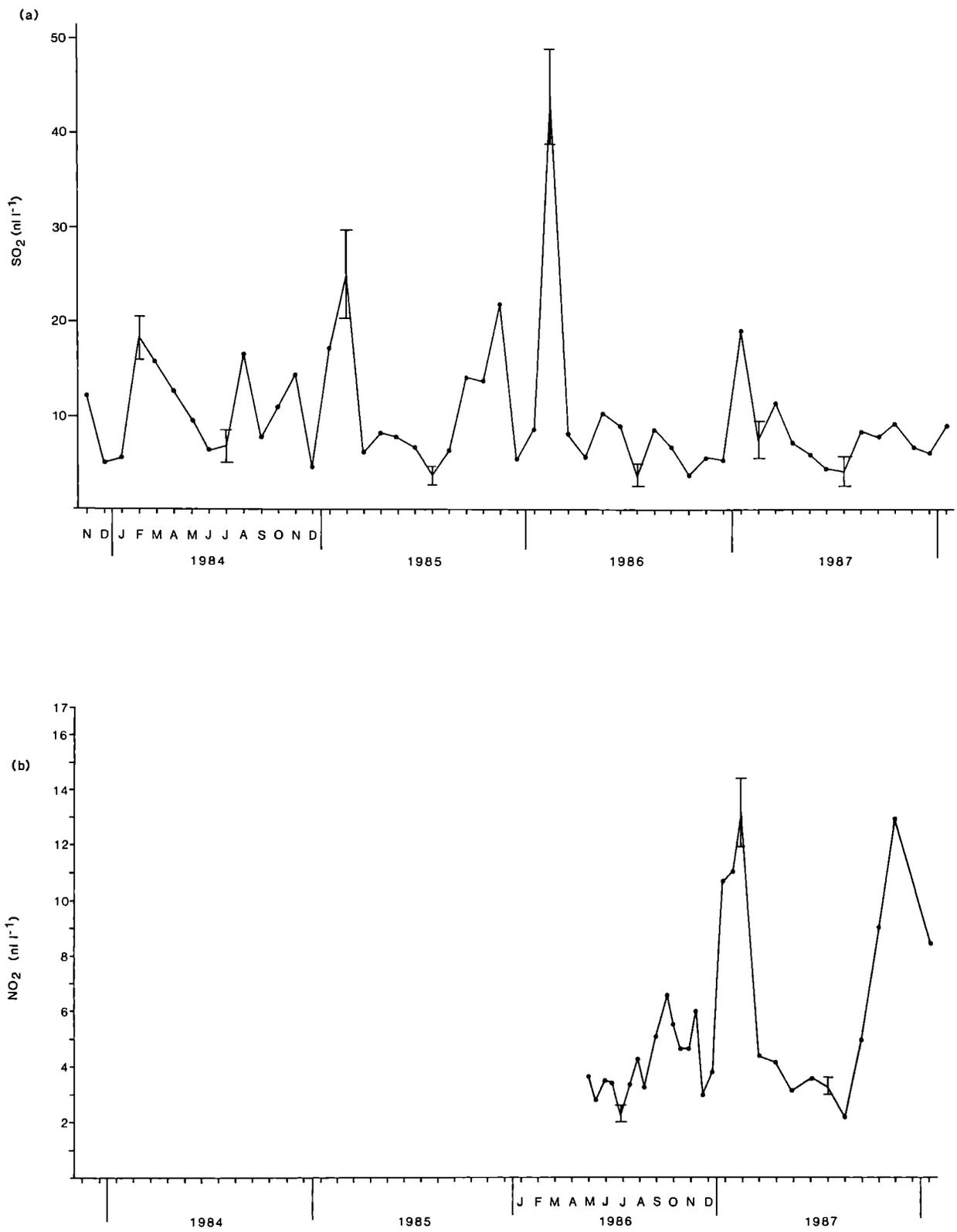


Figure 2.2 Atmospheric pollution on the South Wales coalfield. (a) Mean monthly concentrations of SO₂ calculated from the sulphation rate of six lead dioxide gauges. (b) Mean 14-day concentrations of NO₂ calculated from diffusion tubes exposed at the same six monitoring stations. Vertical bars represent standard errors above and below the means for the months of February and July.

SO₂ concentrations over 1-month periods is a coarse measurement and there must have been periods when concentrations were well above or below the monthly means.

Mean NO₂ concentrations for the 11 months of measurement ranged from 4.40 to 6.86 nl l⁻¹ at the different monitors (Table 2.1). Monitors with the lowest (numbers 1 and 5) and highest (number 6) mean NO₂ values also showed the lowest and highest SO₂ concentrations. For both gases there was little variation among the other three monitors. The graph of periodic changes in NO₂ (Figure 2.2(b)) also shows similarities with SO₂, with the highest concentrations in January and February.

Discussion

The 4-year mean concentration of SO₂ for the five monitors in the experimental area was c.10 nl l⁻¹. According to Warren Spring isopleths the area has an annual mean of only 2-4 nl l⁻¹. Possible reasons for this difference are: firstly, Warren Spring Laboratory has no volumetric monitors close to the experimental area, so that the SO₂ concentrations in the experimental area may generally be greater than the model figure calculated for the region by Warren Spring Laboratory. Secondly, although our monitors received some protection from the forest, the windiness of the area will have increased the sulphation rate recorded, giving an overestimate of SO₂ concentration. Presumably the wind will also have increased the dose of SO₂ received by the forest canopy.

The SO₂ concentration calculated from the mean sulphation rate of monitor 6 near Margam (15 nl l⁻¹) corresponds reasonably with the 22 nl l⁻¹ recorded by Warren Spring Laboratory from August 1981 to March 1982 at their nearest monitor (number 17); that monitor is also on a hill but it is closer to sources of pollution on the coast and would be expected to give the higher value.

The minimum concentrations of SO₂ required to influence the growth of Sitka spruce in the field have not been defined unequivocally and threshold values will be dependent on site conditions. However, observations made in the Pennines (Lines, 1984) can be related to the present results. In sites rather comparable to those in the coalfield, mean SO₂ concentration in the 1950s was 55.8 nl l⁻¹ and the growth of Sitka spruce was estimated to be some eight yield classes lower than in less polluted but otherwise comparable

areas elsewhere. Sites in the Pennines were grouped according to sulphation rate and, with some exceptions, growth was found to be inversely related to this rate. Pollution decreased after the Clean Air Act of 1956 and the measurements made in 1978-1981 showed a 52% reduction in SO₂ concentration to 32.5 nl l⁻¹. Tree growth had improved remarkably. The sulphation rate found in South Wales in the present study was only about one-third of that associated with good growth in the Pennines, thus it is unlikely that SO₂ has been inhibiting growth directly. In a national survey Innes and Boswell (1989) have found no clear association between levels of atmospheric pollution and the crown condition of Sitka spruce.

The NO₂ concentrations found agree well with those estimated for the area in 1986 from a network of monitors in other parts of Wales (Ashenden and Bell, 1989). These workers point out that mean values of 4-8 nl l⁻¹ are low compared with inner city areas but are comparable with rural areas in Britain and Germany. These low concentrations are unlikely to be directly damaging to trees although they may possibly enhance certain effects of SO₂ because some species can be particularly sensitive to the two gases in combination (Ashenden and Mansfield, 1978; Whitmore and Freer-Smith, 1982). This point should be borne in mind during the discussion that follows.

Although the pollution concentrations described probably cause no direct damage they may enhance susceptibility of the tree to other damaging agencies. When Freer-Smith and Mansfield (1987) fumigated Sitka spruce with SO₂, NO₂ or both together at 30 nl l⁻¹ for 8 weeks, NO₂ alone had little effect but SO₂ increased the number of buds damaged by frost; in this instance the combination of the two gases did not significantly enhance the effect.

The susceptibility of Sitka spruce to the green spruce aphid can also be increased by SO₂. McNeill *et al.* (1987) found that pre-fumigation of potted seedlings with 100 nl l⁻¹ SO₂ increased the relative growth rate of the aphid. Warrington and Whittaker (1990) extended this work by inoculating potted trees with four aphids each, and growing them in 'solar-domes' with and without fumigation. The aphids on plants grown in 28.5 nl l⁻¹ SO₂ produced a damaging attack and increased to 985 after 2 months, three times as many as on control plants grown in ambient air containing 3.5 nl l⁻¹ SO₂. The concentration of SO₂ associated with this response is

about three times higher than the mean for the monitors measured in South Wales, and is higher than all but one of the monthly means shown in Figure 2.2(a). However, higher levels will have prevailed for shorter periods. The significance of SO₂ episodes is considered by Freer-Smith and Dobson (Chapter 12). Pollution may now be decreasing in South Wales as indicated by the decreasing annual means for SO₂ concentration from 1984 to 1987; the Port Talbot steelworks has reduced production and with closure of the mines less coal is burnt in the valleys.

It is concluded that the pollution climate of the coalfield may favour the green spruce aphid but it is not possible to say how large the effect is likely to be. The mean concentration of S found in the foliage of Sitka spruce in the Coalfield was 0.22% (Coutts *et al.*, Chapter 5). This is a high level indicating direct inputs of SO₂ from the atmosphere. The plateau area of the coalfield has a high rainfall and is frequently covered by mist. Sulphur levels have not been measured in the rain or mist waters but both may contribute significant amounts of S to the forest (Lovett *et al.*, 1982), and may have contributed to the low pH of the peat (Williams, Chapter 7). However, the high foliar concentrations of S found in Sitka spruce needles on the coalfield were inversely correlated with tree growth (Coutts *et al.*, Chapter 5). Direct damage to the trees by either SO₂ or NO₂ is considered unlikely.

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Chapter 3

Water regimes of three soil types in forests on the South Wales coalfield

D.G. Pyatt

Introduction

The Gelligaer Association of soils occupies the plateaux of the central South Wales coalfield including the area containing the 20 main study sites of this project (Rudeforth *et al.*, 1984). The parent material of the soils is a stony, sandy or loamy drift up to a metre thick, which overlies the hard Pennant Sandstone of Upper Carboniferous age. The Gelligaer Association contains three principal soils. The Gelligaer Series is a ferric stagnopodzol (intergrade ironpan soil in the Forestry Commission classification), with a thin peaty top over an E_g horizon with moderate signs of gleying and traces of ironpan over a well-drained B_s horizon. This soil occurs mainly on the convex slopes around the edges of the plateau. On the gentle slopes of the plateau itself the Belmont Series and Rhondda Series predominate. The Belmont (formerly Ebbw) Series is a peaty ironpan stagnopodzol (peaty ironpan soil) with a peat layer typically 15 cm thick over a thin gleyed E_g horizon resting on the thin ironpan and with a well-drained B_s horizon usually less than 50 cm thick. The Rhondda Series is a staghomic gley soil (peaty gley) with typically 20-30 cm of peat over strongly gleyed E_g and B_g horizons. The peaty ironpan soil tends to occur on convexities and the peaty gley on regular or concave slopes, but the soil pattern on the plateau is very complex and intermediate soils with patchy ironpan development and some mottling in the brownish B_{sg} horizon are common.

A fourth soil, the Crowdy Series, an amorphous raw peat soil (a *Molinia* bog, either 9b or 9d in the Forestry Commission classification) occurs in the more distinct depression sites. The peat is about a metre in thickness, normally well decomposed

and dark brown in colour, turning black when exposed to the air. In his survey of 25 000 ha of forests on the coalfield, Toleman *et al.* (1974) found that 21% (5400 ha) of the area was occupied by the Rhondda peaty gley, 9% (2300 ha) by deep peat and only 1% by Belmont ironpan soil. The bulk of the plateau area containing the present experiment was mapped as peaty gley. However, examination of the experiment area by the present author revealed a significant proportion of peaty ironpan soil.

Rudeforth *et al.* (1984) describe the water regime of the Gelligaer Association as a whole as falling into Wetness Class V, defined as 'waterlogged within 40 cm depth for 180-335 days, and usually waterlogged within 70 cm for more than 335 days in most years'. They add that the soil wetness results from a combination of high rainfall, low evaporation and gentle relief and the sponge-like properties of the peaty top layer, although many of the subsoils are relatively permeable. No specific studies of the water regime of these soils are reported by Rudeforth *et al.* (1984) and it is surprising that no clear distinction should be drawn between peaty ironpan soils and peaty gleys in this respect.

During the early stages of planning this project, and particularly during the selection of the 20 sites comprising experiment Afan 1/84, it seemed that there was some association between tree growth in the establishment and thicket stages and soil type or drainage conditions. Poor growth and some of the worst examples of growth decline occurred on obviously waterlogged sites. In contrast, on the well-drained soils of the steep slopes surrounding the plateau, tree growth was generally satisfactory. The 20 sites were not, however, chosen according to

Table 3.1 Soil descriptions for sites 1 to 20

Site number	Soil type	Peat thickness (cm)	Depth of ironpan (cm)	Stoniness	Texture	Remarks
1	peaty gley	18	-	very slightly stony	clay loam to silty clay	
2	peaty gley	25-40	-	moderately stony	sandy clay loam	
3	peaty gley	30	-	moderately to very stony	sandy loam	peat has shrinkage cracks
4	deep peat	90	-	-	-	no pan within 30 cm below peat
5	ironpan soil	10	25-35	very stony	sandy loam	difficult to dig beyond 55 cm depth
6	deep peat	100	?	-	-	deep peat probably over ironpan soil
7	peaty gley	35-45	-	moderately to very stony	sandy clay loam	
8	ironpan soil	10-15	25	extremely stony	sandy loam	difficult to dig
9	ironpan soil	25-40	60	very stony	sand to sandy loam	some peaty gley here also
10	ironpan soil	10-15	25	moderately to very stony	sand to sandy loam	some peaty gley here also
11	peaty gley	25-50	-	-	sandy clay loam	
12	ironpan soil	5-15	15-30	very stony	sandy loam	convex spur site
13	peaty gley	10-15	-	moderately to very stony	sandy clay loam	ironpan soil a few metres downhill
14	peaty gley	20-25	-	very stony	sandy clay loam	
15	deep peat	60-70	-	very stony beneath peat	sandy loam	much ochre in drains
16	peaty gley	20-25	-	slightly to moderately stony	sandy clay loam to clay	
17	ironpan soil	0	?	extremely stony	sandy loam to sandy clay	perhaps better described as freely drained podzol on scree!
18	surface-water gley	0	-	slightly to very stony	loam	
19	deep peat	50-85	70-100	-	sandy clay loam to clay	deep peat over ironpan soil, contour ploughing
20	peaty gley	40	-	very stony	-	

their soil type, this being left to form part of the soil water studies. The soil types and brief descriptions are given in Table 3.1; further information about the sites is given in Table 5.1. Identification of the soil type was not always straightforward, either because of short-range variability or because the depth of the ironpan was sometimes very great. The gley soils were dominantly grey coloured throughout the profile, with only weakly expressed yellow mottling normally characteristic of finer textured subsoils. It was therefore difficult to distinguish between a peaty gley and a peaty ironpan soil with a very thick E_{ag} horizon until the ironpan was reached. Sites 9 and 10 contained both ironpan and peaty gley soils, site 13 was situated close to an obvious soil boundary between peaty gley and peaty ironpan soil, and at sites 6 and 19 the deep peat overlaid an ironpan soil. Site 18 had no peat but in other respects was similar to the peaty gleys. Site 17 was so stony as to make soil identification difficult, but it appeared to be a well-drained profile; it was included with the ironpan soils for simplicity. Notwithstanding these difficulties, all the gley sites except 18 fell within the description of the Rhondda Series, all the ironpan sites except 17 were classified as Belmont Series and all the deep peats were examples of Crowdy Series.

All of the sites had been prepared with a shallow single furrow plough prior to planting and there were occasional cross-drains. The effectiveness of the ground preparation in removing surface water varied both with the direction of ploughing relative to the local slope direction and with the slope gradient, though no attempt was made to quantify this. All sites were on gentle slopes or almost level.

Methods

In March 1984 two boreholes were installed at each of the 20 sites for observation of the water-table. A hole 5 cm diameter was augered, lined with perforated plastic pipe and capped. The target depth was 1 m, but occasionally excessive stoniness made this depth unattainable. The least deep boreholes achieved were 55 to 65 cm in the ironpan soils, but even here the B_s horizon was reached, which was considered sufficient. At the deep peat sites the boreholes usually penetrated to the mineral soil beneath, but not necessarily to the ironpan where present. The depth from the soil surface to the water in the borehole is referred to as the borehole water level

(bwl). In clayey gleys and peats our experience elsewhere is that the bwl corresponds closely with the depth of zero matric potential (see below) on most occasions, i.e. except during times of rapid change due to rain.

A set of five tensiometers (i.e. five depths) was installed at each of the 20 sites to measure soil water potential. The tensiometers were of a mercury manometer type ('Lark' model, Soil Moisture Equipment Corp., Santa Barbara) consisting of a porous ceramic pot bonded to a rigid perspex tube closed at the top with a rubber bung. A flexible nylon capillary tube emerging from the side of the perspex tube through an air-tight gasket led to the mercury reservoir mounted alongside a millibar scale on a metal stake. The tensiometer was inserted into a hole in the ground made with a metal corer to the desired depth, the stake positioned nearby and the instrument filled with de-aerated water. With the bung removed and the water level in the perspex tube adjusted to ground level, the reading of the mercury on the scale (C value) provided the local calibration of the instrument.

To obtain the zero correction for the instrument the C value was added to the installation depth (centimetres converted to millibars by multiplying by 0.98). To convert a normal (positive) tensiometer reading, i.e. with the bung in place, to the soil *matric potential*, the (positive) zero correction was subtracted and the sign of the resulting value changed. Negative potentials indicated unsaturated soil, i.e. that the tensiometer cup was above the water-table; positive potentials indicated that the cup was beneath the water-table. With the datum chosen as the soil surface, the gravitational potential in millibars was the installation depth in centimetres multiplied by 0.98 and was always a negative value. This was added to the matric potential to obtain the hydraulic potential (negative when the water-table was below the soil surface). The gradient of hydraulic potential with depth, obtained from the set of tensiometers at a site, indicated the direction (in the vertical dimension only) of water movement. This might be different at different depths at a particular time. Typical tensiometer installation depths were 10, 17, 35, 60 and 90 cm.

At sites 5, 6 and 13, representing each of the main soil types, additional instruments were installed to give more detailed information about within-site variability and the hydraulic potential

gradient. At each of these sites a further six boreholes and a second set of 10 tensiometers at closer depth intervals were added. In the peaty ironpan soil (site 5) four of the boreholes penetrated the ironpan and four only reached the Eag horizon so as not to break the pan. In the deep peat (site 6) the two deepest tensiometers reached the mineral soil beneath the peat, but only the original two boreholes did so. It was not clear whether any instruments penetrated the ironpan that was presumed to extend beneath the peat from the nearby site 5. Several of the sites, including site 13, were not instrumented until 1985. The additional boreholes and tensiometers at site 6 were not installed until 1986.

In a wide unplanted ride at site 3 a standard Meteorological Office 11 cm diameter rain gauge was placed alongside a tipping bucket gauge able to record the daily amount of rainfall. Rainfall data were also obtained from a standard gauge operated by the Welsh Water Authority and sited at Llyn Fawr at 335 m elevation just beyond the northern edge of the plateau. This gauge was read on each weekday but not at weekends.

Boreholes, tensiometers and the two rain gauges at site 3 were read at approximately weekly intervals from April 1984 to October 1985 with some longer gaps due to bad winter weather. In 1986 only 17 readings were obtained spanning the period from March to November. Vandalism to instruments proved to be much less than expected: only one site was damaged when its presence was given away by our footmarks in the snow, and after restoration the instruments were not tampered with again. The boreholes were, as usual, more or less trouble free, an

annual removal of sludge from the bottom being all that was needed. The tensiometers, however, needed a good deal of attention to maintain their function. In spite of regular purging of air bubbles and checking of airtight seals, the behaviour of some instruments occasionally departed from what would have been expected. These malfunctions were often not noticed until the data were graphed as time-series many weeks later, so long sequences of aberrant results could occur. The 'failure rate' of tensiometers, i.e. the number which behaved anomalously or gave very incomplete records, was worked out for 1986; it was 12 out of 125. This was enough to make a full interpretation of some individual sites difficult.

Results

Rainfall

The automatic gauge suffered from various problems and operated intermittently. The standard gauge at site 3 gave good service; its readings were similar to but slightly lower than those at Llyn Fawr (Table 3.2).

Since data from Llyn Fawr seem reliable and appropriate for the experiment sites, as well as having the advantage of being available on almost a daily basis, these are used in the following examination of the soil water regimes. Monthly rainfalls for the 3 years are given in Table 3.3.

The spring and summer of 1984 were unusually dry. In contrast, the summer of 1985 was wet; 1986 was even wetter overall than 1985, but this was mainly because of high monthly totals in November and December.

Table 3.2 Rainfall (mm) at Llyn Fawr and site 3 in 1985 and 1986

1985		1986	
Llyn Fawr	Site 3	Llyn Fawr	Site 3
2856.3	2508.0	3183.1	3049.0

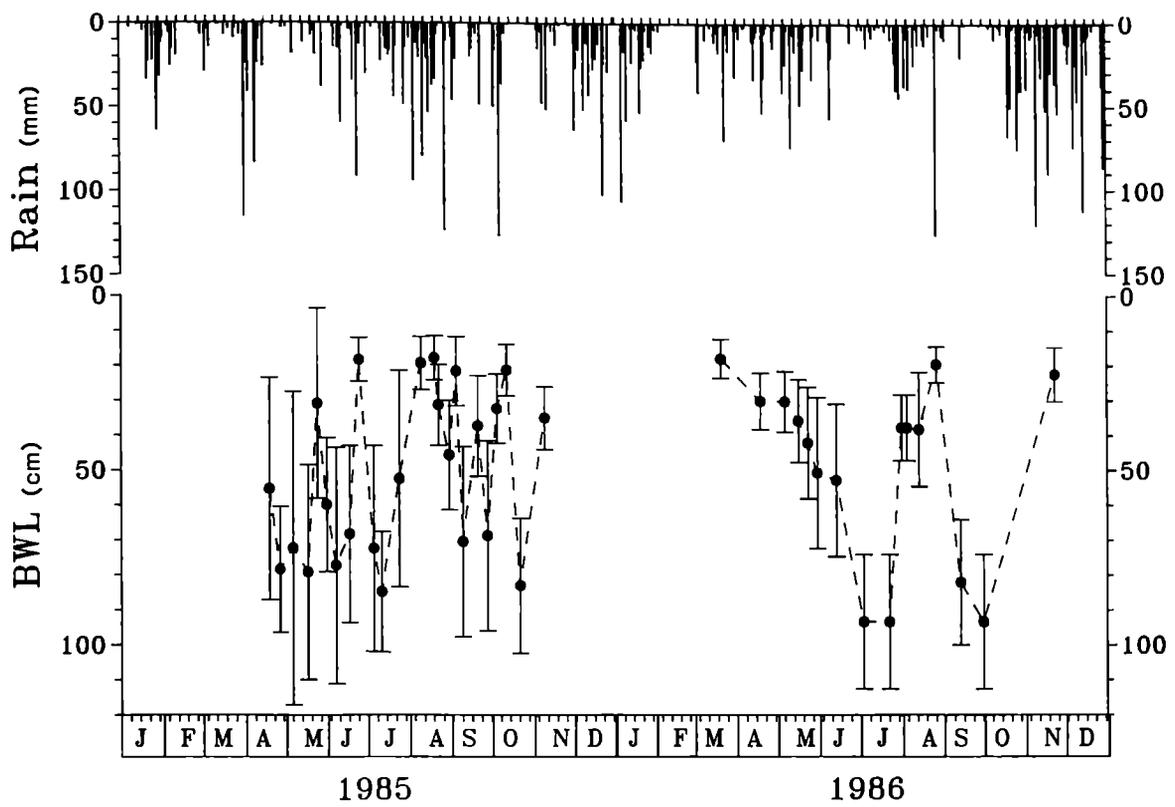


Figure 3.1 Daily rainfall at Llyn Fawr and borehole water level in the peaty gley at site 13 (mean and $p < 0.05$ confidence limits for eight boreholes) in 1985 and 1986.

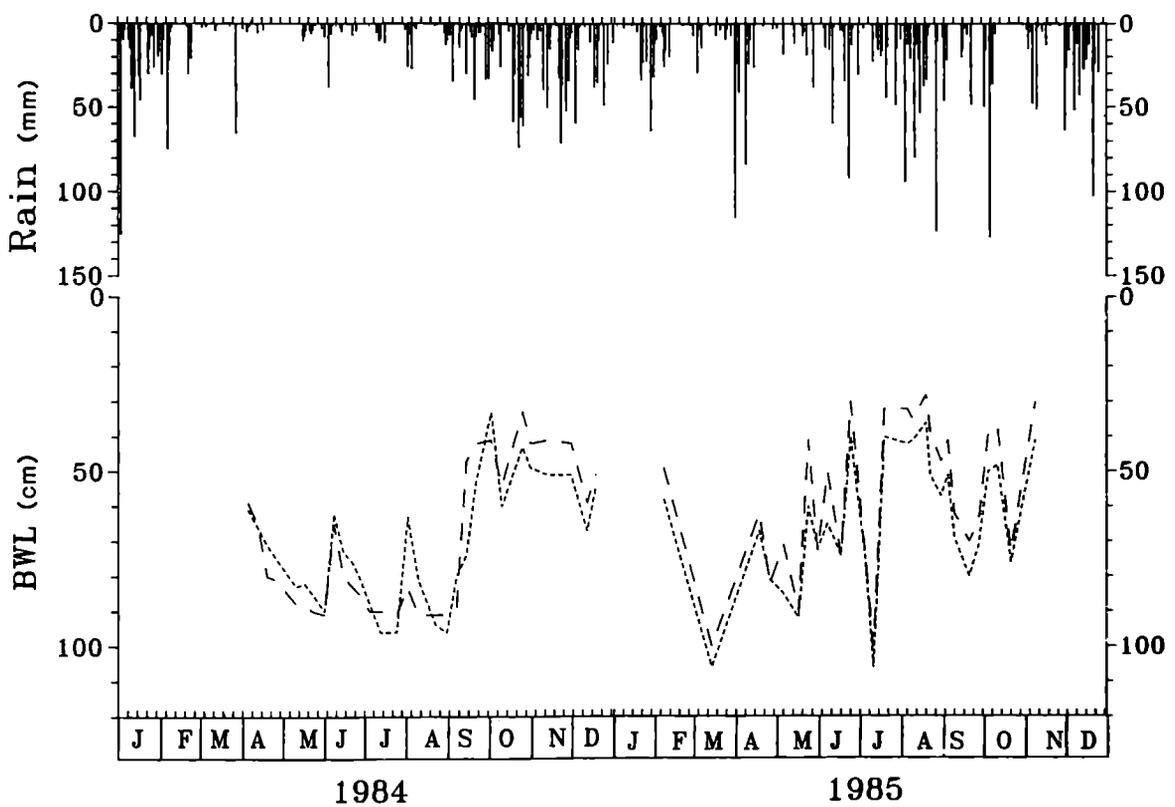


Figure 3.2 Daily rainfall at Llyn Fawr and water level in two boreholes in the peaty gley at site 1 in 1984 and 1985.

Table 3.3 Rainfall (mm) at Llyn Fawr

	J	F	M	A	M	J	J	A	S	O	N	D	Year
1984	466	196	78	17	48	70	45	95	245	417	368	265	2310
1985	211	77	197	224	103	280	205	540	176	248	147	448	2856
1986	389	5	236	190	317	113	160	294	38	344	589	507	3183

Table 3.4 Mean borehole water level (bwl) in gley soils in 1985 (cm)

Site	11	16	2	7	20	13	18	1	14	3
Bwl	23	24	36	38	44	52	52	60	72	90

Gley soils: water-table depths

Fluctuations in bwl in response to rainfall are illustrated for site 13 in Figure 3.1. The most interesting feature of the results was the size of the fluctuations, which were two or three times larger than we have found on clayey gleys. Even though the summer of 1985 was wet most of the boreholes emptied completely on several occasions. The implication was that hydraulic conductivity was much greater on this sandy clay loam textured soil than in a (non-fissured) clay. Moreover, the average depth of the water-table was larger, particularly at both ends of the growing season, than on clayey gley.

There were usually close similarities between the results for the two boreholes at each site, as well as in the pattern of response to rainfall on different sites. Mean borehole water level for the period of measurement was calculated for each site; dates when a borehole was empty were given a value of 95 cm. In 1985 differences in mean bwl between sites were large (Table 3.4).

Apart from site 3 having one of the lightest textures and a peat layer which showed evidence of seasonal drying in the form of shrinkage cracks, there was no obvious explanation for this large range of water-table depths within the gley soils.

The difference in bwl fluctuation between years was also large and reflected the marked difference in pattern of rainfall between 1984 and 1985 (Figure 3.2). In 1984 the spring and summer were unusually dry and water levels would have been low, but rapid and prolonged rewetting took place from September onwards. The spring of 1985 included periods of dry weather but the summer was continuously wet. There were greater variations between months in 1986 with dry spells from mid June to mid July and from early September to mid October. Overall the growing season was intermediate in wetness compared with the previous 2 years.

Gley soils: matric potentials

A typical range of results showing the great difference in matric potentials between the dry summer of 1984 and the wet summer of 1985 is illustrated in Figure 3.3. The marked seasonal contrast between summer and autumn in 1984 was not present in 1985. In 1984 there was a complex series of drying and wetting cycles. The rewettings of the profile in mid May and early June were almost complete whereas those in July and August were only partial. During this latter stage the lowest matric potentials in the profile were at depths of 32 or 62 cm. Looking back at the bwl graph for 1984 (Figure 3.2) the partial nature of the spring and

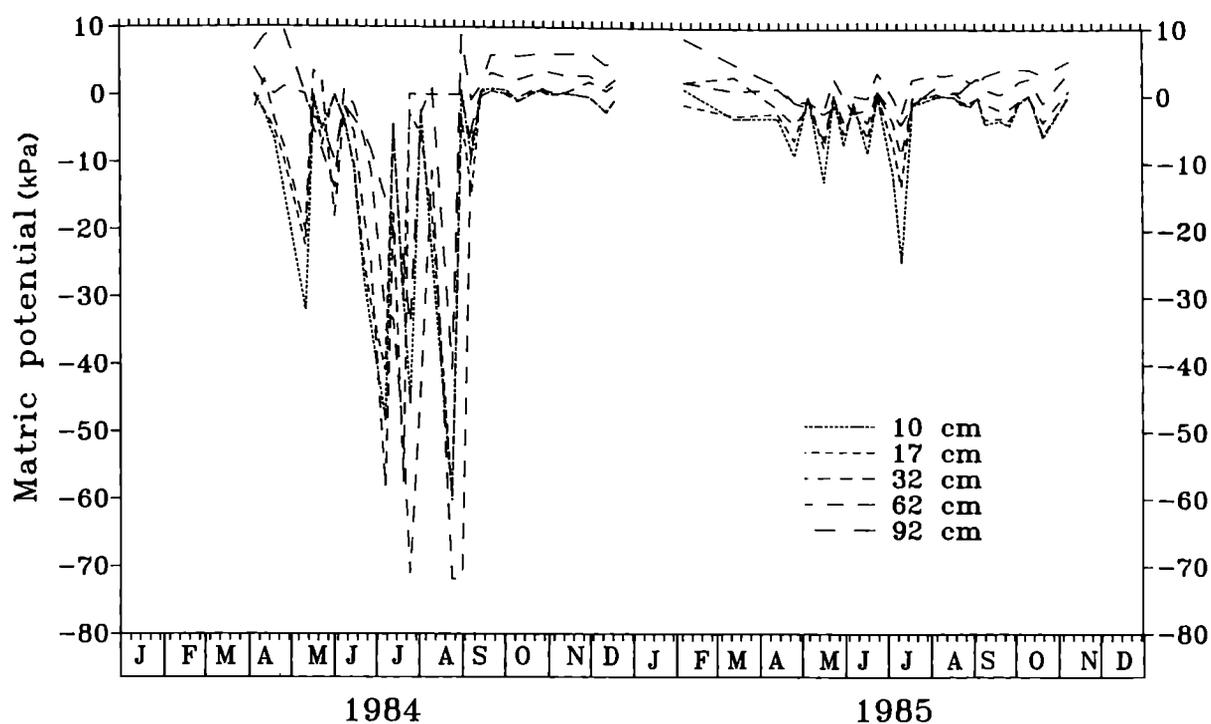


Figure 3.3 Matric potential at five depths in the peaty gley at site 1 in 1984 and 1985.

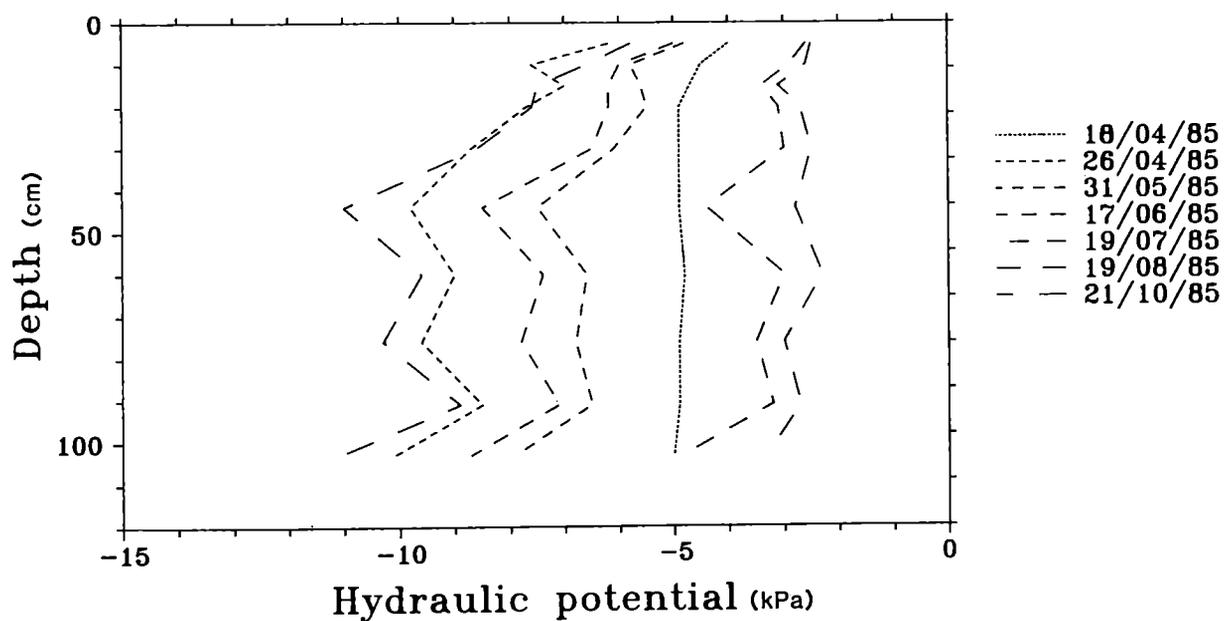


Figure 3.4 Hydraulic potential at 10 depths in the peaty gley at site 13 for selected dates in 1985.

Table 3.5 Gley sites ranked according to 'summer dryness' (kPa)

Site	11 (wetter)	20	7	16	13	2	18	3	1	14 (drier)
1984				-7.6					-52.2	-61.1
1985	+1.9	-1.7	-3.8	-2.5	-3.4	-2.7	-5.6	-7.3	-10.8	-9.5
1986	+1.5	-2.4	-4.1	-5.6	-6.1	-8.6	-9.3	-17.0	-23.5	-24.9

summer rewettings was confirmed. It was also evident that the major rise in the water-table in September did not take place until matric potentials had risen throughout the profile. In 1985 the frequent rains severely limited the development of low matric potentials. Data were sparse in 1986 (not illustrated), but it was clear that there were only two periods when the profile at site 1 dried appreciably, these being June-July and September-October. Matric potential reached -50 kPa at 10 cm depth and -30 kPa at 62 cm depth in July, but only -15 kPa at 10 cm depth in September.

Patterns of fluctuation of matric potential were similarly related to the distribution of rainfall at all sites, but within each year there were large differences in the size of the fluctuations. In an attempt to rank the sites in terms of the degree of 'summer dryness', the mean of the lowest matric potentials experienced by each of the five tensiometers each year at each site was calculated (Table 3.5).

The similarity between the rankings of Tables 3.4 and 3.5 is of more than passing interest. While water-table depth and matric potential are different measures of the same broad property, namely soil wetness, the former may be expected to reflect the inherent water regime more than the current effect of the trees growing there, and the latter to do the reverse. It is of course equally plausible that the inherent soil water regime has influenced tree growth. Due to the variation in ages of the stands in the experiment, there is little point in looking for correlation between measures of crop growth and soil water regime. However, it is noteworthy that sites 1, 14 and 18 have three of the tallest crops

whereas sites 11 and 20 have two of the shortest (see Table 5.1).

Gley soils: hydraulic potentials

Hydraulic potentials at 10 depths in the peaty gley at site 13 are shown for a selection of dates in 1985 in Figure 3.4. Very similar results were obtained in 1986 and in the other gley soils. High hydraulic potentials occurred during or soon after substantial rain; the lower potentials occurred during the short dry spells, such as on 21 October.

On most occasions there was a very small gradient down the profile, this being most noticeable in the upper part of the profile on the 'drier' days. The days when the potentials were high and the gradient least were the occasions when the water-table was high, and vice versa. It can be concluded therefore that when the water-table was high there was a slow downward movement of water; when the water-table was low there was relatively rapid downward movement in the unsaturated zone. The amount of flow would depend not only on the size of the gradient of hydraulic potential, but also on the hydraulic conductivity (see above).

A feature of many gley soils developed on Silurian and Ordovician rocks in mid Wales is a thick layer of stony scree beneath the normal C horizon of fine loamy texture before the bedrock is reached. It has been suggested that the stony layer has higher hydraulic conductivity than the layers above, indeed that it may not be saturated with water. Either of these possibilities would be seen as an increased downward gradient of hydraulic potential at the base of the soil profile. There was no evidence of this in any of the gley profiles at Afan, except perhaps at site 20 where the deepest tensiometer often gave a lower hydraulic potential than the next two shallower ones.

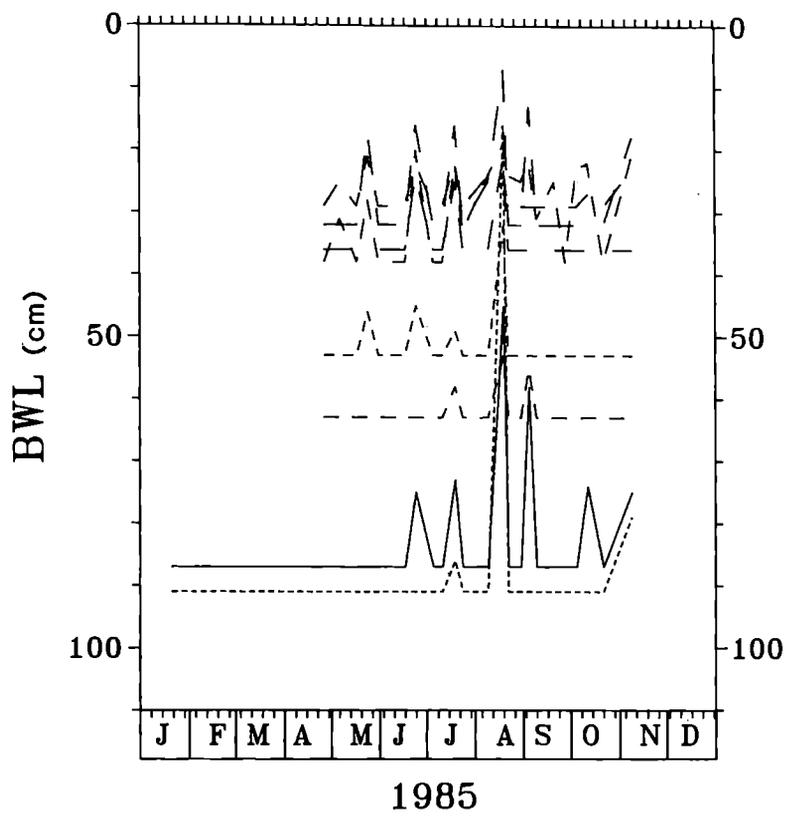


Figure 3.5 Water level in eight boreholes in the ironpan soil at site 5 in 1985. Horizontal lines show the depths of the boreholes and represent dates with no water present.

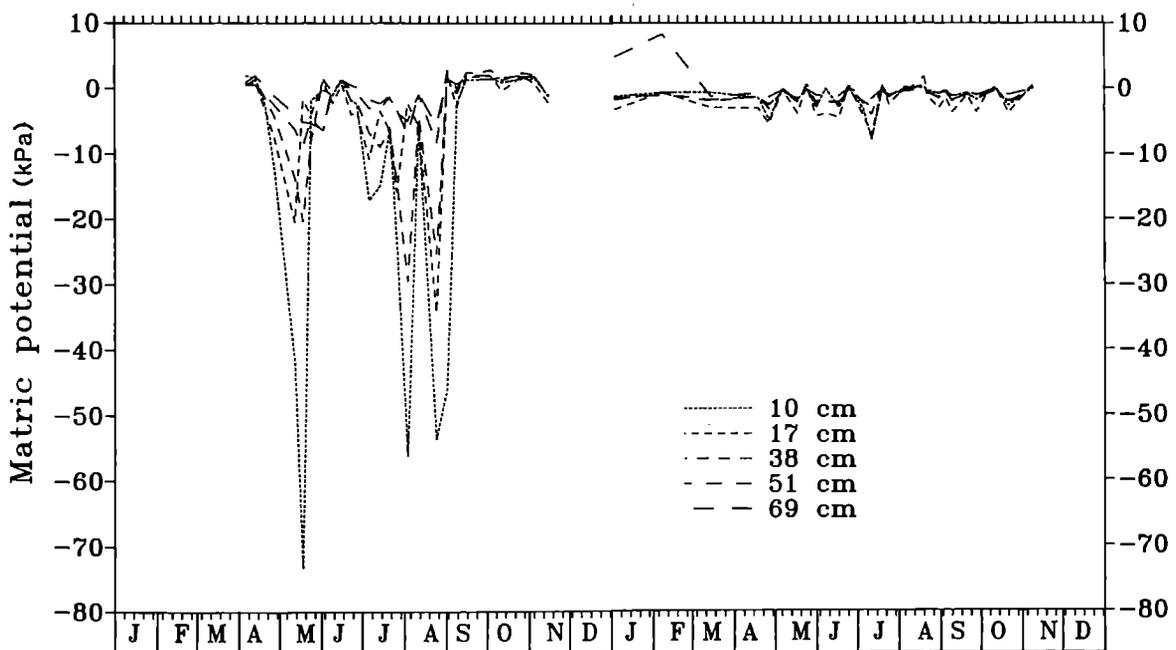


Figure 3.6 Matric potential at five depths in the ironpan soil at site 5 in 1984 and 1985.

Table 3.6 Mean number of weeks with water in deep boreholes in ironpan soils in 1984, 1985 and 1986

Site	17	8	12	9	5	10	Total number of weeks
1984	8			6		0	(30)
1985	13	10	10	5	4	1	(24)
1986	9	7	6	3	2	1	(17)

Peaty ironpan soils: water-table depths

At site 5, two of the boreholes were very deep (about 90 cm into the C horizon), two were moderately deep (about 58 cm into the Bs horizon) and four penetrated only to the E_g horizon, at a depth of about 30 cm. The shallow boreholes contained water slightly more often than the deeper ones, but even in the wet summer of 1985 this profile showed only occasional waterlogging (Figure 3.5). The mean number of weeks (out of 24) with water present in boreholes of each depth group was: shallow 8; moderately deep 4; very deep 4. In 1986 out of 17 weeks the numbers were: shallow 4; moderately deep 3; very deep 2.

At the other ironpan sites only very deep boreholes were used. The results, including those for site 5, are summarised in Table 3.6.

Water present in deep boreholes in ironpan soils does not necessarily indicate saturation in the soil at that depth because some of the water will have run into the borehole from above the ironpan. Indeed, the presence of water which does not persist from one measurement to the next, as here, is taken as not representing waterlogging unless matric potentials are also positive.

Not only did the peaty ironpan soils show water in the boreholes less often than the gley soils but also the amount of water was much less. It is tempting to conclude that the water was moving more rapidly through the ironpan soils than through the gleys, but this

should be clearer from the tensiometer results.

Peaty ironpan soils: matric potentials

There was a marked difference between the degree of drying of the peaty ironpan soil profiles between the dry summer of 1984 and the wet summer of 1985 (Figure 3.6). In 1984 the upper horizon began to dry first followed by progressively deeper horizons, and there was partial rewetting of the profile at times as well as complete rewetting in late June. In 1985 the soil was maintained in a moist condition at all depths throughout the summer. The depth and intensity of drying in site 5 was less than in the gley soil of site 1, but this would have been partly due to the smaller size of the trees. The main difference from the gley soils was that even during wet weather the deeper horizons tended to show negative matric potentials. Indeed, during wet weather the peaty ironpan soils had an almost uniform matric potential throughout the profile, in contrast to the increasing matric potential with depth of the gley soils. In 1986 (not illustrated) there were only two periods of modest drying: June-July and September-mid October. The lowest matric potential reached was -14 kPa at 10 cm depth on 3 July. The sets of 5 and 10 tensiometers showed almost identical results.

In 1984, site 10, which had the tallest trees of any of the 20 sites, showed more intense soil drying, especially in the subsoil, than site 5. The freely draining, extremely stony soil at site 17, also with quite tall trees, dried similarly to site 10. The mean of the lowest matric potentials experienced by the five tensiometers at each site in each year is used to rank the sites in Table 3.7.

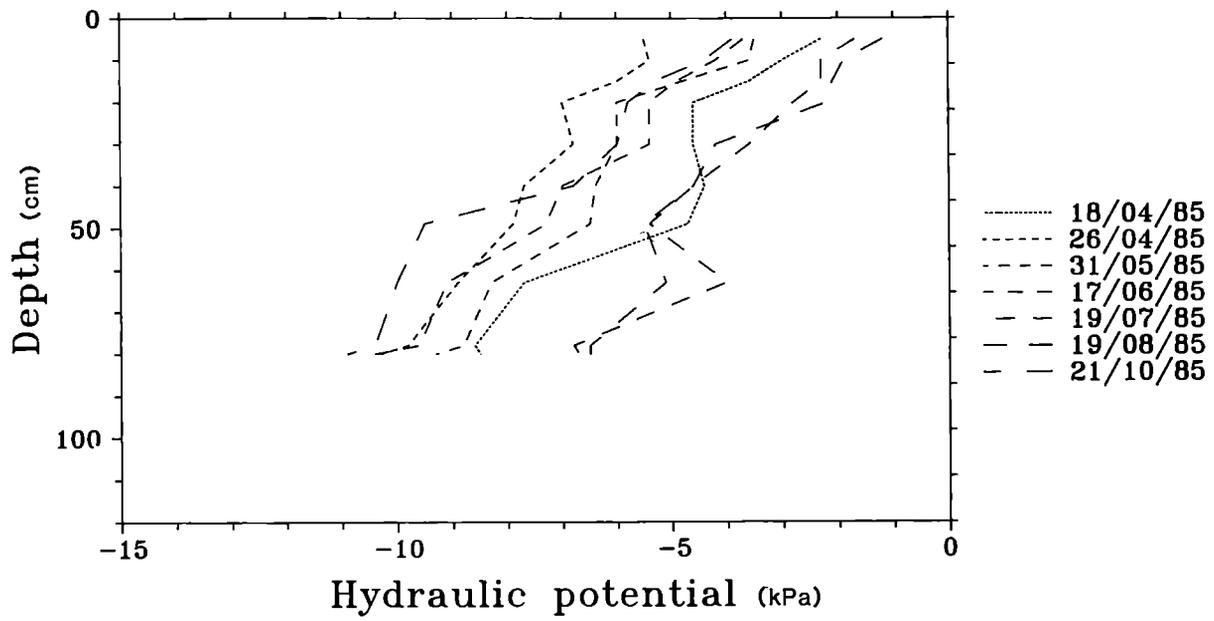


Figure 3.7 Hydraulic potential at 10 depths in the ironpan soil at site 5 for selected dates in 1985.

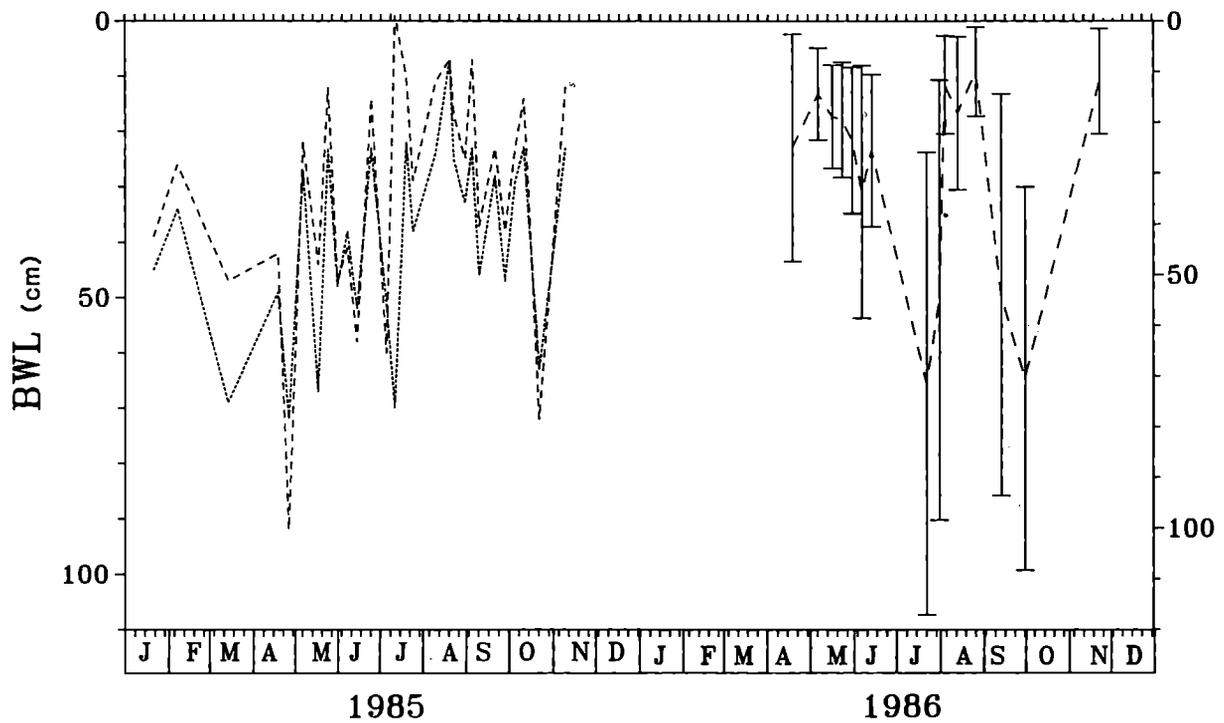


Figure 3.8 Borehole water level in the deep peat soil at site 6 (two boreholes in 1985, mean and $p < 0.05$ confidence limits for the eight boreholes in 1986).

Table 3.7 Peaty ironpan soil sites ranked according to 'summer dryness' in 1984, 1985 and 1986 (kPa)

Site	8 (wetter)	5	9	12	10	17 (drier)
1984		-30.6			-57.4	-57.7
1985	-5.4	-4.8	-6.0	-5.5	-9.6	-8.8
1986	-4.8	-7.9	-9.4	-12.3	-15.1	-23.1

There is no obvious correlation between the rankings of the ironpan soils in Tables 3.6 and 3.7, but neither of the rankings suggests there were major differences between the soils.

Peaty ironpan soils: hydraulic potentials

Hydraulic potentials at 10 depths in the ironpan soil at site 5 are shown for a selection of dates in 1985 in Figure 3.7. There were similarities with the hydraulic potentials in the gley soil (Figure 3.4) in that the lines were essentially straight and parallel and the magnitude of the potentials varied with rainfall in the same way, but there was a clear difference in that the gradient down the profile was much stronger. Each of the ironpan soils could be distinguished from the gley soils each year in this respect, in spite of occasional inconsistencies in the strength of the gradient. There was no change of gradient at the depth of the ironpan, indicating that the pan was not a barrier to capillary water flow or even to saturated flow. Indeed the gradient was much as would have been expected in a freely draining soil. This was in spite of there being no evidence that cultivation prior to planting had

been deep enough to cause general disruption of the ironpan. Nor did the matric potentials indicate that there was extensive water uptake from the subsoil by roots except at site 17 where the ironpan was lacking.

Deep peats: water-table depths

Fluctuations of bwl in the deep peat soils were generally similar to those in the gley soils but at shallower depths (Figure 3.8). Of the eight boreholes at site 6 two (but not the original, deepest two) were always empty and there was more variation between the other six than in the gley soils. This cast doubt on whether the bwl properly represented the water-table in this soil. With hindsight it would have been better to have installed some boreholes to shallower depths, i.e. not extending beyond halfway through the peat. There was no obvious difference in bwl behaviour between the peats that were known or suspected to overlie ironpan soil (sites 6 and 19) and the others. Table 3.8 ranks the sites by their mean bwl in 1985.

In spite of quite large differences in peat depth, there was little difference in bwl between the sites.

Table 3.8 Mean bwl in deep peats in 1985 (cm)

Site	19	15	6	4
Bwl	35	37	39	40

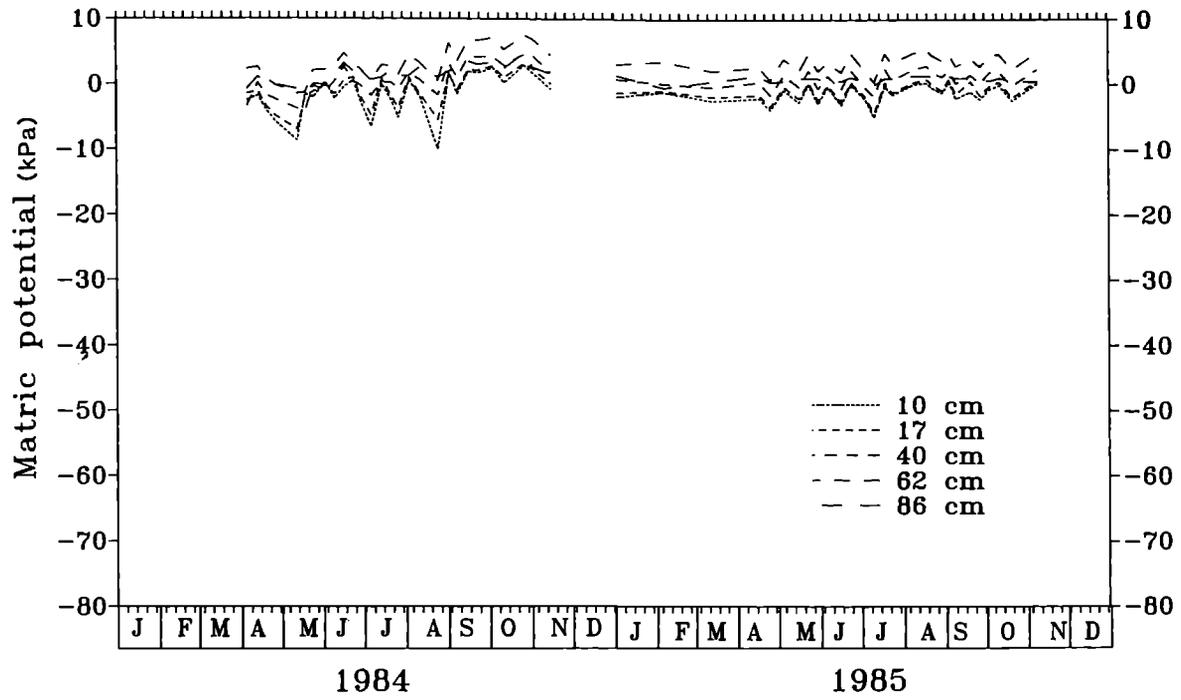


Figure 3.9 Matric potential at five depths in the deep peat soil at site 6 in 1984 and 1985.

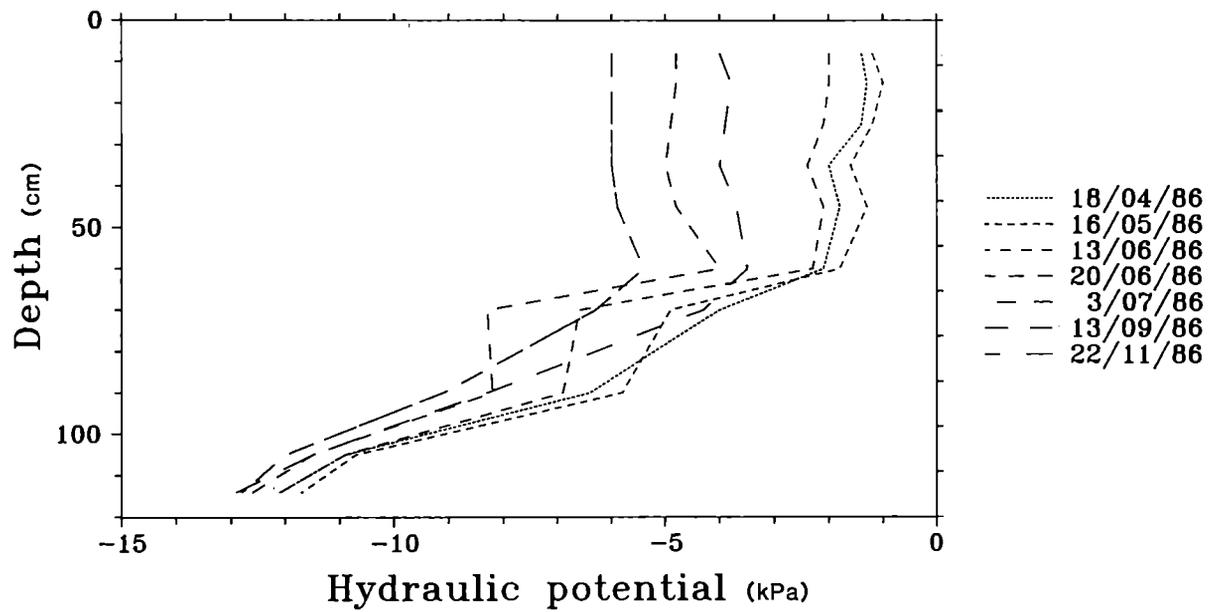


Figure 3.10 Hydraulic potential at 10 depths in the deep peat soil at site 6 for selected dates in 1986.

Deep peats: matric potentials

At site 6, matric potentials remained high in 1984 and 1985 (Figure 3.9), and also in 1986 where the lowest potential reached was -11.9 kPa at 10 cm depth on 3 July. At site 15, where the trees were much taller than at the other three sites, lower potentials were reached in 1984, namely -41.9 kPa on 23 August. Elsewhere, and in other years at site 15, potentials did not fall below -10 kPa. The general absence of low matric potentials in the deep peat sites may be put down to the smaller trees placing a lesser demand on soil water (and intercepting less in the canopy) and partly to the large quantity of water in peat within the relevant range of potentials.

Deep peats: hydraulic potentials

Hydraulic potentials at 10 depths in the deep peat at site 6 are shown for selected dates in 1986 in Figure 3.10. In the upper 60 cm of the peat hydraulic potentials were almost constant with depth, whereas in the lower 40 cm of the peat and the upper 14 cm of the mineral substrate (probably an ironpan soil) there was a strong downward gradient, the transition being sharp. This pattern persisted throughout the period from April to November. Matric potentials at depths of 105 and 115 cm within the mineral soil were almost always negative (0 to -1.7 kPa). Thus the mineral soil exerted a constant suction on the peat. The magnitude of the gradient varied on different dates from 0.15 to 0.20 kPa cm⁻¹, which may be compared with the gradient throughout the full depth of the ironpan soil (site 5) of 0.075 kPa cm⁻¹. The hydraulic conductivity of the peat and therefore the vertical flux of water would probably have been much less than in the ironpan soil proper, in spite of the steeper gradient.

A similar change of gradient at a depth of 60-70 cm was revealed by the original set of five tensiometers at site 6, and this was present in all 3 years. Sites 4 and 19 showed a similar change of gradient at a depth of 50-70 cm in 1985 and 1986 (there were no results for 1984). Site 15 did not show a change of gradient with depth; its results were similar to those for the gley soils.

Discussion

Borehole and tensiometer results revealed clear differences between the water regimes of the three soil types. The gley soils were characterised

by large and rapid fluctuations in the permanent water-table, fluctuations which reflected the distribution of rainfall and which showed little if any predictable seasonal pattern. Even in midsummer the water-table could be situated within 20 cm of the surface for periods of 2 or more weeks; conversely at some of the sites the water-table could fall beyond 100 cm depth at any time of the year given 2 or 3 weeks of fairly dry weather. Annual ranges of more than 80 cm in the bwl were not uncommon at several of the sites. Such ranges are greater than we have found in clayey gleys at Newcastleton (Pyatt *et al.*, 1979), Kershope (Pyatt *et al.*, 1985) and elsewhere in Scotland and northern England where the annual rainfall is about half that at Afan. High rainfall presumably combined with relatively rapid hydraulic conductivity in the sandy or loamy soils would be responsible for the large fluctuations in the water-table. The water-table frequently fell to depths well beyond the depth of plough furrows or even drains, which suggests that some of the water moved vertically through the profile. This interpretation is supported by the existence of a downward gradient, albeit small, within the saturated zone. Drying of the profiles during the summer was very variable between the 3 years of the study. The dry summer of 1984 allowed substantial drying to occur while the wet summer of 1985 allowed very little; 1986 was intermediate.

In the peaty ironpan soils the zone above the pan was saturated more often than the zone beneath; but when the high rainfall was taken into account these soils behaved as almost freely draining. There was no evidence of the true groundwater-table influencing the profile within 100 cm depth, and negative matric potentials prevailed at all depths. There was a strong downward gradient of hydraulic potential most of the time. Apart from the small effect on borehole water levels there was no evidence that the ironpan itself exerted a strong control on the water regime. The effect of the peat layer was not obvious, but its influence could have been reduced by the disruption caused by furrow ploughing. The ironpan soils dried out in summer in a similar way to the gley soils. During the dry summer of 1984 partial rewetting took place leaving the subsoil relatively dry; but this condition did not persist for several weeks as it did in Newcastleton Forest in 1976 (Pyatt, 1987). These results confirm the conclusions of several workers that ironpan soils are affected by a periodic 'perched water-table' in the zone above the ironpan which induces anaerobic

conditions, whereas beneath the pan the subsoil remains unsaturated and well aerated (Muir, 1934; Crompton, 1956; Crampton, 1963; Pyatt and Smith, 1983; Anderson, 1990).

Three of the four deep peat soils revealed a perched water-table within the peat, overlying an unsaturated mineral substrate, the fourth overlay saturated material. The fluctuations of the water-table were shallower but of a similar size to those in the gley soil, but if the boreholes had not penetrated to the mineral material the water levels might have been even shallower and less variable. This was indicated by the absence of a hydraulic potential gradient within the upper zone of the peat and by the strong downward gradient in the lower zone to the mineral soil, clear evidence that deep boreholes could have caused by-pass flow.

In the gley soils roots of Sitka spruce, which are not tolerant of flooding when they are actively growing, would have been put under oxygen stress during periods of rapidly rising water-table as were seen in each of the years (Coutts and Philipson, 1978). Conversely, moisture stress would also have been experienced in 1984 and to a lesser extent in 1986, but not at all in 1985. Matric potentials of less than -20 kPa are thought to cause death of fine roots (Deans, 1979). The peaty ironpan soils had a more favourable water regime for deep rooting than the gley soils or deep peats, but some oxygen stress would have been likely in the zone above the ironpan in wet periods. Moisture stress for shallow roots would have been as likely as in the gley soils. The levels of moisture stress were not greater than have been recorded in other gley or ironpan soils where Sitka spruce was growing well (Pyatt and Smith, 1983). There is therefore

no suggestion that genuine drought conditions prevailed in the Afan soils. The deep peats provided poor conditions for deep rooting of Sitka spruce, with near saturated conditions prevailing most of the time even in dry periods, however moisture stress would not have been a problem.

It is tempting to speculate that the great throughput of water and the frequency of anaerobic conditions in the gley soils of Afan would tend to deplete the soil in those elements susceptible to chemical reduction and leaching, including iron and manganese. In clayey gleys this process is confined to an upper zone underlain by subsoil horizons where there is either redeposition of some of the leached products or localised redistribution with little loss. The Afan gleys were generally pale grey coloured, with little of the yellow mottling caused by iron oxides. In the peaty ironpan soils the combined reduction and leaching process would not be effective because the mineral horizon affected by gleying, the Eag, was very thin and because it was underlain by oxygenated horizons.

For each site in each year a wetness class was assigned using the time-series graphs of bwl and matric potential (wetness classes are defined in Rudeforth *et al.* (1984) and Robson and Thomasson (1977). Some extrapolation was required to interpret the graphs for complete years; this was done with reference to the rainfall distribution. Wetness class varied by up to one class interval in different years at the same site, but it was possible in each case to choose an average class for each site. These are listed in Table 3.9.

Table 3.9 Average wetness class over 2 or 3 years by soil types

Wetness class	VI (wetter)	V	IV	III	II	I (drier)
Deep peats		4, 6, 19	15			
Gley soils	11	2, 7, 13, 16, 20	1, 18	14	3	
Ironpan soils				9, 17	5, 8, 10, 12	

No attempt was made to rank the sites within each of the wetness classes. These assignments were done without reference to the various rankings given earlier. The wetness classes accord as well as would be expected with the rankings of the gley soils in Table 3.4, although class V covers rather a wide range of mean bwl. Again, it should be said that the deep boreholes and tensiometers probably led to an underestimate of wetness class for the deep peat soils. Wetness class was difficult to assign to ironpan soils, indeed the method may not strictly be applicable to them. There is no relationship between the classes in Table 3.9 and the rankings of Tables 3.6 or 3.7.

We can now examine the relationship between the current (1984) crop growth and health and the soil types and water regimes of the 20 sites (see Table 5.1). The most obvious fact is that on the four deep peat soils (sites 4, 6, 15 and 19) growth and health were poor, and only on site 15 had growth been satisfactory in the past. Coutts *et al.* (1992) showed that the trees on three of the deep peats were deficient in N and marginally deficient in K and on sites 4 and 6 were also deficient in P (no information was given for site 19). Although these deficiencies may have been exacerbated by the water regime, Dutch (Chapter 6) showed that the application of P, PK or NPK fertilisers could elicit a growth response without attention to the drainage.

The peaty ironpan soils carried crops with good, moderate or poor health. The ironpan soil with the thickest peat layer, site 9, carried the only poor crop on this type. There was some peaty gley at this site. It was also the site with by far the deepest ironpan (except of course for two of the deep peats). The crops on the other peaty ironpan soils were either healthy or had yield classes of 8 or more. The two crops with yield class 8 and only moderate health were sites 8 and 12. There was no obvious relationship with water regime.

The gleys carried a very wide range of growth rates and crops had good or poor health. Four of the poorest crops (sites 11, 7, 16 and 20) were in wetness classes VI or V, whereas the four best crops (1, 14, 18 and 3) were in wetness classes II to IV. Nevertheless, two good crops (sites 2 and 13) occurred in wetness class V. Of the four poorest crops on the gleys, three sites (11, 7 and 20) had the thickest layers of peat. It is quite possible therefore that the poor growth has a nutritional basis. According to Coutts *et al.* (see

Figure 5.3) sites 11, 7 and 20 were marginally deficient in K and 11 and 20 were also deficient in N. The prospects for improvement in crop growth through application of fertilisers are therefore much better than through improvement of drainage.

Conclusions

1. The use of boreholes and tensiometers for 2 or 3 years allowed the water regimes of gley soils, ironpan soils and deep peats within the Gelligaer Association to be distinguished. In spite of some unreliability, tensiometers provided useful supplementary information to that obtained from boreholes, particularly regarding the extent and direction of any vertical water movement. Using boreholes of different depth was essential for ironpan soils and would have been useful for the deep peats where the peat overlay mineral soil within 1 m depth.
2. The water regimes of the gley soils and deep peats could be ranked either by their mean water-table depth or by wetness class, but neither of these provided a good indication of the degree of drying experienced by the soil during dry summer weather. The water regime of the peaty ironpan soils was less easily expressed in terms of wetness class because these soils did not contain a true water-table.
3. The growth of Sitka spruce was worst on the deep peat sites, probably because of nutritional deficiencies but possibly exacerbated by excessive soil wetness. On the gley soils the poorest crops were found on the sites with the thickest peat layer and the best crops were found on the less peaty sites, probably for nutritional reasons, although peat thickness also reflected soil water regime. Likewise, although growth was generally better on the peaty ironpan soils, the poorest crop was on a site with thicker peat and transitional to a peaty gley.

Acknowledgements

I am indebted to A.R. Anderson for help with the installation of equipment, to N.P. Danby and S.J. Corcoran for taking the instrument readings, to I.M.S. White and R.W. Blackburn for statistical services and to D. Ray for computer graphics. T.R. Nisbet made many valuable comments on a draft of the chapter.

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Chapter 4

Stem analysis of healthy and declining Sitka spruce

M.P. Coutts and S. Corcoran

Introduction

The analysis of past growth can be helpful in attempting to unravel the causes of forest decline, by revealing the period over which decline has been taking place, and perhaps by showing associations between a change in growth rate and known changes in the environment such as drought years or outbreaks of defoliating insects (Le Blanc *et al.*, 1987; Innes and Cook, 1989). Past growth can be measured in terms of height and growth ring width by the use of a stem analysis technique. The pattern of growth between pith and cambium in a 'radial sequence' at a given height, the type 2 sequence described by Duff and Nolan (1957), is influenced by crown competition and changes in the allocation of assimilates as the tree develops. A 'vertical sequence' (type 1), in which a ring at particular ring number from the pith is measured in each internode, is less sensitive to such disturbances, especially for rings found in the upper part of the crown, and it better reflects environmental influences.

The annual height growth of conifers can be considered in terms of two components, the number of needles on the leading shoot (termed needle number) and stem unit length which is the length of the shoot divided by the number of needles on it. The retrospective measurement of these components could give further information about forest decline because they are produced by different meristems and to some extent respond to conditions obtaining at different times (Romburger, 1963). Needle number, except in juvenile trees, is determined by the number of needle primordia produced in the bud in the year before shoot elongation, whereas stem unit length is influenced more by the condition of the tree and the environment

during the short period of shoot extension in the spring. Interpretation can be difficult however because conditions favouring the rapid initiation of stem units in the bud tend to be correlated with the amount of metabolites available for elongation in the spring (Bongarten, 1985), and needle number and stem unit length are sometimes inversely correlated (Kremer and Larson, 1983).

In this study, stem analysis was applied to Sitka spruce trees from a crop in decline on the plateau area of the South Wales coalfield. The trees had suffered from defoliation in past years and most of the needles produced up to and including 1981 were missing, but it was found that the positions where needles had been attached could be identified on the stem internodes. These points of attachment gradually disappeared as the stem grew in thickness and the bark became weathered, but could still be counted on internodes 10-12 years old. Trees used for stem analysis were therefore also measured in terms of needle number and stem unit length.

Site, tree selection and analysis

The site is in Afan Forest District, 51° 40'N, 3° 35'W, elevation 520 m; the soil is a peaty ironpan. The crop was of Queen Charlotte Islands seed origin and was planted in 1963. Local yield class of this declining crop was about 6. The trees had been planted at a stocking density of 4600 ha⁻¹ but in 1985, when this study was made, there were 4080 trees ha⁻¹.

Trees in an obvious state of decline, with short leading shoots, thin crowns and dieback of branches were found to be mixed with comparatively vigorous trees. The latter were not growing as well as would be expected from

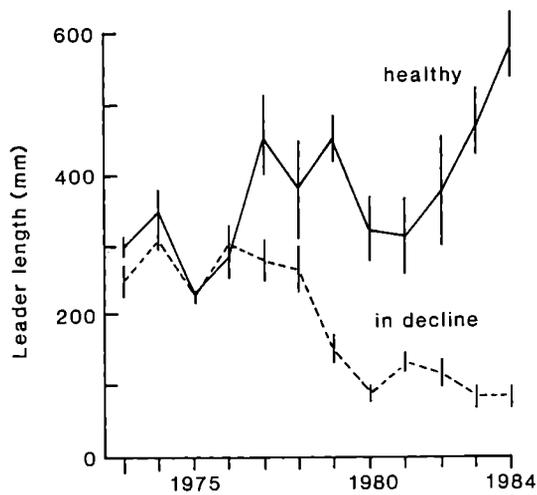


Figure 4.1 Mean leader length of Sitka spruce planted in 1963. Each curve is a mean of eight trees. Vertical bars represent one standard error above and below the mean.

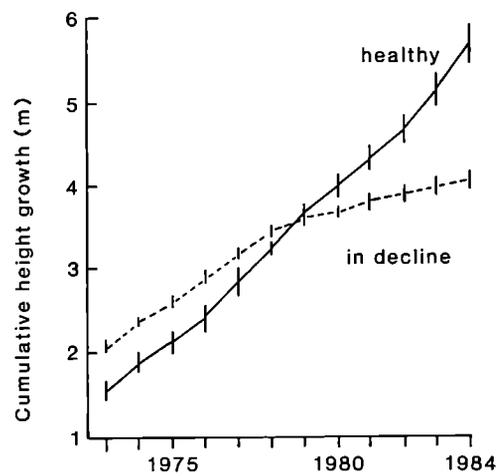


Figure 4.2 Mean cumulative height growth.

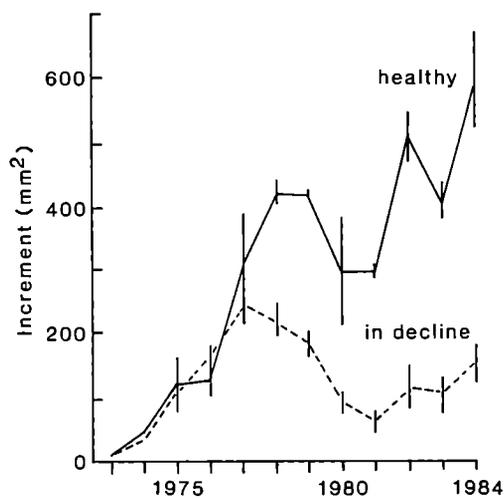


Figure 4.3 Mean cross-sectional area increment of the second growth ring from the pith using a vertical sequence.

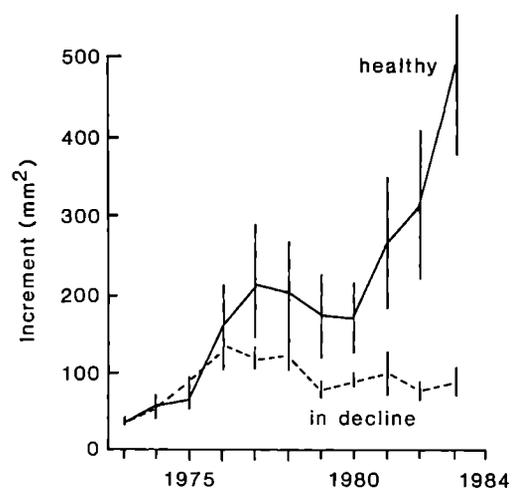


Figure 4.4 Mean cross-sectional area increment in a radial sequence through the internode formed 10 years after planting (in 1973).

the climate, elevation and soil type, but the stem internodes showed no evidence of sustained decline and the current leading shoot was much longer than in the declining trees. This variation between trees in the crop presented an opportunity to compare the growth of declining and relatively healthy trees on the same site. In spite of some doubts about the state of the better trees, the two types are called healthy and declining in this account.

Eight trees characteristic of each type were used for analysis. Preliminary work showed that breakage of the leading shoot by wind made it difficult to tell the exact ages of the stem internodes, especially in the declining trees. Trees with signs of past leader breakage were therefore excluded. Analysis was also carried out on two additional samples of trees from other sites on the coalfield but results on these are not reported in detail.

After the trees had been felled the length of 10 of the upper stem internodes was measured and the internodes were separated by sawing through the branch whorls. The number of needles on each internode and the points of attachment of missing needles were counted. For growth ring analysis a disc was cut out half way along the internode. The wood surface was cleaned on three radii with a scalpel. Pith diameter and the width of the growth rings on the three radii were measured and cross-sectional area increments calculated for radial and vertical sequences.

Results

Leader length

The leader length of the healthy trees increased from about 300 mm in 1973 to 580 mm in 1984 (Figure 4.1) but a substantial decrease in length occurred in 1975 and 1980, years when serious outbreaks of the green spruce aphid (*Elatobium abietinum* Walker) occurred, followed by recovery over 2-3 years. Leader length of the declining trees was similar to the healthy ones until 1977, 15 years after planting, when the declining trees began to show a progressive reduction in growth from which they failed to recover. By 1984 mean leader lengths of the healthy and declining trees were 580 and only 80 mm respectively. The cumulative growth curves (Figure 4.2) show that the declining trees had been slightly taller than the healthy ones during the early years of the period analysed.

Cross-sectional area increment

Cross-sectional area increment of a vertical sequence (second growth ring from the pith; Figure 4.3) behaved in a comparable manner to height growth; decline again became apparent in 1977. However, a radial sequence through the internode formed in 1973 did not indicate declining growth until 1978 (Figure 4.4).

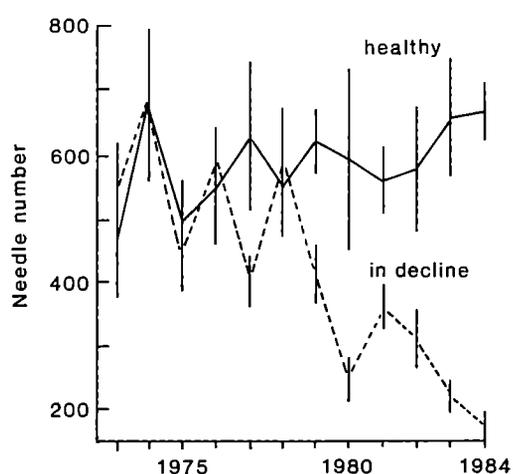


Figure 4.5 Mean number of needles formed on the leading shoot.

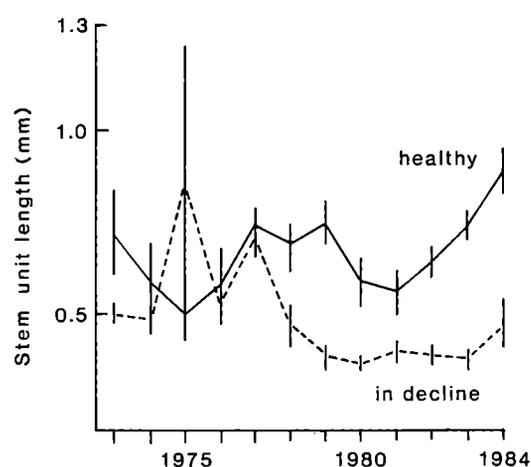


Figure 4.6 Mean stem unit length on the leading shoot.

Table 4.1 Mean leader length, number of needles on leading shoot and stem unit length of Sitka spruce

Site	Elevation (m)	Crop age ^a (years)	Leader length (mm)	Needle number	Stem unit length (mm)	Reference
South Wales coalfield ^b	520	11-12	301	587	0.51	This chapter
Bush, Scotland ^b	180	11-12	695	851	0.82	Coutts, unpublished
Tywi, mid Wales	488	7	398	770	0.52	Cannell <i>et al.</i> , 1976
Bush, Scotland	180	7	327	564	0.57	Cannell <i>et al.</i> , 1976

^a Crop age from seed.

^b Values for leader length, needle number and stem unit length are means for the 11th and 12th years. In the crop on the coalfield many trees went into decline at about age 17 years from seed.

Needle number

Mean needle number in both groups of trees showed large variation from 1973 to 1978 (Figure 4.5) and ranged from *c.* 400 to *c.* 680. Thereafter the healthy trees had 550 to 650 needles on the leading shoot. Needle number became smaller in the declining trees than in the healthy ones from 1978 onwards, and by 1984 the declining trees had a needle number of only 160.

Stem unit length

Mean stem unit length of the healthy trees was variable between 1973 and 1981 (Figure 4.6) but then showed a sustained increase to 0.90 mm by 1984. Stem unit length of the declining trees, although usually similar to the healthy ones in the first 5 years of measurement, decreased in 1978 (a year earlier than needle number) and levelled out at the low value of *c.* 0.40 mm.

Discussion

The slow height growth of trees in decline resulted from a reduction in both needle number and stem unit length, and the reduction in height growth was associated with reduced diameter growth. Decline in growth began about 15 years after planting when cross-sectional area growth of even the healthy trees was decreasing, probably because of canopy closure (see Chapter 9). Before the decline in growth began about 15 years after planting, the growth rate of the trees which declined had been similar to that

of trees described as healthy. However, even the growth of the healthy trees had been slower than would be expected from the general character of the site; this is common for crops on the coalfield (Mayhead *et al.*, 1974). So far as needle number and stem unit length are concerned, no data are available for a truly satisfactory comparison with the results presented because of variations in crop age, elevation and other factors.

Table 4.1 summarises data available for Sitka spruce. Data for ages 11 to 12 years for a crop in Scotland show much larger values for leader length, needle number and stem unit length than the crop on the coalfield site but the crop in Scotland was at a lower elevation. Trees at Tywi forest in mid Wales, which were younger than the coalfield trees but growing at a comparable elevation, were found by Cannell *et al.* (1976) to have longer leaders and greater needle number than the coalfield crop but stem unit length was about the same.

Decline became apparent in different years, depending upon the parameter measured. Leader length and basal area increment (vertical sequence) indicated decline in 1977, whereas it was not clear in basal area increment (radial sequence) and stem unit length until 1978. The data on needle number are more difficult to interpret because of the variation from year to year, however there was no sustained decline until after 1978. Individual trees showed variable behaviour; for any given parameter they did not all decline in the same year. Furthermore, results varied from site to site. On

one of the additional sites measured, which was the same age as the site described in detail, decline in basal area increment (radial sequence) and leader length began slightly earlier, in 1976. On the other site, which was planted earlier, in 1960, decline in leader length, needle number and stem unit length all began in 1975.

Although the results show that decline occurred about 15 years after planting, decline at a later stage has also been observed in parts of the coalfield. Information is available from Forestry Commission experimental records for two older crops in Margam forest, an area of the coalfield closer to industrial sources of pollution than experiment Afan 1 (see Figure 2.1, station 6). One of the crops was planted in 1931 and was found to be healthy when it was line-thinned in 1968. The crop failed to close canopy and was found to be in decline in 1978, 47 years after planting. The other crop was planted in 1941, was healthy (yield class 14) in 1970, but was found to be in decline in 1976 when aged 36 years. It thus appears that the younger and older crops declined during the 1970s.

The work described shows when growth began to decline, the rate of decline and the period (about 4 years) over which it took place. However, the causes of the decline remain a matter of conjecture. The reduction in both needle number and stem unit length found in the declining trees could not have been caused by limiting conditions for growth during the period of shoot extension alone; conditions during that period might reduce stem unit length but could not affect needle number in that year.

The results are consistent with the view that decline resulted from periodic defoliation of trees growing under other, more general conditions of stress. Damaging outbreaks of the green spruce aphid are known to have occurred in 1949, 1950, 1957, 1961, 1970/71, 1975 and 1980/81, but information is usually lacking on specific trees or sites affected. Aphid defoliation can be very patchy. However, the reduction in growth in 1980, which was detected in healthy and declining trees at all three sites where stem analysis was carried out, was associated with a particularly heavy and widespread outbreak in which substantial areas of forest were totally defoliated. Carter (1977) has shown that defoliation by aphids can significantly reduce the growth of young Sitka spruce. In the present study healthy and declining trees showed reduced growth in an aphid outbreak year, the difference between the behaviour of these two categories was that growth of healthy trees

recovered over a 2-3 year period, whereas that of declining trees did not. The ability to recover from defoliation might be an important aspect of tolerance to the type of forest decline described. Factors which influence recovery are discussed in Chapter 5.

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Chapter 5

Correlations between tree growth, leaf chemistry and site factors in an area of declining Sitka spruce

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Introduction

The decline of Sitka spruce crops on the South Wales coalfield, especially those planted during the 1960s on the exposed plateau area at elevations above 400 m, is described in Chapter 1. A number of stress factors with a potential role in decline occur on the coalfield, namely spring drought, periodic waterlogging of the soil, frost, defoliating insects and fungi, root aphids, strong wind, atmospheric pollution and nutrient deficiency. The experiment described here (Forestry Commission Experiment Afan 1) was carried out to identify some of the main stress factors involved in decline, bearing in mind that certain factors common on sites with normal growth might well contribute to decline where other conditions were unfavourable. A hypothesis was developed that:

Decline was triggered by the repeated defoliation of trees suffering from a variety of other stresses.

To test this hypothesis, defoliating insects, particularly the green spruce aphid (*Elatobium abietinum* Walker), which is known to have caused substantial defoliation in the past, were controlled by spraying, and measurements were made of tree chemistry and growth. The experiment was central to other investigations described in this publication and certain of the site characteristics and stress factors are dealt with in detail in other chapters.

Methods

Twenty sites with crops spanning a range of growth rate and tree condition, from a serious state of decline (see Chapter 1) to apparent good health, were selected in 1983. The area is shown in Figure 2.1 and details of location and site

factors are given in Table 5.1. Elevation ranged from 390 to 525 m and yield class from 4 to 14 m³ ha⁻¹ yr⁻¹. The sites had been planted between 1960 and 1968, with the exception of sites 3, 10 and 19 which were planted in 1978, 1958 and 1980 respectively. Tree stocking varied from 2000 to 3700 stems ha⁻¹. The soils were deep peat, peaty gley, peaty ironpan and surface-water gley and are described in Chapter 3. The crops had not received any fertiliser: its application at planting was not normally considered to be necessary in South Wales other than on unflushed deep peats.

At each site eight of the dominant to co-dominant trees expected to form part of the final crop were selected for measurement. These are termed the experimental trees. Four of the experimental trees at each site were sprayed annually to control the green spruce aphid (see Chapter 10).

The height of the experimental trees was measured annually from 1983 to 1986 but this measurement was then abandoned because of the high incidence of leading shoot breakage by wind. Stem diameter at 1.3 m (dbh) was measured annually from 1983 to 1989. The pattern of diameter growth during the season was also measured, using spring-loaded vernier growth bands at a height of about 1 m. The bands were read at intervals of about 14 days from 1984 to 1986. The depth of root penetration was estimated from the mean depth of the deepest roots found in four narrow soil pits which were dug at each site. Crown density was scored in 1984 and 1985. The scoring system was based on 0 (no needles) to 5 (normal dense foliage of healthy trees). The upper, mid and lower crown were scored separately and the results averaged for the tree. This scoring

Table 5.1 Site and tree characteristics for Sitka spruce on the South Wales coalfield

Site number	Grid reference	Elevation (m)	Soil type	Planting year	Number of trees (ha ⁻¹)	Rooting depth (m)	Mean height (m) ^a	Mean height increment (m) ^b	Yield class	Mean foliage density score ^c	Health assessment
1	940026	470	peaty gley	1968	2700	>0.58	7.41	0.72	14	4.9	good
2	935026	460	peaty gley	1968	3700	0.25	6.71	0.72	12	5.0	good
3	939019	440	peaty gley	1974	2500	>0.40	3.81	0.55	14	4.9	good
4	906017	515	deep peat	1963	5000	0.14	3.95	0.17	4	3.1	poor
5	902994	500	ironpan	1968	3300	>0.36	5.74	0.74	12	4.5	good
6	902993	500	deep peat	1968	3800	0.10	3.45	0.16	6	2.9	poor
7	907983	500	peaty gley	1960	3500	0.17	4.71	0.30	6	3.7	poor
8	908978	510	ironpan	1960	3500	0.35	6.83	0.50	8	4.7	moderate
9	906974	520	ironpan	1963	3700	0.31	5.06	0.21	6	2.7	poor
10	874975	390	ironpan	1958	2300	0.61	11.05	0.47	12	4.4	moderate
11	898997	480	peaty gley	1968	2000	0.27	4.15	0.27	8	2.1	poor
12	898001	500	ironpan	1968	2000	0.19	3.68	0.33	8	3.4	moderate
13	898003	490	peaty gley	1968	3300	>0.56	6.40	0.82	12	4.7	good
14	896003	460	peaty gley	1960	3100	>0.53	8.95	0.71	12	4.9	good
15	903002	515	deep peat	1960	4300	>0.34	6.86	0.21	8	2.7	poor
16	902023	525	peaty gley	1963	3200	0.22	5.30	0.29	8	3.7	poor
17	901023	510	ironpan	1964	4080	>0.50	8.01	0.66	12	4.4	good
18	885020	475	surface-water gley	1962	3800	0.36	8.01	0.62	10	4.0	good
19	859000	490	deep peat	1980	2000	0.23	2.04	0.14	-	2.2	poor
20	853990	460	peaty gley	1964	3300	0.13	4.35	0.19	6	2.9	poor

^a Mean height of the eight dominant to co-dominant experimental trees in 1984.

^b Mean height growth of the eight experimental trees in 1984.

^c Means for a subjective score on eight experimental trees in 1984; 0 = no needles present to 5 = dense crown.

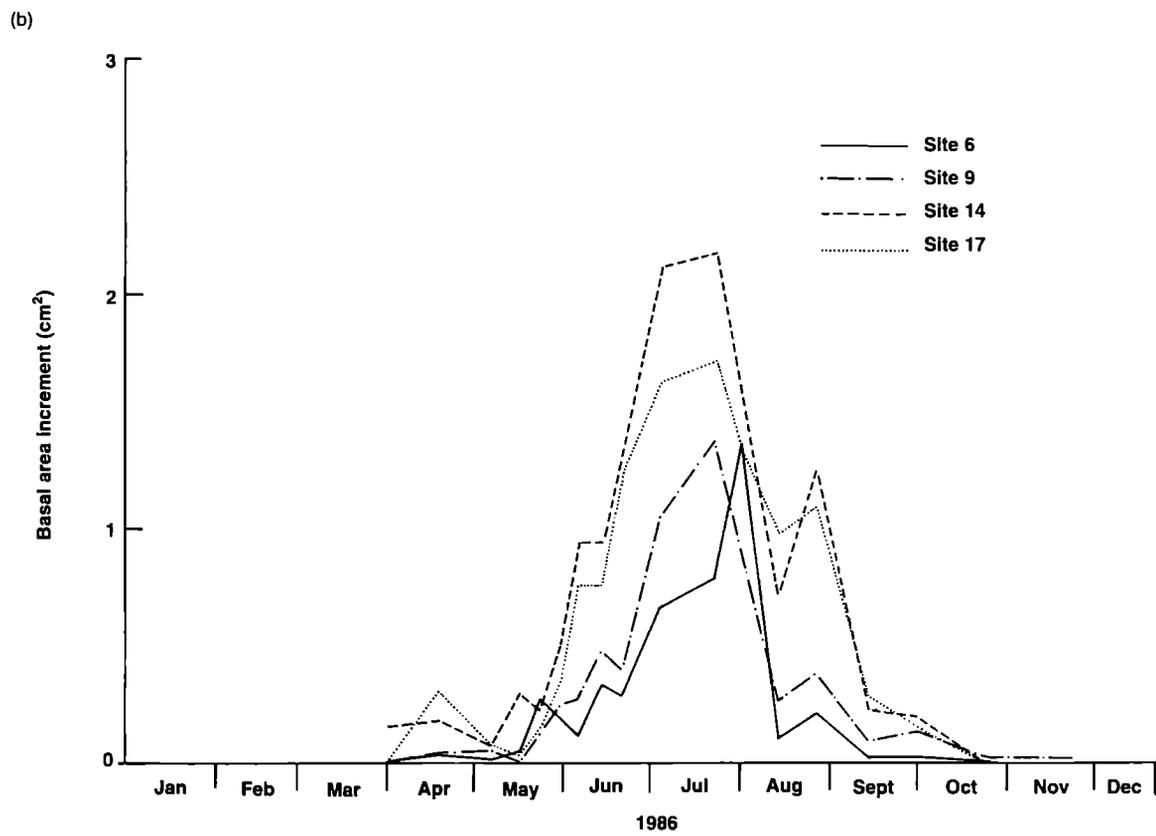
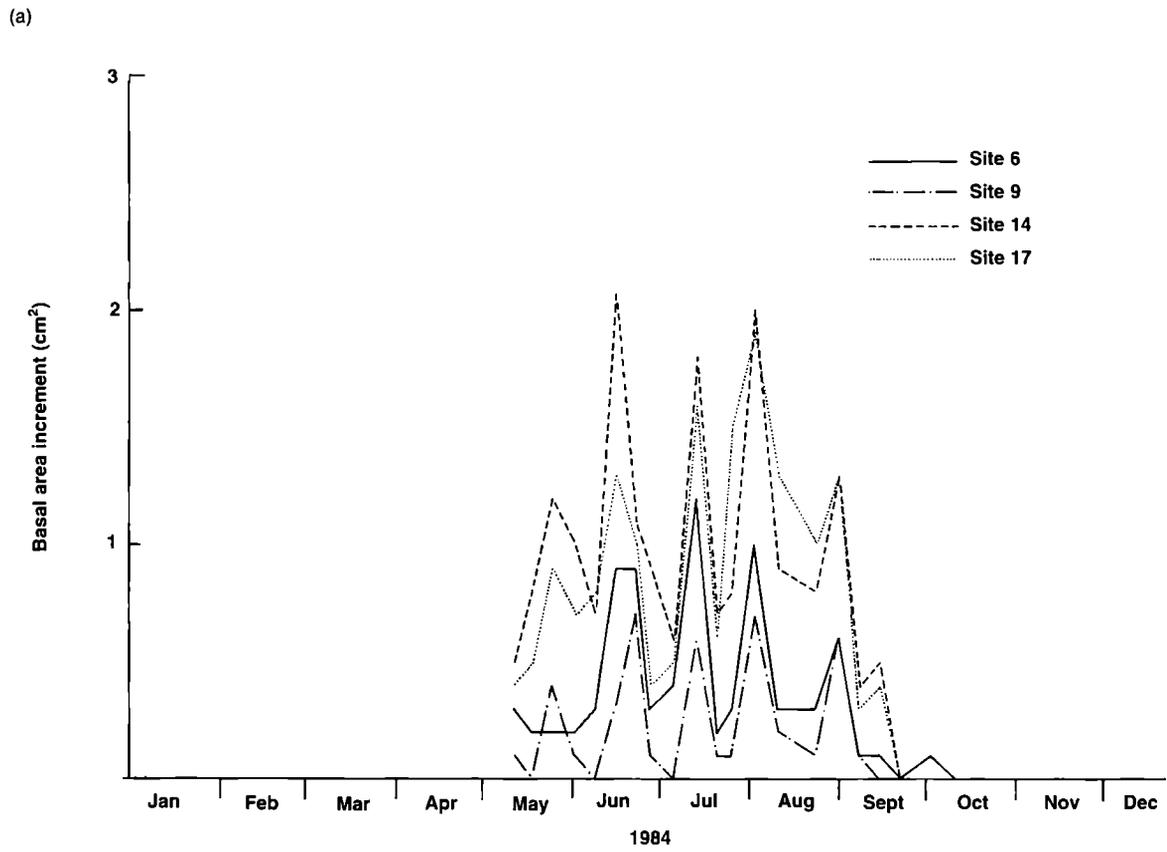


Figure 5.1 Mean basal area increment of eight co-dominant trees on each of four sites in (a) 1984 and (b) 1986. Sites 6 and 9 are in decline, sites 14 and 17 are healthy.

system was adequate for comparing crops on different sites at any one time but was found to be too subjective for making comparisons between years.

Foliar analysis for the nutrient elements N, P, K, Ca and Mg was carried out on needles from an upper-whorl branch of each experimental tree (Everard, 1973). The samples were taken in late autumn, annually from 1984 to 1987. Part of the 1987 sample was also analysed for Zn, Cu, S and Mn. Levels of Zn and Cu were measured because relationships between tree growth and the concentration of these elements in the soil solution had been found (Chapter 8); S because it could have been present in inhibiting amounts in the needles as a result of atmospheric pollution; and Mn because an indication had been obtained that some of the trees in the coalfield were deficient in this element (Chapter 9).

Results of foliar analysis and basal area increment were compared for sprayed and unsprayed trees using parallel regressions. Site 19 was omitted from analyses which included basal area increment because the trees were too small for the conventional dbh measurement.

Results

Tree growth

Mean annual height of the experimental trees for the 20 sites was 5.8 m in 1984, and in the 17 sites planted between 1960 and 1968 site means (i.e. means of the eight experimental trees on a site) ranged from 3.4 to 7.4 m. Mean annual height increment was about 0.80 m on the better sites and often less than 0.20 m on those in decline (Table 5.1). Leader breakage occurred in every year of measurement in healthy and declining crops; during the years 1984 to 1986, 52 breakages were recorded among the 160 experimental trees. This amount of breakage shows that the area is exposed and windy but it is not necessarily exceptional for upland sites in Britain.

Mean annual basal area increment increased from 8.8 cm² per tree in 1984, which was an exceptionally dry year, to 12.2 cm² in 1985 and showed little change thereafter. Site means of basal area increment per tree ranged from less than 5 cm² to more than 20 cm² in any year. Basal area increment is influenced by stocking density

and the low density of sites 1 and 3 compared to the rest will have influenced the relationship between increment and other factors in Figures 5.2 and 5.3. However, basal area increment was linearly correlated with height increment ($r = 0.63$, $df = 17$). Furthermore, the overall relationships between basal area increment and factors such as mineral nutrient concentrations in the leaves, were similar to those using height increment, and as height increment is known to be independent of spacing over the range encountered here, the variation in stocking density rarely hindered the interpretation of the results. Relationships with basal area increment are therefore presented instead of height increment because of the variable effects of leader breakage on the latter in certain years.

The pattern of basal area increment during the growing season for two crops which are healthy and two in decline are shown in Figure 5.1. Monthly rainfall for the years illustrated is given in Table 3.3. The growth pattern in 1984 (rainfall 2300 mm) shows a series of peaks which are associated with the rainfall, and deep troughs in June and July in dry periods. By contrast, in 1986 (rainfall >3000 mm) deep depressions of growth did not occur in June and July. In 1984 measurements were begun after growth had started, but the time when it started in 1986 and when it ended in both years, together with variation in growth rate caused by the weather, were similar for healthy and declining crops. The main difference was in the amount of growth, not in its periodicity.

Aphids

Although the green spruce aphid was always present in crops on the coalfield, very small numbers were found at most sites from 1984 to 1989 (Chapter 10). The mean basal area increments (all sites) for sprayed and unsprayed trees were not significantly different in any year (Table 5.4) and data for the two treatments were therefore combined for comparisons between tree growth and other factors.

Soil type

Table 5.1 indicates no clear relationship between soil type and yield class or tree health. However, the four deep peat sites all had particularly poor growth and Pyatt (Chapter 3) concludes that peat depth is also associated with poor growth on the peaty gleys.

Table 5.2 Correlation coefficients for basal area increment of Sitka spruce and concentration of nutrient elements in the foliage in 1987

	Basal area increment	Needle weight	Nitrogen	Phosphorus	Potassium	Magnesium	Calcium	Zinc	Copper	Manganese	Sulphur
Needle weight	0.616										
Nitrogen	0.607	0.470									
Phosphorus	0.456	0.616	0.596								
Potassium	0.820	0.485	0.683	0.275							
Magnesium	-0.348	-0.046	-0.396	0.279	-0.451						
Calcium	0.273	0.252	0.662	0.521	0.287	0.101					
Zinc	-0.109	-0.142	0.018	0.139	-0.027	0.389	0.552				
Copper	0.546	0.251	0.388	0.308	0.585	0.125	0.406	0.278			
Manganese	0.222	0.358	0.175	0.268	0.231	-0.085	-0.104	-0.023	0.223		
Sulphur	0.697	0.512	0.798	0.677	0.672	-0.142	0.561	-0.108	0.379	0.045	
S/N ratio	-0.054	-0.049	-0.558	-0.024	-0.225	0.484	-0.288	-0.163	0.107	-0.215	0.047

Correlations in bold type are significant at the 5% level.

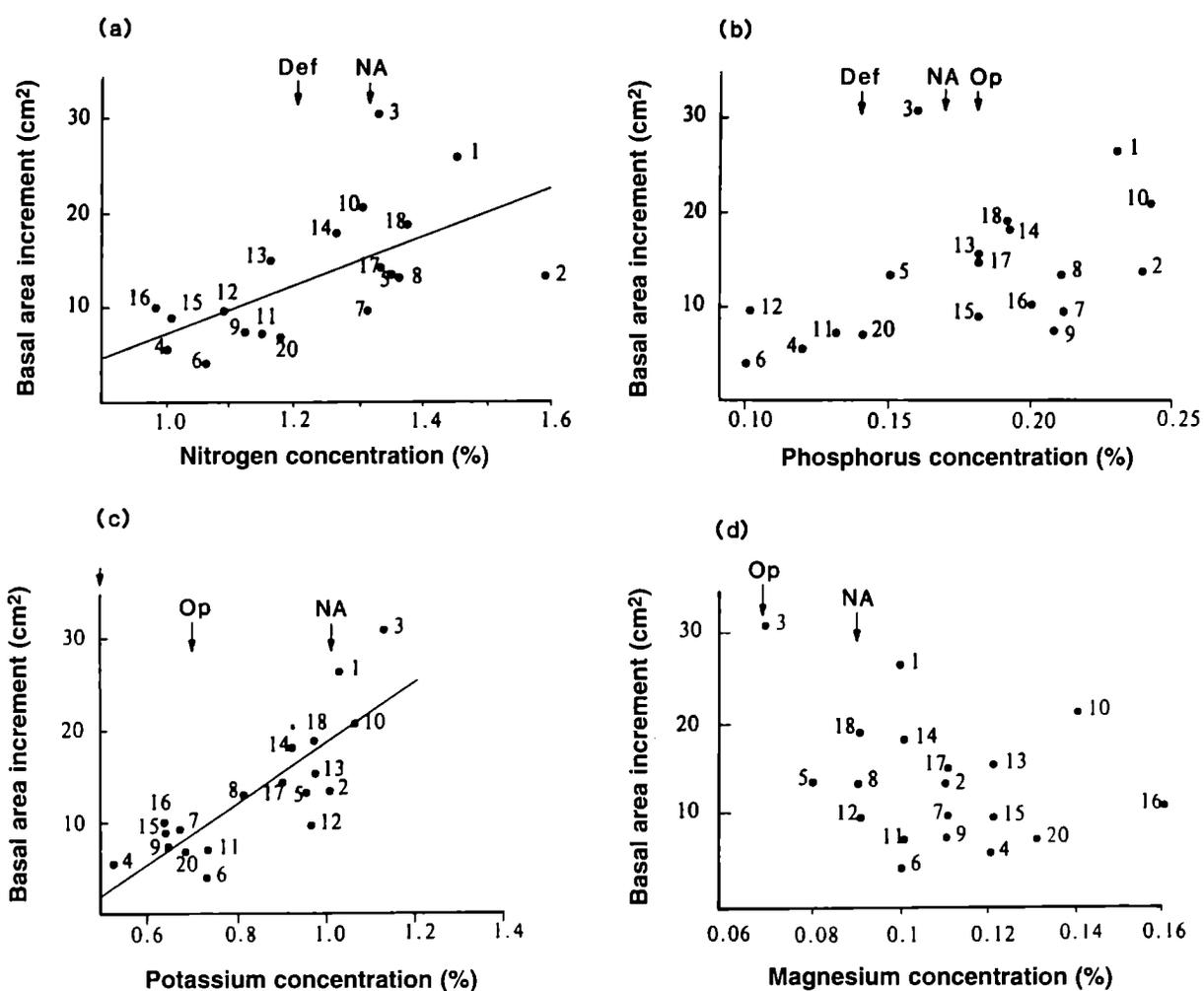


Figure 5.2 Basal area increment for the sites in Experiment Afan 1 and foliar concentration of (a) nitrogen, (b) phosphorus, (c) potassium, (d) magnesium. Regression lines are shown for (a) and (c). Def and Op indicate deficiency and optimal foliar concentrations for young crops; NA indicates the average of the National Survey for older trees.

Table 5.3 Coefficients of correlation between concentrations of nutrients in the foliage and the basal area increment for 8 co-dominant to dominant trees on each of 20 sites in South Wales in different years.

Element	Year of measurement			
	1984	1985	1986	1987
Nitrogen	0.65	0.61	0.65	0.61
Phosphorus	0.58	0.71	0.47	0.46
Potassium	0.87	0.72	0.77	0.82
Magnesium	-0.61	0.02	0.22	-0.35
Calcium	-0.14	-	0.44	0.27

Correlations in bold type are significant at the 5% level.

Rooting depth

Site means of rooting depth for the 20 sites ranged from 13 to 61 cm (Table 5.1). There was considerable variation within each soil type as found on sites in South Wales by J.M.B. Brown (Mayhead *et al.*, 1974). Furthermore, there was much variation between the depth recorded in different soil pits on individual sites, and on some sites with deep rooting the sampling method was found to be inadequate because roots were present below the depth to which it was possible to dig. (The pits were kept narrow to avoid excessive disturbance to the crop.) However, there was a high coefficient of correlation between mean basal area increment (1984) and mean rooting depth and there was strong evidence of a linear relationship ($r = 0.82$, $df = 17$).

Nutrition

Foliar analysis was carried out annually from 1984 to 1987 and the results for 1987 are presented in detail in Figures 5.2 and 5.3. Correlations between nutrients and growth in the other years are given in Table 5.3. For comparative purposes the mean foliar nutrient concentrations found in Sitka spruce in a national survey (J.L. Innes, personal communication) are shown in Figures 5.2 and 5.3. The survey was carried out in 1985 on trees 30-50 years old. Wherever possible, nutrient levels associated with deficiency and optimal growth in young trees (Binns *et al.*, 1980) are also shown.

Nitrogen

Twelve of the 19 sites had N concentrations below the average of 1.3% needle dry weight found in the National Survey, nine were below the deficiency level of 1.2% for young trees and only one site had a level above the optimum of 1.5% (Figure 5.2(a)). There was a positive correlation between basal area increment and foliar N concentration, with coefficients of correlation of 0.61-0.65 between 1984 and 1987 (Table 5.3). Nitrogen appears to be a limiting factor to tree growth on some sites.

Phosphorus

Only four of the sites had foliar P levels below the deficiency level of 0.14%, three were marginal, and 12 were above the optimal level of 0.18% (Figure 5.2(b)). Seven were below and 12 above the national average for older trees of 0.17%. Phosphorus concentration was only weakly correlated with growth except in 1985 (Table 5.3).

Potassium

Foliar potassium concentrations were mostly below the national average of 1.0% but all were above the accepted deficiency level of 0.5% for young crops. In spite of this, K concentration was the strongest discriminator for growth; there was a clear positive relationship between K levels and basal area increment (Figure 5.2(c)). The coefficient of correlation was higher than for the other elements during every year of measurement, and ranged from 0.72 to 0.87 (Table 5.3).

Calcium

Mean foliar Ca concentration was 0.28% (range 0.14-0.47%), slightly below the national average of 0.32%, but within what is encountered in healthy Sitka spruce crops elsewhere. In spite of the wide range in foliar levels Ca concentration was not correlated with basal area growth in any year.

Magnesium

Foliar Mg concentrations were above the 0.07% minimum level for optimal growth in young crops, and in most of the sites the levels were well above the national average of 0.09% (Figure 5.2(d)). Foliar Mg was not significantly correlated with growth except in 1984 when a significant negative correlation was found (Table 5.3).

Sulphur

Sulphur was present in the leaves in high concentrations. The mean foliar S concentration was 0.22% and the range of site means was 0.19-0.29%. The range of values for individual trees was 0.13-0.36% and six trees had concentrations above 0.30%. All sites had mean S levels above the mean of the National Survey (0.15%, range 0.09-0.22%). Foliar S concentrations showed a significant positive correlation with tree growth (Figure 5.3(a)), suggesting that the high S levels were not toxic. Sulphur concentrations were correlated with those of other major nutrients (Table 5.2), therefore S may not have been influencing growth directly.

Zinc

The mean Zn concentration was 31 (range 17-41) ppm, similar to that found in the National Survey (mean 33, range 20-51 ppm). There was no significant correlation between concentration of foliar Zn and tree growth (Table 5.2) despite a

Table 5.4 Effect of controlling the green spruce aphid by spraying, on basal area increment of Sitka spruce on 19 sites in the South Wales coalfield

Year	Mean basal area increment per tree (cm ²)	
	Sprayed	Control
1984	8.88	8.83 ns
1985	12.62	12.25 ns
1986	11.46	10.84 ns
1987	12.42	12.57 ns
1988	12.77	12.73 ns
1989	12.88	13.01 ns

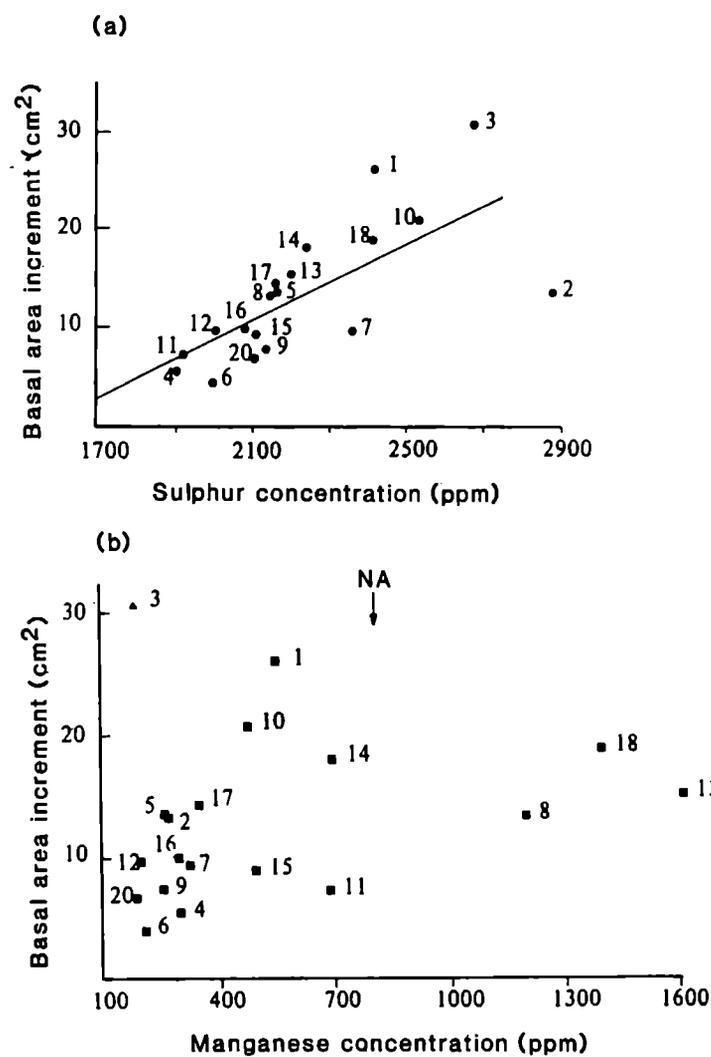


Figure 5.3 Basal area increment and foliar concentration of (a) sulphur, (b) manganese. NA indicates the average manganese concentration found in the National Survey.

negative relationship that has been found between Zn concentration in the soil solution and growth (Chapter 8).

Copper

The mean Cu concentration was 4.26 (range 2.41-6.41) ppm, similar to the national average of 4.37 (range 3.00-12.80) ppm. Copper levels were significantly correlated with growth but also with foliar K concentration (Table 5.2). Growth has evidently not been inhibited by toxic levels of Cu in the foliage. Concentrations of 2 ppm Cu are now considered to represent marginal deficiencies (Miller and Miller, 1987) and all of the Afan 1 sites showed levels above that value. It is concluded that concentrations of foliar Cu are within the range for optimal growth.

Manganese

The mean foliar Mn concentration was 497 (range 170-1600) ppm, i.e. well below the national average of 807 (range 260-2270) ppm. There appears to be no linear relationship between foliar Mn and growth. However, Figure 5.3(b) shows that site 3, which was low in Mn but had a large basal area increment, may have obscured any relationship which existed. The crop at site 3 was younger and more widely spaced than most and the canopy was not completely closed. The data suggest that Mn concentrations below 500-600 ppm were generally associated with poor growth. However, these concentrations are an order of magnitude higher than that (less than 20 ppm) associated with deficiency symptoms in Norway spruce (Ingestadt, 1958); and van Praag and Weissen (1986) found that decline of Norway spruce was associated with Mn levels of 90 ppm compared with 480-1100 ppm in healthy stands elsewhere in Belgium.

Discussion

Forest decline in South Wales probably results from multiple causes as in examples of decline which have been studied in detail elsewhere (Krahl-Urban *et al.*, 1988). The experimental part of this study, which was the control of the green spruce aphid on half of the trees by spraying, failed to test the hypothesis that decline was caused by defoliation of otherwise stressed trees, because no major outbreak of aphids occurred during the 5-year period of observation. The chapter is therefore mainly a descriptive account of site and tree condition for healthy and declining crops. Although the observations do

not demonstrate the causes of decline they do clarify some of the factors involved.

The most striking characteristics of crops in decline were that they had thinner crowns than healthier crops, and the needles often showed discoloration associated with nutrient deficiencies. Thus, the direct cause of slow growth may be attributed to a small leaf area, but reduced efficiency of the needles for photosynthesis as a result of nutrient deficiency (Chandler, 1989) may also play a part. The measurements with vernier growth bands showed that crops in health or in decline differed in the amount of basal area growth but not in its periodicity; they all started and finished growth at much the same time during the season.

Tree growth was generally poorer on the wet deep peat sites, and where the peat was relatively deeper on the other main soil types present (Chapter 3). The positive relationship found between rooting depth and growth, despite the variation and the problems encountered in sampling, is consistent with Day's (1946) observations which showed that the height growth of Sitka spruce at elevations above 427 m in Mynydd Dhu Forest was positively correlated with the depth of freely rootable material. Loss of fine roots caused by periodic waterlogging of the soil may contribute to decline. Pyatt (Chapter 3) describes how on the gley soils the water-table could lie within 20 cm of the surface for periods of 2 or more weeks, even in summer, and this would result in the death of many fine roots.

The colour of the foliage on the poorer sites suggested nutrient deficiency. Evidence of deficiency was also provided by regressions of foliar nutrient concentrations against growth rate. The importance of nutrition on the coalfield had not always been appreciated in the past, partly because initial growth was rarely improved by fertiliser application in South Wales, and partly because analysis of thicket and pole-stage crops had shown nutrient concentrations greater than the standard levels used to judge deficiency. However, these standards were based on young crops 0.3-3.5 m tall. McIntosh (1984) summarised results of older, established stands of Sitka spruce in Britain. Some stands responded to applications of N, P and K by increased growth, but in all unfertilised controls foliar levels of P and K were above those considered to be adequate for young crops (Everard, 1974; Binns *et al.*, 1980), indicating that the optimum foliar nutrient

concentration increases with age. For N, McIntosh showed that in established stands with closed canopy the optimum foliar concentration was 1.8-2.0%, considerably higher than in young crops, and higher than in all 20 of the sites in this experiment. A further comparison indicative of nutrient deficiency in coalfield crops is the 1985 National Survey of 30 to 50-year-old trees. The proportions of the 20 sites in Afan 1 with foliar concentrations of major nutrients below the national average were 65%, 40% and 80% for N, P and K respectively. Potassium concentration was the strongest discriminator for growth in each year of measurement.

The only indication of possible micronutrient deficiency was for Mn. Foliar levels in 85% of the sites were below the average of the National Survey. However, the results for this micronutrient are difficult to interpret because Mn deficiency has not been recognised in Sitka spruce elsewhere in Britain and the foliar levels may not be low enough to constitute deficiency. Further discussion of Mn is given in Chapter 9. Results for Zn show neither deficient nor toxic concentrations. The lack of toxic levels is of interest because a correlation has been found between growth and Zn concentration in the soil solution (Chapter 8). In the present study, foliar Cu concentration was correlated with tree growth. However, the concentrations were above what is regarded as a deficiency level, and the correlation with growth can perhaps be explained by the significant positive correlation found between Cu and K (Table 5.2). Foliar Mg levels were always adequate, in contrast to Type 1 spruce decline in Europe (Roberts *et al.*, 1989).

The high concentrations of foliar S are of interest. The site means ranged from 0.19 to 0.29%. Eight sites had mean S levels above the maximum found in the National Survey and above Malcolm and Garforth's (1977) values for Sitka spruce in a polluted part of Scotland. The S concentrations found in the present study also exceed these recorded by Cape *et al.* (1990) on Norway spruce on 12 sites located over a geographical range from southern Germany to northern Scotland. Innes and Boswell (1989) showed that foliar S levels for Sitka spruce in Great Britain were related to atmospheric levels of SO₂ and concluded that variations in foliar S were probably caused more by uptake from the atmosphere than from the soil. The high foliar S levels of trees on the coalfield are consistent with this view because pollution by SO₂ has been demonstrated in the area (Chapter 2). However, Innes and Boswell recognised that trees also take S from the soil, and the amount in the soil will be

augmented from the atmosphere. Table 5.2 shows that S levels were correlated with those of the other major nutrient elements and particularly with foliar N. Thus, as with Cu, the positive correlation between foliar S concentration and tree growth may not indicate a causal relationship. However, the relationship found suggests that high foliar concentrations of about 0.13% are not toxic in Sitka spruce although Landalt *et al.* (1989) consider 0.12-0.21% to be critical concentrations for Norway spruce.

Although the trees on most of the experimental sites have sustained little damage from aphids since 1982, the crops in decline have not shown much increase in basal area. In the poorest sites the death of some of the older needles and gradual dieback of shoots in the lower crown has continued although there was an increase in the size of the green crown between 1984 and 1988. However, continued slow growth does not militate against the probable role of aphids in decline because growth of the poorer crops is still limited by poor nutrition. In Corsican pine (*Pinus nigra var. maritima* (Ait.) Miller (1984) found that almost half of the requirement of N for spring growth is met from reserves within the tree, mainly from stores in the foliage. Defoliation therefore removes reserves of mineral nutrients required for growth. Miller showed that when the supply of nutrients from the soil is inadequate the tree uses up its reserves and this leads to reduced growth and the accelerated senescence of older leaves. The unexplained dying of leaves described in Chapter 1 may be partly attributable to this cause.

The association between decline and K deficiency is comparable to that described for sugar maple (*Acer saccharum* Marsh) in Quebec by Bernier and Brazeau (1988). There had been heavy past defoliation by insects, as with Sitka spruce in South Wales, and the authors cite reports showing that K-deficient trees are generally less resistant to pathogens, pests and frost, and have poorer root development than trees of higher nutrient status. In addition to mineral nutrients, shoot growth in the spring requires carbohydrates that are translocated from reserves in other parts of the tree (Kozłowski and Winget, 1964). In Douglas fir, the decline in growth that results from heavy and repeated defoliation by the Tussock moth has partly been explained in terms of the depletion of the carbohydrate reserves for shoot and leaf growth (Webb, 1981). The role of depleted carbohydrate reserves in Sitka spruce decline has not been investigated.

To conclude, the crops described showed a wide range of growth rate, with yield class ranging from 4 to 14. Growth was correlated with foliar concentrations of certain elements, especially N and K, although K levels were above those usually associated with deficiency in younger trees. The importance of nutrition has now been confirmed by a fertiliser experiment (Chapter 6). Although low levels of foliar Mn, especially on some of the poorer sites, confirm results by Briffa *et al.* (Chapter 9), the work described above revealed no certain evidence of Mn deficiency. In the absence of heavy outbreaks of the green spruce aphid during the period of observation, the role of the aphids in triggering decline could not be tested. However, there are indications that decline may well result from repeated defoliation of trees of low nutrient status.

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Chapter 6

The role of nutrition in the decline in Sitka spruce

J.C. Dutch

Introduction

In the past foliage analyses of forests in the South Wales coalfield indicated no general nutrient deficiency (Everard, 1974) and so, as in most of Wales, there has been no tradition of fertilising crops at planting. However, it is commonly observed that the foliage of Sitka spruce in South Wales lacks the blueness characteristic of healthy crops, and nutrient deficiency is now being proposed as one of the factors contributing to the poor growth and decline of plantations on the coalfield.

Fertiliser experiments on the coalfield

Before going on to discuss the experiment, Afan 2/86, set up to test the hypothesis that fertilisers may help to overcome the observed decline, it is worth looking at the existing fertiliser trials in the area.

Establishment fertiliser experiments

Three factorial experiments were established in the early 1970s to examine the response to P and K fertilisers applied at, or soon after, planting. An additional plot of NPK was also included at two of the sites. All three experiments were located on the Carboniferous Pennant Sandstone lithology, two on grass-dominated mineral soils (Rhondda 2 P71 on an ironpan soil and Margam 7 P71 on an intergrade ironpan soil) and one on deep peat types 9b and 9d (Cymer 2 P74).

The experimental treatments at Rhondda and Margam were a factorial combination of P and K at three different rates (0, 50 and 100 kg P ha⁻¹ and 0, 100 and 200 kg K ha⁻¹) with additional plots of NPK at 150 kg N ha⁻¹, 50 kg P ha⁻¹ and

100 kg K ha⁻¹. The NPK plots were retreated with N 7 years after the initial treatments. At Cymer the factorial combination of P and K consisted of only single rates, 50 kg P ha⁻¹ and 100 kg K ha⁻¹. In 1985, when the experiment was retreated using the original rates of fertiliser, an additional treatment of NPK was introduced with N at 300 kg ha⁻¹, P at 100 kg ha⁻¹ and K at 200 kg ha⁻¹.

A 10-year assessment of height at Rhondda revealed no height growth response to fertiliser (N, P or K) and at 15 years when a basal area assessment was carried out, again there was no significant treatment effect. This accords with the foliar analyses results for the control being above the satisfactory level. At Margam, however, although the foliar analyses generally indicated adequate nutrition, there were years where both N and P concentrations dropped to marginal levels, and at this site a modest response to P fertiliser at the highest rate (100 kg P ha⁻¹) was observed in terms of growth in basal area, but not height, when measured at age 15. Earlier assessments of height only had shown no effect of fertiliser. In contrast to the experiments on mineral soils, P fertiliser at Cymer produced a large increase in height growth measured at 12 years over that of the control (+ 30%), with the application of K in combination with P producing an additional response (+ 39% of control). The experiment was top-dressed at 12 years when the high rate NPK treatment was included. The latest assessment 2 years after top-dressing does not indicate that N has produced any additional benefit. Foliar analyses of the control indicate marginal to deficient concentrations of both P and K, with N also being marginal in some years.

Many of the forests in the coalfield occur on freely draining mineral soil (40%, Toleman *et al.*, 1974), e.g. brown earths. Early height growth in

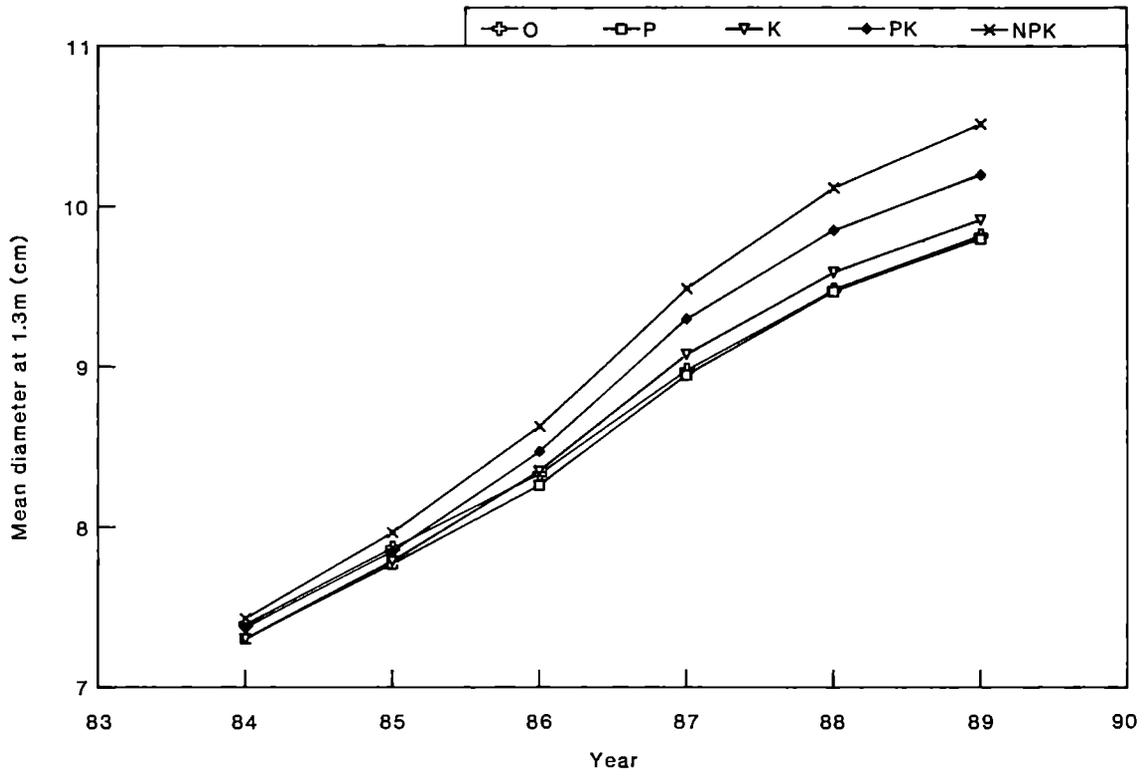


Figure 6.1 Mean diameter at breast height at Tywi 68/85. Treatment applied in summer 1985.

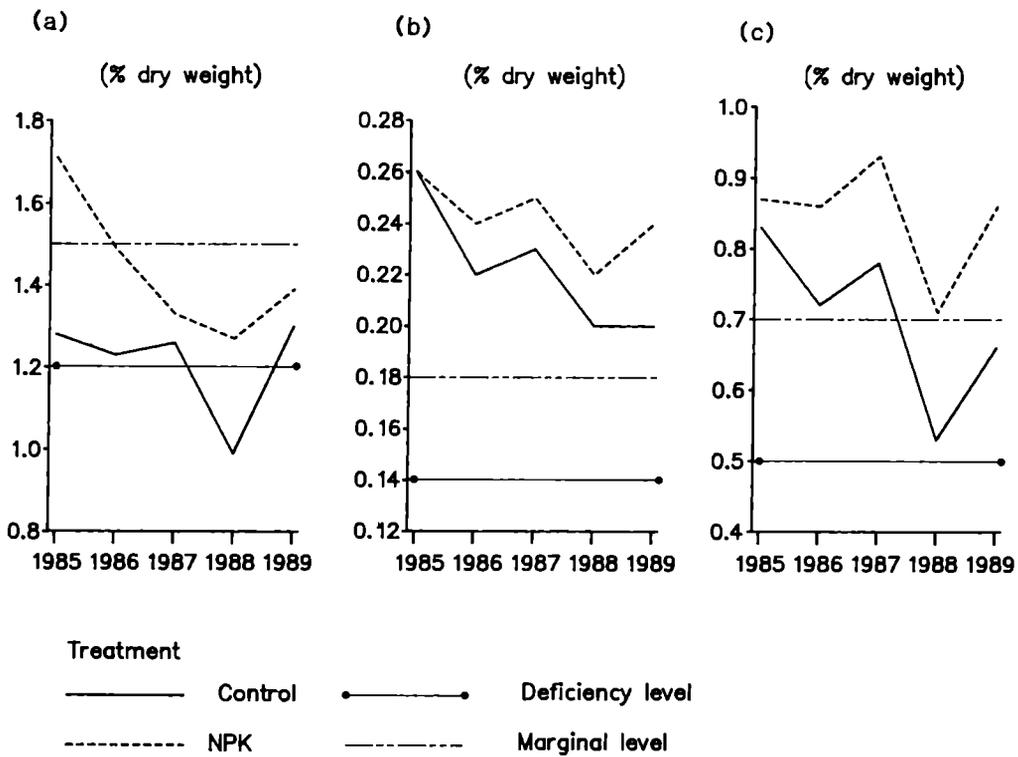


Figure 6.2 Tywi 68/85. Foliar nutrient levels following fertiliser application in 1985: (a) foliar N, (b) foliar P, (c) foliar K.

experiments on establishment indicated that nutrition was not a problem on such sites. However, the very exposed nature of the plateau results in a high incidence of leader breakage. Height data may, therefore, not be a very reliable guide to crop response, a better indicator being basal area growth once the crops are large enough for diameter measurements. Evidence from Margam 7 P71 does indicate that, at least at some sites, growth responses may be hidden when height alone is considered.

The other major soil types on the plateaux are the poorly drained mineral and organo-mineral soils (46%). These are not represented in the establishment experiments, although they may be expected to have a poorer nutritional status than the freely drained mineral soils. Cymer 2 P74 illustrates the infertile nature of the deep peats which occupy 9% of the forests on the plateau.

Decline is, however, a problem of thicket and older stage crops and so experiments designed to assess the effect of fertiliser applied at planting may not be directly applicable to the current study.

Pole stage fertiliser experiments

Evidence about the responsiveness of older crops to fertiliser applications is more difficult to obtain as the reliability of foliar analyses results in predicting response, especially of spruce crops, decreases as the canopy closes. After canopy closure internal nutrient cycling becomes relatively more important than soil supply as a source of nutrition for new growth (Miller, 1981). There are three experiments on the coalfield which examined the response to fertiliser applications in the pole stage. The oldest of these, Ebbw 4/60 planted on a surface-water gley, gave no significant response to applications of N, P or K when applied at year 25. Two more recent experiments gave contrasting results with no response to N or P applications being observed at St Gwynno 7/77, growing on a peaty gley and aged 28 at the time of fertiliser application, but a positive growth response to P being seen at Margam 10/73, a site with an intergrade soil type and a crop aged 42 when the fertiliser was applied.

These results were studied along with data from other pole stage fertiliser experiments by McIntosh (1984); he was unable to find any reliable method to predict which spruce crops

would respond, although there was an indication that response to N was most likely where foliar concentrations dropped below 1.8%. This figure is higher than that used to indicate responsive crops prior to canopy closure (Binns *et al.*, 1980).

To the north of the coalfield area in Wales, an experiment in Tywi Forest, Tywi 68/85, illustrates the responses achieved after application of fertiliser to an early pole stage crop of Sitka spruce planted in 1967 at an elevation of 520 m on deep peat overlying Silurian shale (grid reference SN 820 616). Treatments were applied in 1985 and consisted of a factorial combination of P at 60 kg P ha⁻¹ and K at 100 kg K ha⁻¹. An additional treatment of NPK was included with N being applied at 150 kg N ha⁻¹.

The results from Tywi 68/85 are shown in Table 6.1 and Figure 6.1 in terms of diameter growth and, in terms of foliar nutrient content for the control and the NPK treatment, in Figures 6.2 (a)-(c). These results indicate that while both P and K applications can increase growth at this site, the combination treatment of NPK gave by far the greatest response. This response also continued to be evident for a number of years after the response to the single element applications.

Normally it is thought that once thicket stage is reached, internal nutrient cycling increases in importance and the nutritional demands from the soil reduce (Miller, 1981). However, other factors, such as pollution, aphid attack or *Lophodermium*, may interfere with this internal cycling. If, for example, defoliation is severe, the trees will be unable to mobilise nutrients in older foliage to supply new growth in subsequent years and hence an increased demand will be made on the soil reserves. As the trees have a large area of crown by this stage it is possible that this demand may be greater than before canopy closure. Foliar analysis of the crop in the year of defoliation will give misleading results as available nutrients will be concentrated in the remaining current foliage. Similarly, if pollution or other stress factors were to limit internal cycling or contribute to defoliation, the crop may run into nutritional problems.

The current experiment Afan 2/86 is an attempt to arrest or reverse the decline of Sitka spruce on the coalfield by the addition of nutrients in standard fertilisers and by the addition of lime and a mixture of trace elements.

Table 6.1 Mean diameter (cm) at 1.3 m for experiment Tywi 68/85. Figures in brackets are annual increments (cm)

Treatment	Year					
	1984	1985	1986	1987	1988	1989
0	7.39 (0.48)	7.87 (0.46)	8.33 (0.65)	8.98 (0.50)	9.48 (0.34)	9.82
P	7.30 (0.47)	7.77 (0.49)	8.26 (0.69)	8.95 (0.52)	9.47 (0.33)	9.80
K	7.30 (0.49)	7.79 (0.56)	8.35 (0.73)	9.08 (0.51)	9.59 (0.33)	9.92
PK	7.37 (0.49)	7.85 (0.61)	8.47 (0.83)	9.30 (0.56)	9.85 (0.34)	10.20
NPK	7.43 (0.53)	7.97 (0.66)	8.63 (0.85)	9.49 (0.64)	10.12 (0.40)	10.52
Increment SED	(0.058)	(0.058)	(0.074)	(0.055)	(0.052)	

Site description

The site is located close to Afan 1 (see Chapter 5), on the middle peneplain at the watershed divide of the Rhondda fawr and an Afan Valley tributary, at grid reference SN 904 005. The soil for the main part of the experiment is a deep peat with a *Molinia* vegetation overlying a lithology of Carboniferous sandstones and grits (Pennant). The crop at the site had been planted in 1967 following shallow DMB ploughing, and was showing poor growth similar to classes 4/5 developed for Afan 1. It is thought that no fertiliser had been applied at planting. Elevation was 508–525 m with an average slope on the site of 20° and an annual rainfall of 2200–2500 mm.

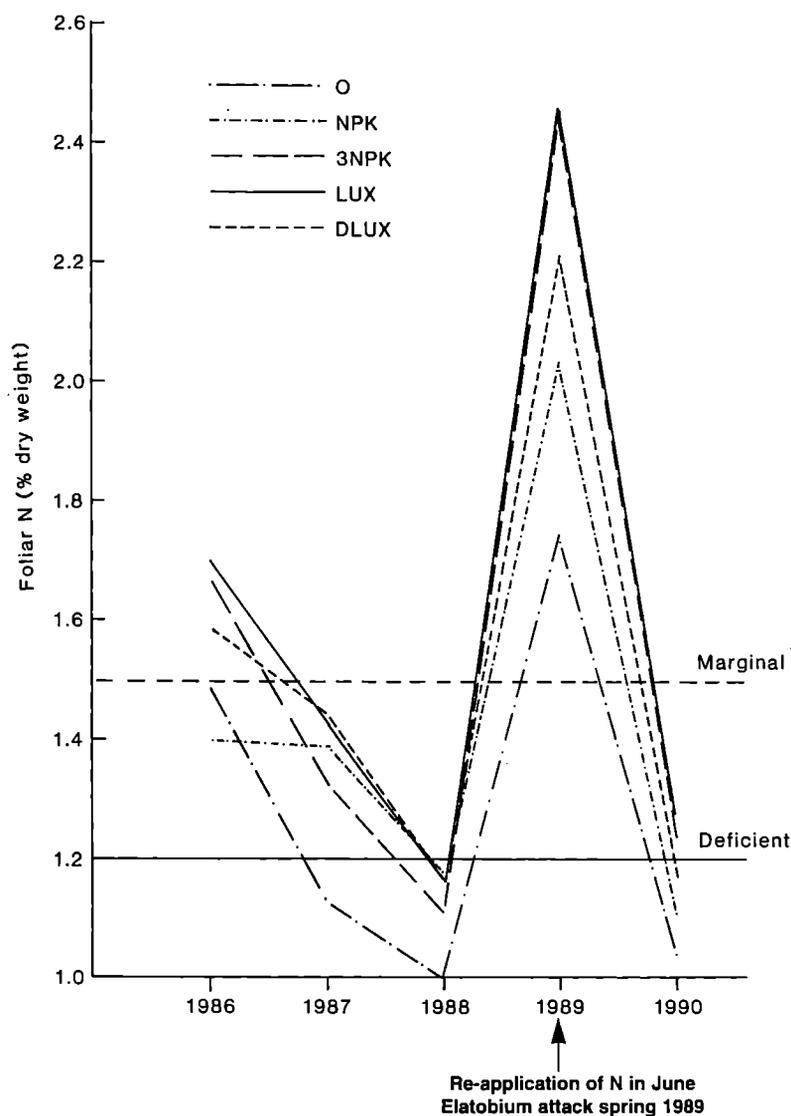
Methods

Five fertiliser treatments were used in a randomised block design with five replicates. Two additional unreplicated blocks were located close by, one in an area of moderate growth on an intergrade ironpan soil (Extension A) and one in an area of poor growth on a peaty gley soil (Extension B). The same treatments were applied to these as to the main experiment. Treatments were as follows:

- 0 – control, no treatment
- NPK – fertiliser at standard rates, i.e. nitrogen at 150 kg N ha⁻¹, phosphorus at 60 kg P ha⁻¹ and potassium at 100 kg K ha⁻¹
- 3NPK – fertiliser applied at three times the standard rates detailed above
- LUX – fertiliser as for 3NPK plus trace elements
- DLUX – inputs as for LUX plus 1000 kg ha⁻¹ magnesium limestone.

Nitrogen was supplied as ammonium nitrate, phosphorus as triple superphosphate and potassium as muriate of potash. The trace elements were applied as 25 kg ha⁻¹ FRIT, an SAI horticultural product '253A' which supplies a mix of trace elements.

Plots of 0.05 ha (0.01 ha in extension A) were brashed to shoulder height in May 1986 to allow access for the manual application of fertiliser treatments. Assessment plots of 0.02 ha (0.04 ha in extension A) were established within these treatment plots. Fertiliser treatments were applied during the summer of 1986, with a further top-dressing of N in June 1989 at the original rates.



(a)

Figure 6.3 Foliar nutrient levels at Afan 2/86. Treatments applied during summer 1986 with a further N top-dressing during summer 1989: (a) foliar N, (b) foliar P, (c) foliar K.

The crops were assessed annually for mean diameter (measured at 0.5 m height) and height. Foliar samples were taken annually in the autumn and analysed for N, P and K content. Total N was determined by the indo-phenol method, P by the phosphomolybdenum method and K by inductively coupled plasma (OCP) spectrometry, after a Kjeldahl digestion of the plant material. Analysis of variance was used for statistical analysis of the data sets.

Results

Foliar analyses

Foliar analyses for the control plot at the end of 1986 showed levels of P and K which are

considered to be satisfactory for young crops, although some of the values for N were in the marginal category (Figures 6.3 (a)-(c)). There was no significant difference between the control and the fertilised plots for any of the nutrients. These levels indicate that only a small response, if any, should be obtained to fertiliser application. However, foliar levels in the control plots decreased during the next 2 years to below the deficiency threshold for N and into marginal levels for P and K. This decrease in nutrient content of the foliage also occurred in the fertilised plots but to a smaller extent than in the control. A similar trend of decreasing foliar nutrient levels over this period was also observed in the Tywi 68/85 data set. The concentrations of all the major nutrients (N, P, K) in

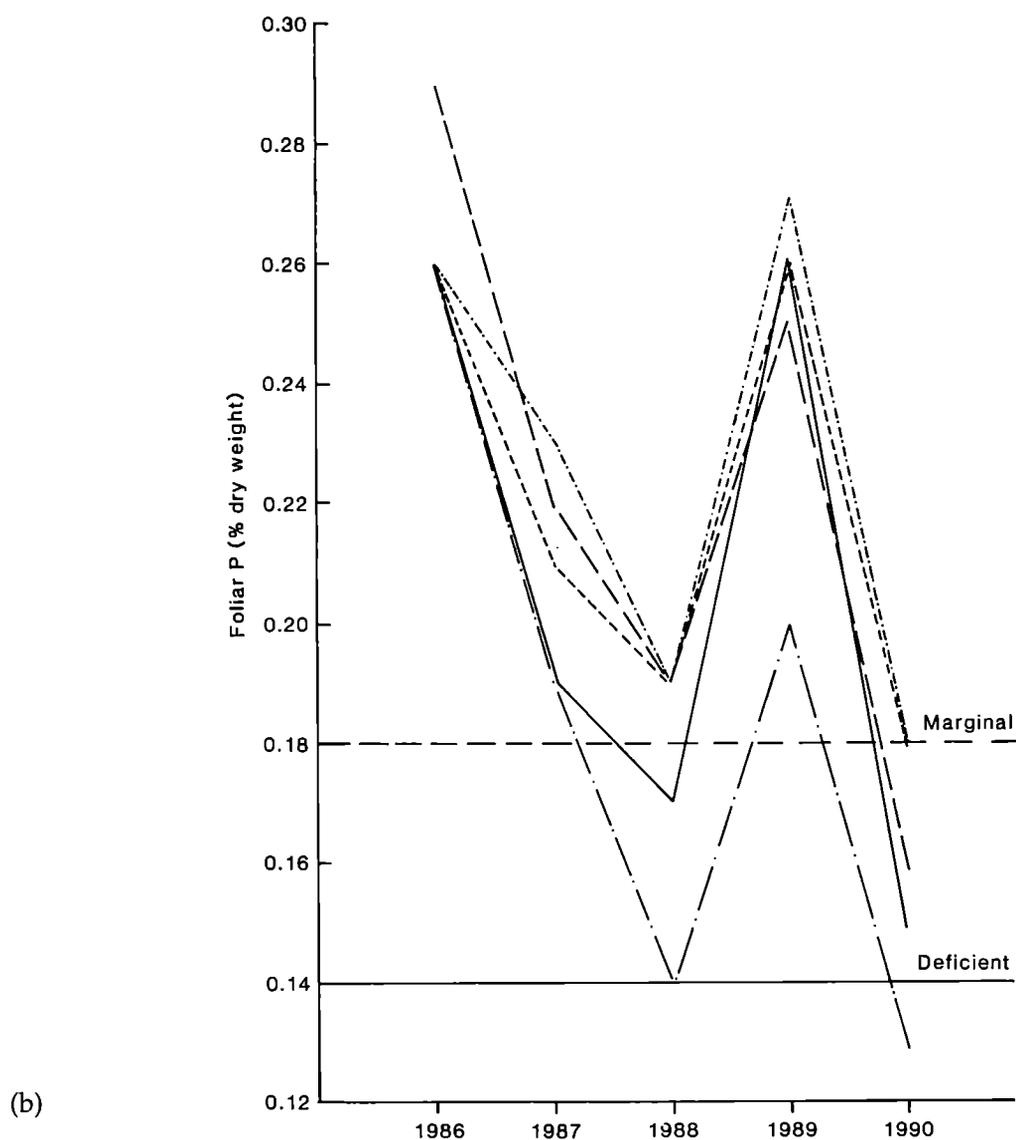
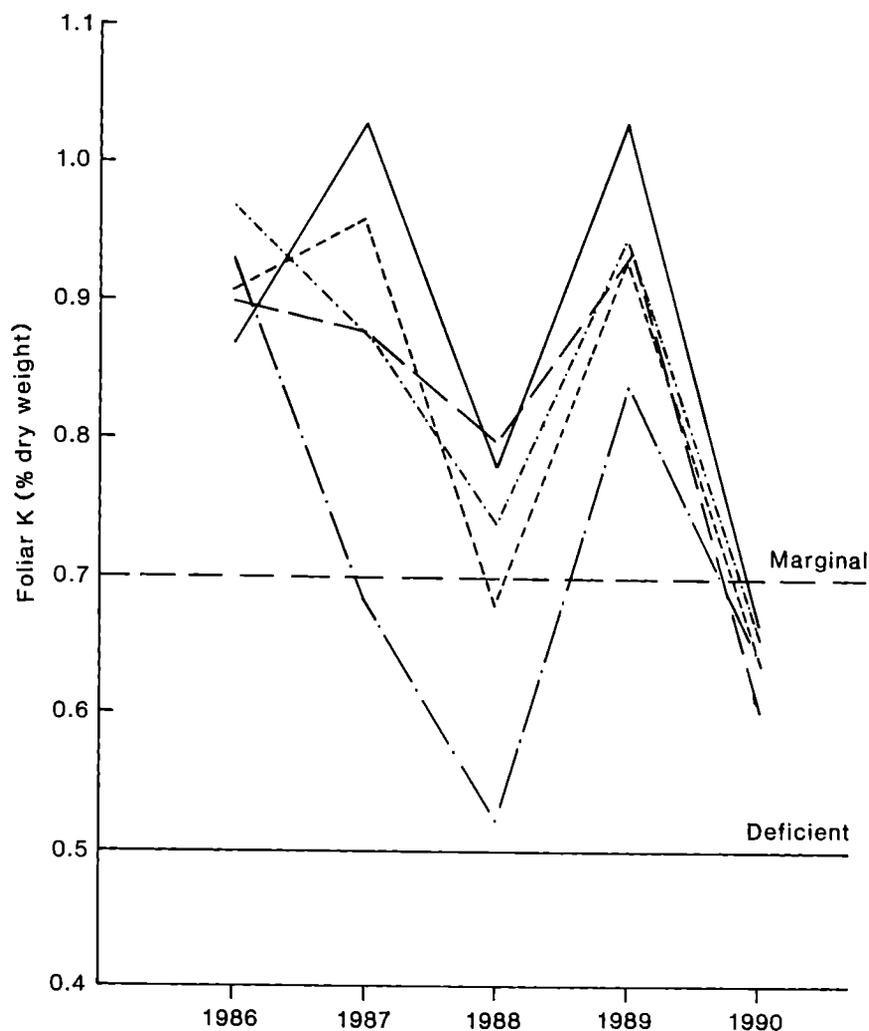


Figure 6.3 continued.

the fertilised plots were significantly greater than in the control plots (with the exception of foliar K levels in 1990); however, there were no major differences between the plots which had received fertiliser. The sudden increase in foliar nutrient content in 1989 was probably caused by an attack of *Elatobium abietinum* Walker which was estimated as having caused 70-80% needle loss across all treatments during the spring to early summer of 1989 (S. A. Mead, personal communication). This would have obscured any response to the 1989 top-dressing of N. In 1990 foliar levels of all nutrients then dropped to, or below, the level observed before the *Elatobium* defoliation in 1989.

Diameter and height

Figures 6.4 and 6.5 show the diameter and height data respectively for the main experiment. These all indicate a positive growth response to fertiliser application. For example, in 1990 standard NPK increased diameter increment from 0.06 to 0.18 cm, i.e. a threefold increase (Table 6.2). The increment in the treated plots is up to 450% and 204% that of the control plots increment for diameter and height respectively. At Tywi, for comparison, the treated plots had, at maximum, an increment 143% that of the control. When considering the Afan and Tywi data sets it must be remembered that the



(c)

Figure 6.3 continued.

diameter measurements were taken at 0.5 m above ground level at Afan but at the standard 1.3 m above ground level at Tywi and so, although at first it appears that the crops at the two sites are of a similar size, the crop at Tywi is, in fact, larger (mean height aged 19 at Tywi was 4.9 m as opposed to 3.9 m at Afan). At Tywi fertilised plots started to display a similar growth pattern to the unfertilised control 2 to 3 years after application, indicating that the fertiliser response was completed within this time. At Afan the fertilised plots were still diverging in growth pattern from the control up to 3 years after application, when the treatment plots received a further N input.

Statistical analyses of the most recent diameter data (1990) showed a significant ($p < 0.01$) increase in the plots which had received fertiliser

compared with the control. No significant differences were found between the fertilised plots. Analyses of the diameter increment between 1985 and 1990 similarly revealed a significant ($p < 0.001$) increase in the increment of the fertilised plots compared to the control but no differences between fertiliser treatments.

Lack of replication of the additional blocks on other soil types means that no statistical analyses can be carried out on the data. However, a similar trend to that observed in the main experiment occurred in both cases.

The height data set is not as complete as that for diameter, lacking the initial 1985 and the most recent 1990 data, but the available data (Figure 6.5, Table 6.3) confirm the pattern observed for diameter.

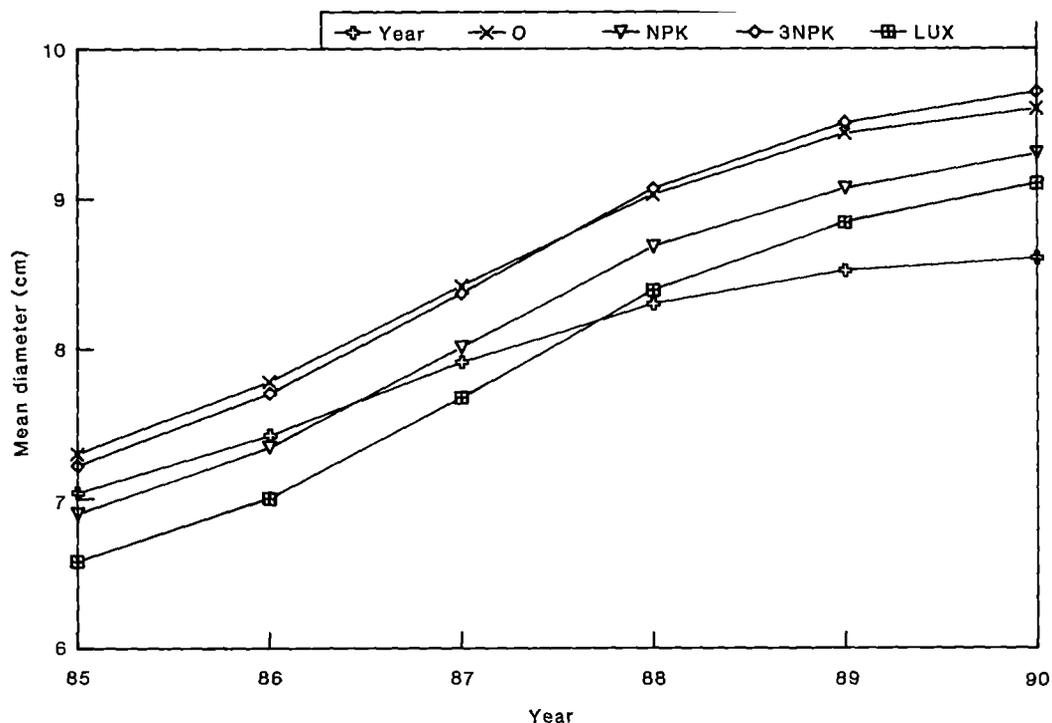


Figure 6.4 Mean diameter (measured at 0.5 m) at Afan 2/86. Treatments applied during the summer 1986, with a further N application during summer 1989.

Table 6.2 Mean diameter (cm) at 0.5 m for the main experiment, Afan 2/86, in which fertilisers were applied in summer 1986 (with additional N in summer 1989). Figures in brackets are annual increments (cm)

Treatment	Year					
	1985	1986	1987	1988	1989	1990
0	7.04	7.42 (0.38)	7.91 (0.49)	8.30 (0.39)	8.52 (0.22)	8.58 (0.06)
NPK	7.30	7.78 (0.48)	8.42 (0.64)	9.03 (0.61)	9.44 (0.41)	9.62 (0.18)
3NPK	6.90	7.34 (0.44)	8.01 (0.67)	8.68 (0.67)	9.07 (0.39)	9.34 (0.27)
LUX	7.22	7.70 (0.48)	8.37 (0.67)	9.07 (0.70)	9.51 (0.43)	9.72 (0.21)
DLUX	6.58	7.00 (0.42)	7.67 (0.67)	8.39 (0.72)	8.84 (0.45)	9.08 (0.24)
Increment SED		(0.040)	(0.065)	(0.070)	(0.045)	(0.052)

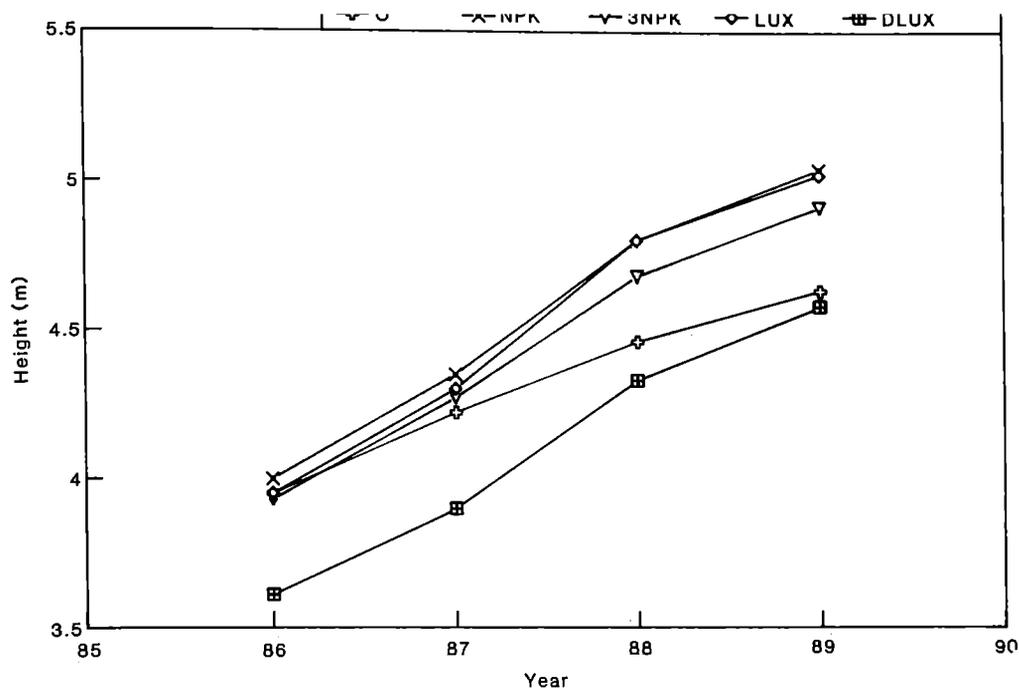


Figure 6.5 Mean height at Afan 2/86. Treatments applied during the summer of 1986, with a further N application during summer 1989.

Table 6.3 Mean height (m) for the main experiment at Afan 2/86. Figures in brackets are annual increments (m)

Treatment	Year				
	1985	1986	1987	1988	1989
0	–	3.95	4.22 (0.27)	4.46 (0.24)	4.63 (0.17)
NPK	–	4.00	4.35 (0.35)	4.80 (0.44)	5.04 (0.25)
3NPK	–	3.93	4.27 (0.34)	4.68 (0.41)	4.91 (0.22)
LUX	–	3.96	4.31 (0.35)	4.80 (0.49)	5.01 (0.21)
DLUX	–	3.61	3.90 (0.29)	4.33 (0.44)	4.58 (0.25)
Increment SED			(0.020)	(0.041)	(0.030)

Discussion and Conclusion

The results from this experiment clearly show that nutrition can be a limiting factor for growth on at least some site types in the coalfield. The relative importance at Afan of the three main nutrients, N, P and K, cannot be examined using the existing experiment and is currently being investigated in a new study. However, the results from Tywi, although on a different lithology, indicate that N may be necessary to obtain the maximum response. At Afan, although the growth response achieved with fertiliser was large when considered in terms of growth of the control trees, the response is difficult to evaluate in economic terms. This is due to two factors. Firstly, the measurements made on the crop were non-standard mensuration measurements due to the small size of the trees at the start of the experiment; secondly, the longer term growth patterns of both the fertilised and non-fertilised trees remain unknown.

It seems unlikely from the Afan results that any trace elements are involved in the decline as no significant growth differences were observed between the trees receiving only standard fertiliser and those receiving lime and trace elements in addition. However, no analyses have been carried out on the trace element concentrations of the trees in the experiment. The high organic content of the soil and the addition of lime with the trace elements may have resulted in the trace elements being relatively unavailable to the trees (Mengel and Kirkby, 1978) and so the possibility remains that trace element deficiencies may be a contributory factor.

Again, it seems unlikely that above standard rates of fertiliser will give increased benefit as the plots receiving three times standard rates were not significantly different from those receiving standard rates. It is, however, not yet known how long the response from the different rates will last.

It is as well to point out at this stage that the crop in the main experiment at Afan 2 may not be representative of the majority of forest crops on the coalfield, being planted on deep peat (deep peat occupies around 9% of the coalfield forest: Toleman *et al.*, 1974). However, the similar trends observed in the extensions indicate that responses can be obtained on other soil types such as the peaty gleys and ironpan soils.

The question then remains as to why initial experimentation has resulted in the recommendation that no fertiliser be applied to coalfield crops, and why these crops were not immediately recognised as being nutrient deficient. A study undertaken by Everard in the early 1970s of the foliage nutrient content of trees growing on freely drained soils of the coalfield indicated that there were few areas where nutrient levels were deficient. A significant proportion (24%) did, however, show marginal nutrient contents (Mayhead *et al.*, 1974). Early results from past experiments on establishment nutrition of freely drained mineral soils in South Wales, referred to above, indicated no growth response. However, later results have shown that a diameter response may be obtained even where no height response has been observed. This is probably largely due to the high incidence of leader breakage on the exposed plateau masking treatment effects in the early years.

Poorly drained soils, gleys and peats occupy 55% of the area of the coalfield (Toleman *et al.*, 1974). Visual indications of P deficiency in Sitka spruce, supported by foliar analysis, were reported in the early 1970s on the poorly drained peaty gleys and peats of the coalfield with both N and K deficiencies also occasionally occurring (Broad and Brown, 1971, 1972). The results from Cymer 2 confirm that foliar concentrations of both P and K can be deficient in crops growing on deep peat sites.

In his Booklet on fertiliser use in coniferous crops in Wales and Southern England, Everard (1974) recommended that no fertiliser should be applied at planting to crops in Wales growing on purely mineral soils or to those on organo-mineral soils overlying Carboniferous lithologies, except where heathery vegetation was common or where the lithology was Millstone grit. Certain deep peat types were also included in the areas recommended for fertiliser applications but Everard considered that this was not required on the *Molinia/Deschampsia flexuosa* dominated deep peats of South Wales. Peats requiring fertiliser occurred mainly in Mid and North Wales. No specific recommendations were given for crops on upland soil types overlying the Pennant Sandstone lithology which dominates the plateau, although they had in the past been reported as being nutritionally poor (Legard and Harris, 1964) and in some areas nutritional problems had been suspected as long ago as 1966 (Crampton, 1966).

Annual foliar analyses of unfertilised crops in Afan 1 and Afan 2 show average values often in the marginal category for N and P. Everard also found a significant proportion of his sites to be marginally nutrient deficient. These observations, together with the questionable nutritional value of soils derived from the Pennant Sandstone lithology, give the general picture of crops suffering from mild nutrient stress, a factor which must increase their susceptibility to other stresses. Such mild nutrient stress may not produce obvious symptoms of deficiency, and so would not be immediately picked up on a visual inspection. It must also be remembered that the foliar nutrient concentration which indicates responsive crops appears to increase in older crops (McIntosh, 1984). The most obvious additional stress factor which may interact with nutrition is attack by *Elatobium abietinum* Walker which results in large scale defoliation (Carter, 1992, Chapter 10).

Elatobium is common in this area, perhaps partly because of low fatalities in the mild winters of the region (Carter, 1972). Attack not only makes interpretation of foliar analyses in the year of attack difficult, as seen in the 1989 data for the current experiment, but must also increase the demands on the soil in subsequent years as internal cycling of nutrients is severely restricted. Thus, in the year of attack, nutrient demand may be increased while foliar analyses will not indicate the need for fertiliser inputs. In addition, in areas of moderately high rainfall such as on the plateau, defoliation may result in the rewetting of sites, particularly deep peat sites, and the possible subsequent death of fine roots. For these reasons it is therefore suggested that, where mild nutritional stress is already present before attack, anything which results in severe defoliation may disrupt the normal internal cycling of nutrients to such an extent that decline results for a number of years after the attack. It will be interesting to see if the fertilised plots in Afan 2 are better able to recover from the 1989 aphid attack.

Defoliation can also be seen on crops suffering from *Lophodermium* infection (Smith and Magan, Chapter 11). However, it has been suggested that *Lophodermium* only affects needles already weakened and in the process of being cast, possibly due to K deficiency or waterlogging.

In conclusion, Afan 2 has demonstrated that nutrient stress is an important factor in at least

some of the coalfield forests. In such cases decline can be partly overcome by the application of standard rates of N, P and K fertiliser. Further work is required to determine which of these three fertilisers is the most important, and to characterise the interaction of *Elatobium* and nutritional status.

Acknowledgements

I would like to thank all those who have contributed to the work described. In particular, I would like to record the work done by the Silviculture (North) outstation staff, especially Neville Danby, Simon Mead, Stan Corcoran, Chris Jones and Nigel Hayworth, who between them have been responsible for establishing, maintaining and assessing the experiments. I would also like to acknowledge the contribution of previous project leaders, Charlie Taylor and John Everard, for initiating the nutritional experiments. Thanks are also due to the laboratory staff at Alice Holt Research Station, particularly Ernest Ward, for the chemical analyses of foliar samples.

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Chapter 7

Afan peat: nutrient content and nitrogen mineralisation

B.L. Williams

Introduction

The nutrient content of deep peat (greater than 0.45 m depth) correlates well with the topography of the peatland and the vegetation (Pyatt *et al.*, 1979). As these factors reflect nutrient supply to the bog and to the vegetation, they have been used as a basis for a site classification system for afforestation of peatland (Toleman, 1973). It follows that the total contents of nitrogen (N), phosphorus (P) and potassium (K) are greater in mesotrophic than oligotrophic peats. However, as N and P are present almost entirely in organic substances, their availability for plant uptake depends on the activities of microorganisms. Consequently, measures of readily mineralised forms of nitrogen in soils can be obtained by incubating samples in the absence of plants. Although such incubation experiments do not provide values for actual rates of mineralisation in the field, they can be used for comparisons of potentially available N in soils.

Total contents of the inorganic nutrients, K, calcium (Ca) and magnesium (Mg) also reflect trophic conditions in peatland and the nature of the minerals in the underlying horizons and rocks (Pyatt *et al.*, 1979). The monovalent elements K and Na are present in peat almost entirely as exchangeable cations whereas only approximately half of the total contents of Ca and Mg are exchangeable (Gore and Allen, 1956). Consequently, the total contents of these elements in peat can be used as a guide to their availability for plants.

In this chapter, the nutrient contents of the deep and shallow peats in Afan 1 are reported together with measurements of the mineral and

readily mineralised nitrogen. The results are discussed in relation to the peat type and the condition of the tree crop.

Materials and Methods

Peat cores were taken from 18 locations beneath Sitka spruce at Afan 1 and the horizon at 5 to 10 cm depth was sampled after removal of the LFH material. Cores were transported to the laboratory inside sealed plastic pots and stored at 4°C prior to analysis. At each location, the peat and soil profile had been characterised and samples were grouped into three types, deep peat, peaty gley and peaty ironpan soil (Chapter 3). In the peaty gley and peaty ironpan soils, the peat depth was less than 0.45 m.

Moisture contents were determined by drying subsamples to constant weight at 70°C. Dried samples were ground in a ball-mill and ash content measured after ignition overnight at 500°C in an electric muffle. For total elemental analysis, a dried ground sample (150 mg) was digested with a mixture of concentrated H₂SO₄ containing 0.1% (w/v) selenium (Se) and 30% (v/v) hydrogen peroxide (H₂O₂) (Wall *et al.*, 1975). N and P in the digests were measured as ammonium and phosphate using colorimetric methods (Crooke and Simpson, 1971; Murphy and Riley, 1962) and Ca, Mg, K and Na using spectrochemical methods.

To extract mineral N from fresh and incubated samples, 10 g portions were shaken overnight with 50 ml 0.01M CaCl₂ and the suspension filtered through Whatman No. 42 paper. Filter and sample were then shaken for 2 hours with 1M KCl to extract exchangeable ammonium. Ammonium in CaCl₂ and KCl extracts was analysed colorimetrically (Crooke and Simpson, 1971) and nitrate in CaCl₂ extracts determined as

NO₂ after reduction on a copperised cadmium column (Henriksen and Selmer-Olsen, 1970).

Readily mineralised N in the peat was measured by incubating samples (10 g fresh peat) at 30°C for 30 days under waterlogged conditions obtained by adding 20 ml distilled water to the sample in a 30 ml glass bottle which was tightly stoppered. At the end of the incubation period, the suspensions were mixed with an equal volume of 2M KCl, shaken, extracted and extracts analysed for ammonium as before. Acidity of the samples was measured by recording pH in the CaCl₂-peat suspension after overnight shaking.

Results and Discussion

All three groups of peat contained more mineral material (Table 7.1) than most flushed mesotrophic types, but pH was at the low end of the range for those types (Pyatt *et al.*, 1979).

Afforestation with lodgepole pine increases peat acidity relative to unplanted areas and it is probable that Sitka spruce has a similar effect. However, it is unusual that the appreciable mineral content of the peat did not maintain greater pH values as at other sites (Williams, 1984).

Total contents of N and P in the peat (Table 7.2) were comparable with values for flushed mesotrophic blanket bogs (Pyatt *et al.*, 1979). K was present in concentrations greater than those obtained for mesotrophic peat even though it seems that no applications of P and K fertilisers were made at planting to raise the concentrations of these elements and of the mineral component in the peat (Chapter 6).

The amounts of mineral N in the fresh peat were similar in all three types (Table 7.3), but the presence of nitrate was unexpected in view of the acidic nature of the peat. Nitrate content and pH

Table 7.1 Mean moisture, ash contents and pH of three peaty soil types taken from 18 locations at Afan 1

Peat type	Moisture content (kg H ₂ O kg ⁻¹ dry matter)	Ash content (% dry matter)	pH (CaCl ₂)
Deep peat (4) ^a	4.9 (± 0.39) ^b	18.2 (± 3.92)	3.01 (± 0.05)
Peaty gley (9)	4.2 (± 0.53)	16.9 (± 3.62)	3.10 (± 0.06)
Peaty ironpan (5)	2.9 (± 0.48)	27.3 (± 5.10)	2.86 (± 0.04)

^a Number of samples of each type.

^b Standard error of the mean.

Table 7.2 Mean total concentration (g kg⁻¹ dry matter) of N, P and K in the three peaty soils at Afan 1

Peat type	N	P	K
Deep peat (4) ^a	22.2 (± 1.8) ^b	1.5 (± 0.25)	1.0 (± 0.21)
Peaty gley (9)	21.9 (± 1.5)	1.2 (± 0.12)	1.4 (± 0.50)
Peaty ironpan (5)	18.5 (± 2.1)	0.9 (± 0.08)	0.9 (± 0.27)

^a Number of samples of each type.

^b Standard error of the mean.

Table 7.3 Mean concentrations (mg kg⁻¹ dry matter) of NH₄⁺, NO₃⁻, mineral N (NH₄⁺ + NO₃⁻) in fresh samples and readily mineralised N in peat incubated for 30 days at 30°C under waterlogged conditions for three peaty soils at Afan 1

Peat type	NH ₄ ⁺	NO ₃ ⁻	Mineral N	Readily mineralised N
Deep peat (4) ^a	20 (± 1.7) ^b	25 (± 3.0)	45 (± 2.6)	321 (± 25.4)
Peaty gley (9)	21 (± 2.9)	24 (± 2.4)	46 (± 3.1)	334 (± 25.2)
Peaty ironpan (5)	24 (± 2.7)	13 (± 3.2)	37 (± 2.7)	237 (± 14.2)

^a Number of samples of each type.

^b Standard error of the mean.

were significantly ($p < 0.01$) correlated with a correlation coefficient of $r = 0.71$. In a comparison of samples from different unplanted peatland types (Williams, 1984) only blanket bog peat with a mineral content greater than 23% produced nitrate. While the Afan samples had ash contents in the range 4.7 to 36.0%, equivalent pH values in water were mainly in the range 3.4 to 4.0. It is possible that nitrification was active in these peaty soils prior to afforestation and that pH was slowly depressed as the tree crop became established enabling nitrifying bacteria to adapt to the more acid conditions.

An alternative explanation for the presence of nitrate is that the nitrate content of the peat which is approximately equal to 2 kg N ha⁻¹ (assuming 150 g dry matter l⁻¹) has been derived from atmospheric inputs. Clearly, some additional measurements of nitrate production during aerobic incubation would establish whether nitrification is active in the peat or not.

Mineral N production during waterlogged incubation was less in the peaty ironpan soil than in the peaty gley and deep peat (Table 7.3). The concentration of readily mineralised N was significantly ($p < 0.01$) correlated ($r = 0.67$) with pH and was equivalent to between 20 and 30 kg N ha⁻¹ in the 5 to 10 cm horizon. These values are comparable to those obtained with samples of unplanted, unflushed blanket bog peat from the Lon Mor, Inchnacardoch Forest, Inverness-shire (Williams and Wheatley, 1988). Compared with samples from a range of peatland types from Polbae in the south-west to Dalharrold in the

north of Scotland (Williams, 1984), the Afan values are closer to those obtained with oligotrophic peats from raised bogs than those from mesotrophic peatland. In a single set of samples taken from beneath lodgepole pine planted on a controlled water-table experiment on the Lon Mor, the drier peat beneath the trees was more acid and contained significantly less readily mineralised N and microbial biomass than unplanted peat from adjacent areas (Williams and Sparling, 1988). Therefore, it may be reasonable to suggest that Sitka spruce has had a similar effect on the acidity and microbial activity in the peaty horizons at Afan.

Contrary to the concentrations of N, P and K, values for Ca and Mg (Table 7.4) were well below those reported previously for unplanted blanket bog peat (Pyatt *et al.*, 1979). Afforestation with lodgepole pine reduces the concentrations of Ca and Mg relative to the unplanted peat (Williams *et al.*, 1978). For Ca, values in planted blanket bog at the Lon Mor and at Naver Forest, Sutherland, were in the range 800 to 1400 mg Ca kg⁻¹ dry matter and included a site that had been planted for 48 years. Evidently, the parent minerals beneath the peat at Afan either contain very small amounts of the base cations Ca and Mg or else these elements have been weathered and leached to a high degree (M.J. Wilson, personal communication). Mg concentrations were smaller by a factor of 2 to 3 compared with other planted peats and Na concentrations which tend to increase in peat beneath trees (Williams *et al.*, 1978) were also small at the Afan site.

Table 7.4 Mean concentrations (mg kg⁻¹ dry matter) of Ca, Mg and Na in the three peaty soil types at Afan 1

Peat type	Ca	Mg	Na
Deep peat (4) ^a	402 (± 61.4) ^b	295 (± 77.1)	260 (± 12.5)
Peaty gley (9)	240 (± 66.7)	243 (± 64.6)	260 (± 30.6)
Peaty ironpan (5)	202 (± 26)	200 (± 19.7)	250 (± 24.2)

^a Number of samples of each type.

^b Standard error of the mean.

Conclusions

The N, P and K concentrations in the peat at Afan were comparable with or higher than those from flushed mesotrophic blanket bog, but mineral and readily mineralised N concentrations were comparable with those found in unplanted unflushed oligotrophic blanket peats. Increased acidity in the peat resulting from tree growth and peat drying may have reduced microbial activity and the rate of N mineralisation to some extent. Ca and Mg concentrations in the Afan peat were much smaller, by factors of 2 to 5, than even those found in unflushed oligotrophic blanket bogs despite relatively high concentrations of mineral matter in the peat. The chemistry and mineralogy of these mineral components of the peat may shed some light on the low base status of this material and possible reasons for poor tree growth.

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11

Chapter 8

The relationship between metal content of the soil solution and tree growth at Afan Forest in South Wales

R.A. Skeffington and A.M. Graham

Introduction

The problems of 'bent top' and reduced growth of Sitka spruce on the carboniferous sandstones of the South Wales coalfield are described in Chapter 1 of this Technical Paper. The investigation described here was conducted in order to determine whether there was a relationship between tree growth on different sites at the experiment at Afan 1 (Chapter 5) and the metal content of the soil solution. The South Wales coalfield area has a long history of metal smelting, and there are still active metal smelting operations locally and at Avonmouth across the Bristol Channel.

As a first hypothesis, it was conceivable that some symptoms of the bent top syndrome could be related to concentrations of heavy metals in the soil solution derived from atmospheric deposition or even possibly from metalliferous substrata. A second possibility was that bent top was related to deficiencies or imbalances in the supply of major nutrient elements from the soil solution. Ulrich (1983) had recently hypothesised that aluminium concentrations in the soil solution of some German forests had reached toxic values, or alternatively that the aluminium:calcium (Al:Ca) ratio had declined below a value critical for the survival of fine roots (Rost-Siebert, 1983), usually taken to be about a molar ratio of 1. The concentration of Al or the Al:Ca ratio in the soil solution may therefore be a third possible cause of the observed decline. The presence of patches of forest in the same general area with widely differing rates of growth and expression of bent top syndrome enabled these three hypotheses to be tested. If heavy metal concentrations, nutrient elements or Al or Al:Ca in the soil

solution were major factors causing growth reductions at the Afan 1 site, there should be a negative correlation between the respective concentrations in the soil solution and growth rates. As a measure of available elements the Equilibrium Soil Solution (ESS) was used as a link to work in Europe (Ulrich *et al.*, 1980).

Methods

Forestry Commission staff took representative samples of soil from Sites 1 to 16, 19 and 20 at experiment Afan 1 (Coutts *et al.*, Chapter 5) in early 1986. Each sample consisted of four bulked sub-samples from below the LF Horizon. The samples were stored at 4°C until analysis was carried out.

In order to make the ESS as described by Ulrich *et al.* (1980), the water content of each soil sample was calculated by drying an aliquot at 105°C, and the sample made up with distilled water to 90% water content by weight. The sample was allowed to equilibrate for 24 h, and part of it filtered under vacuum and the filtrate collected. The pH of this solution was measured immediately, and the remainder of the filtrate stored at 4°C before elemental analysis by Inductively-Coupled Plasma Emission Spectroscopy (ICP).

In order to generate the solutions for the *Agrostis tenuis* Sibth. (*A. capillaris* L.) toxicity test (see below), most of the remaining soil was allowed to equilibrate for 72 h at 90% water content, and then filtered as above. When some top-up solutions were required for certain samples later in the experiment (sites 4, 9, 11, 20) the solid residue from this filtration was re-equilibrated

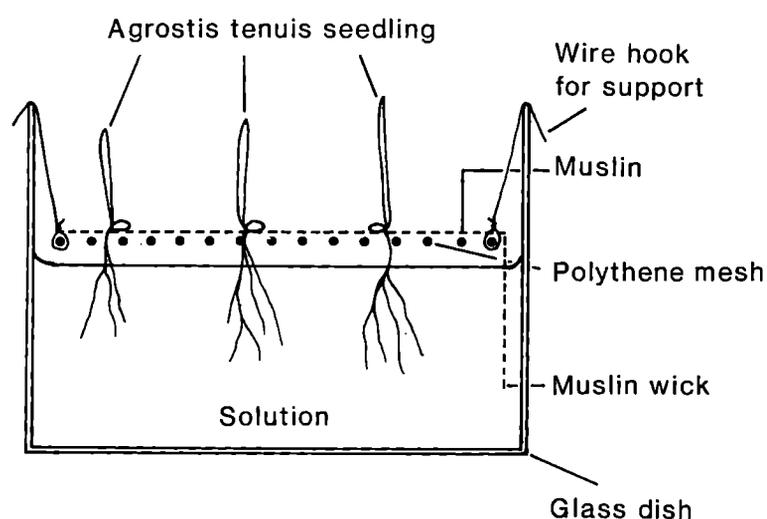


Figure 8.1 Apparatus for toxicity testing using *Agrostis tenuis*.

for 24 h at 90% water content, and the filtrate produced as before.

The remaining part of each soil sample was used to generate a solution for aluminium speciation using the method of Driscoll (1980). A 24 h ESS was produced as above and half was immediately passed through a cation exchange column. Both deionised and non-deionised solutions were analysed by ICP, and the difference between them taken to be a measure of organically complexed aluminium. The procedure was also taken to give a rough indication of the degree of complexation of other elements, although unlike the situation for aluminium no analytical investigations have been made to confirm this.

The *A. tenuis* toxicity test was conducted as follows. On Day 1 (28 January 1986) commercial *A. tenuis* seed (common bent-grass) was germinated on moist filter paper in closed petri dishes. On Day 18, seedlings were carefully transferred onto the moist muslin of the experimental pots (Figure 8.1). The roots subsequently grew through the muslin into the solution below. Initially this was a modified Hoagland's solution (Table 8.1). The pots were kept on the laboratory bench inside a perspex chamber. On Day 37 the solutions in the pots were exchanged for ESSs (see above). There was one pot containing five plants for each soil solution, plus distilled water control. The pots were then transferred to a Heraeus-Votsch growth cabinet and incubated with a regime of 16 hour light at $495 \mu\text{mol photons m}^{-2}\text{s}^{-1}$, 18.1°C

Table 8.1 Composition of nutrient solution used for *Agrostis tenuis* toxicity tests

Salt added	Concentration (mg l^{-1})
$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	184
KNO_3	202
$\text{Ca}(\text{NO}_3)_2$	472
Na_2HPO_4	95
Fe citrate	33.5
Na_2MnO_4	0.078
$\text{MnSO}_4 \cdot 5\text{H}_2\text{O}$	0.115
$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$	0.125
$\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$	0.072
$\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$	0.028
$\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$	0.144

and 95% relative humidity and 8 hour dark at 10.1°C and 95% relative humidity. Pots were topped up daily with distilled water to replace evaporation. Total root length, number of roots and length of longest root were recorded on the date of transfer (Day 37), Day 45, and Day 57 when roots were excised and the experiment terminated. All statistical calculations were performed using the SAS package Version 3.1. The STEPWISE procedure with MAXR option was used for the analysis reported in Table 8.5. This selects the best combination of 1, 2, 3 . . . variables which predict the independent variable.

Table 8.2 Element concentrations in mg l^{-1} in equilibrium soil solutions for each site, and some site data

Site number	Elevation (m)	Soil type	Height increment (cm)	pH	Al	As	B	Ca	Cd	Cu	Fe	K
1	470	PG	72	3.53	3.260	0.047	0.190	10.70	0	0.033	0.137	5.83
2	460	PG	72	3.47	0.679	0.045	0.332	3.75	0	0.033	0.278	6.46
3	440	PG	55	3.75	0.727	0	0.262	3.04	0	0.034	0.155	3.61
4	515	DP	17	4.49	0.522	0.683	0.864	8.50	0.019	0.053	0.264	10.60
5	500	IPP	74	3.76	0.366	0	0.308	3.16	0	0.032	0.057	30.10
6	500	DP	16	3.51	1.240	0.095	0.272	4.79	0.013	0.042	0.215	6.23
7	500	PG	30	3.86	0.545	0.402	0.341	2.48	0	0.042	0.188	4.67
8	510	IPP	50	3.46	0.546	0.046	0.320	3.06	0	0.029	0.145	31.70
9	520	IPP	21	4.76	0.399	0.286	0.579	7.25	0	0.074	0.349	2.82
10	390	IPP	47	4.63	0.437	0	0.337	1.85	0	0.045	0.253	3.07
11	480	PG	27	4.93	0.473	0	0.229	3.65	0	0.032	1.330	3.51
12	500	IPP	33	4.62	0.340	0.161	0.300	1.74	0	0.040	0.220	3.27
13	490	PG	82	3.67	1.400	0	0.216	2.23	0	0.035	0.144	22.40
14	460	PG	71	3.57	0.833	0	0.184	1.90	0	0.030	0.187	6.80
15	515	DP	21	3.51	3.040	0	0.261	3.23	0.014	0.068	0.241	4.09
16	525	PG	29	3.59	2.760	0.041	0.308	4.67	0.021	0.034	0.138	5.11
19	490	DP	14	3.89	0.467	-	0.469	3.96	-	0.045	0.153	4.21
20	460	PG	19	4.29	0.443	0.143	0.734	2.43	0	0.060	0.365	-

PG = peaty gley, DP = deep peat, IPP = ironpan peat. 0 = below detection limit; - = missing value.

Height increment is for 1985. Ironpan peats are peaty soils where ironpan appears to dominate the water relations of the soil, though sites 6 and 19 also have ironpans.

Table 8.2 continued

Site number	Elevation (m)	Soil type	Height increment (cm)	pH	Mg	Mn	Na	Ni	P	S	Si	Zn
1	470	PG	72	3.53	2	0.047	7.01	0	0.246	3.50	3.090	0.498
2	460	PG	72	3.47	1.550	0.014	10.50	0	0	8.75	1.560	0.855
3	440	PG	55	3.75	1.510	0.022	7.37	0.018	0	2.50	0.983	0.590
4	515	DP	17	4.49	2.190	0.029	18.70	0.019	0.693	11.80	2.050	1.770
5	500	IPP	74	3.76	1.280	0.021	7.83	0	0.288	3.46	2.770	0.781
6	500	DP	16	3.51	3.020	0.041	8.27	0.015	0	4.47	2.550	0.896
7	500	PG	30	3.86	0.988	0.019	8.30	0	0	5.60	2.180	0.777
8	510	IPP	50	3.46	1.070	0.203	8.19	0	0.309	4.27	3.760	0.703
9	520	IPP	21	4.76	0.849	0.017	14.00	0.018	0.332	7.54	1.830	1.070
10	390	IPP	47	4.63	0.202	0.003	6.46	0	0.422	4.71	3.430	0.477
11	480	PG	27	4.93	1.350	0.809	9.62	0.037	0.211	8.68	3.030	0.741
12	500	IPP	33	4.62	0.469	0.004	7.15	0.016	0	4.94	1.400	0.527
13	490	PG	82	3.67	1.210	0.079	7.26	0.016	0	2.12	2.040	0.528
14	460	PG	71	3.57	1.100	0.029	6.68	0	0	3.49	2.890	0.472
15	515	DP	21	3.51	2.280	0.021	9.11	0.028	0	4.11	3.150	0.772
16	525	PG	29	3.59	2.800	0.020	10.40	0.042	0	3.97	2.260	1.150
19	490	DP	14	3.89	2.030	0.212	12.60	0	0.431	9.88	1.880	1.260
20	460	PG	19	4.29	1.110	0.005	16.30	0	0.275	12.30	1.490	1.380

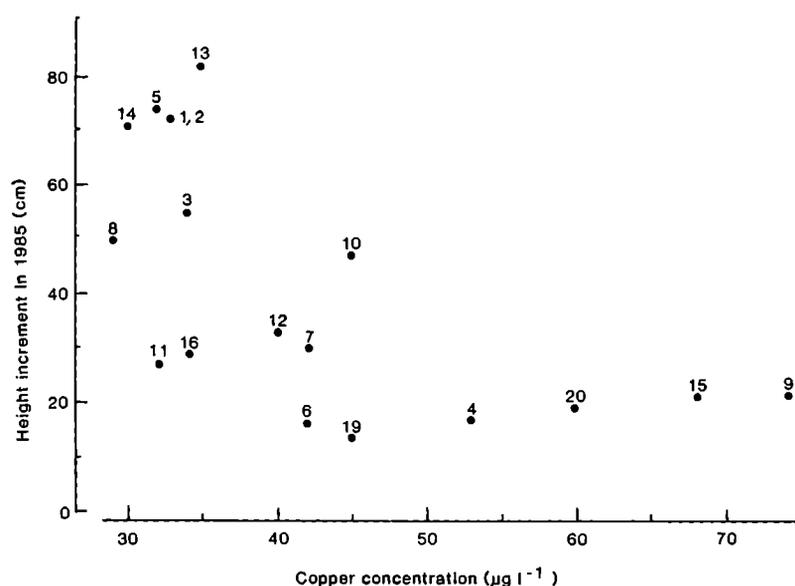


Figure 8.2 Relationship between copper concentration in the ESS and mean height increment of Sitka spruce at the Afan 1 sites. Site numbers are given on the figure.

Soil solution data

The composition of the ESSs for each site is shown in Table 8.2, together with some site data from Pyatt (Chapter 3). The elements cobalt (Co), chromium (Cr), mercury (Hg), molybdenum (Mo), lead (Pb), antimony (Sb), titanium (Ti), and vanadium (V) were also measured but were usually not detectable. It should be noted that the method used is not very reliable for arsenic (As). The wide variation from site to site in most elements is notable. A second extraction (for Al speciation, see Methods) gave very similar results showing that the results of the analysis are consistent. How well the samples represent each site cannot be determined without a wider sampling programme. The soil solutions range from acid to very acid, and there are generally higher than expected concentrations of zinc, and in many cases, major nutrient cations (Bowen, 1979). Detectable concentrations of potentially toxic heavy metals do occur in some samples. As, Cd, Cu, Ni and Zn are all known to be phytotoxic in some situations. Sodium is also high, reflecting high marine deposition at the site.

A second ESS from each site was passed through a cation exchange column to determine the proportion of Al which was positively charged (and therefore assumed to be potentially toxic to tree roots). Positively charged Al remains on the column whereas uncharged Al (assumed to be complexed, probably with organic matter and therefore non-toxic) passes through. Contrary to expectation that most Al would be organically

complexed in these peaty soils, there was a wide variation in the 'complexed' proportion (Table 8.3). There is a clear pattern that sites with the highest total Al (1, 15, 16, 13) have the lowest proportion of complexed Al. There is no obvious relationship to soil type. Other metals of interest are also shown (Table 8.3). There is wide variation between sites in the proportion of Cu and Fe which is complexed in non-ionic form, with a mean around 40% for Fe, 50% for Cu. In contrast, Mn occurs largely in ionic form except for a few sites where there is a small proportion of complexed Mn, and Zn is around 98% ionic. As expected, base cations are exclusively present in ionic form whereas S and B are present as anions or uncharged.

Regression of tree growth on soil solution concentrations

Mean height increment at each site in 1985 was used as the response variable for growth (Table 8.2) and treated as the dependent variable in the calculations below. Coefficients of multiple correlation for simple linear regressions of growth on soil solution concentrations are shown in Table 8.4. Values below detection limit are treated as missing in the analysis. Zn and Cu have the strongest negative relationships with growth, and S, Na and B also have significant negative relationships. Examination of scatter plots (Figure 8.2) shows that growth appears to show a threshold relationship with Cu concentration: growth is low above the threshold and not well correlated with concentration below it. Zn, S and B have patterns similar to those shown in Figure 8.2.

Clearly, growth is influenced by a multitude of factors, and no single variable has an overwhelming influence. Table 8.5 shows the results of a stepwise multiple regression on the variables measured here, to determine the set of variables which gives the best prediction of growth. To provide some measure of consistency, the analyses were performed using both sets of ESSs. For both solutions, Cu was the factor giving the best single-variable model (this differs

from Table 8.4 because SAS program requires 'undetectable' values to be treated as zero). Copper appears as a predictor variable in all sets bar one. Thereafter the two soil solutions differ somewhat, Fe and As being common to both 6-variable sets. The best 5-variable set for soil solution 1 is notable for containing elements which individually have a strong negative correlation with growth, but this is not true for solution 2.

Table 8.3 Percentage of various metals in ESSs which pass a cation exchange column (Amberlite 120, Na form)

Site number	Al	Cu	Fe	Mn	Zn
1	8.6	69	21	1.8	1.5
2	48	41	50	0	1.1
3	22	29	22	0	1.2
4	40	79	70	5.0	3.0
5	64	100	44	12	1.5
6	35	43	10	0	1.1
7	83	59	59	0	1.7
8	53	60	25	1.3	2.3
9	86	79	88	0	1.8
10	67	64	55	0	3.9
11	-	57	6.5	0	1.7
12	84	73	92	0	4.3
13	16	33	16	0	1.4
14	40	80	27	13	2.5
15	7.9	26	8.3	0.9	1.0
16	9.8	27	11	1.9	0.7
19	40	42	42	3.3	1.2
20	56	285	41	18	2.8

- = missing data.

***Agrostis tenuis* bioassay**

The *Agrostis* plants responded to transfer from nutrient solution to soil solutions by producing many, relatively short roots. There was wide variation in root growth both within and between pots. Both total root length increase after transfer, and root length increase relative to the root length at transfer, were used as response

variables. Total root length increase 8 days after transfer is shown in Figure 8.3. Root length increase was less than in the distilled water controls in most cases. Some sites (1, 6, 7, 13-16), produced significantly shorter roots and it is notable that these are by and large the sites with the highest inorganic and total Al concentrations (Tables 8.2 and 8.3). Regression analysis confirmed a significant multiple correlator

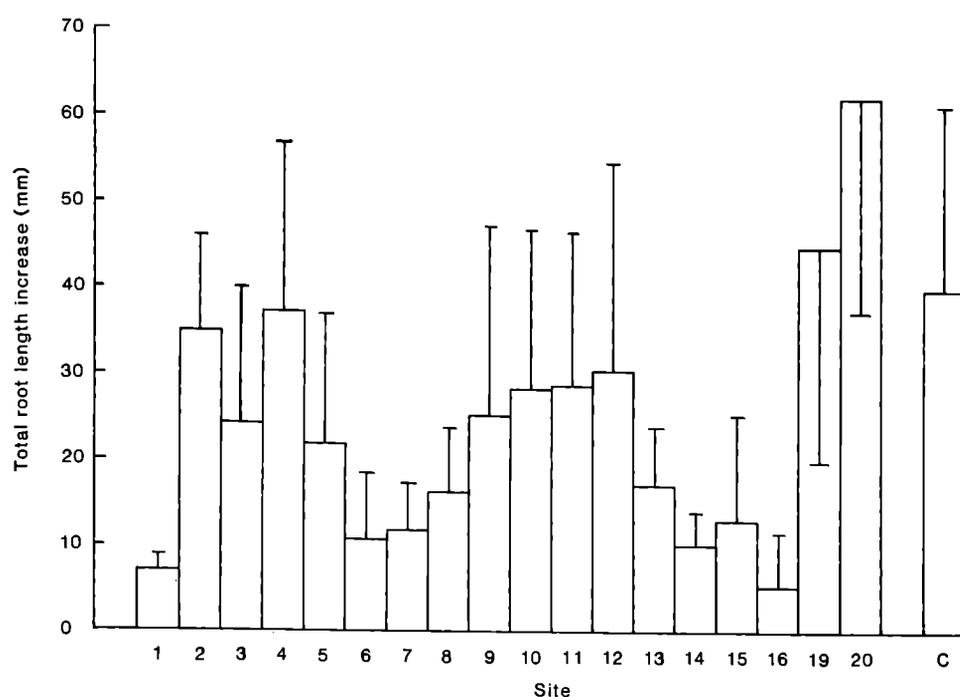


Figure 8.3 Increase in the total root length of *Agrostis tenuis* seedlings after 8 days exposure to ESSs from the various sites. The vertical bar marks one standard deviation ($n=5$). C is a distilled water control.

Table 8.4 Coefficients of multiple correlation (r) from simple linear regressions of growth on soil solution concentration

Independent variable	Sign	r	Independent variable	Sign	r
Al	+	0.100	Cu	-	0.630 ^b
Ca	-	0.109	Zn	-	0.638 ^b
Ca/Al	-	0.365	As	-	0.510
pH	-	0.433	Ni	-	0.237
H+	+	0.425	Fe	-	0.284
Na	-	0.585 ^a	Mn	-	0.154
K	+	0.285	B	-	0.547 ^a
Mg	-	0.288	S	-	0.566 ^a
P	-	0.416	Si	+	0.144

^a $p = 0.05$, ^b $p = 0.01$. 'Sign' is the sign of the regression coefficient: + implies growth increases with value of the independent variable, - implies the opposite.

Table 8.5 Stepwise multiple regression of tree growth on 16 soil solution concentrations

Number of variables	Soil solution 1	r^2	Soil solution 2	r^2
1	Cu	0.41	Cu	0.55
2	pH Cd	0.58	Cu Mg	0.66
3	Cd Cu Fe	0.69	Cu K Mg	0.73
4	Al Cd Cu Fe	0.74	Cu Fe K Mg	0.80
5	B Cu Fe Na Zn	0.81	As Cu Fe K Mg	0.84
6	As B Cu Fe Na Zn	0.83	As Cd Cu Fe K Mg	0.85

Variables: solution 1 = pH Al As B Ca Cd Cu Fe K Mg Mn Na Ni S Si Zn; solution 2 = pH Al As B Ca Cd Cu Fe K Mg Mn Ni Pb S Zn.

coefficient of 0.481* for *Agrostis* growth against inorganic aluminium concentration. Growth versus total aluminium just fails to attain significance at 0.454. There were no other significant regressions out of the set: growth of *Agrostis* against Al:Ca ratio; Zn; Cu; growth of Sitka spruce. If root growth to Day 57 is taken as the independent variable, the pattern is similar but the regressions are less significant. Use of relative growth rate leads to similar conclusions – the same pattern but no significant regressions.

Discussion

This study shows that metal concentrations in the soil solution are not a major factor explaining the problems at Afan 1, at least if the soil samples used can be taken as representative. Statistical analysis shows no evidence that the problems are due to Al toxicity at the tree root,

as suggested by Ulrich *et al.* (1980). There were no correlations between Sitka spruce growth and concentrations of total Al, cationic Al, and Al:Ca ratio. At the same time, inorganic Al concentrations were remarkably high in some samples and root growth in the *A. tenuis* used was apparently inhibited by those samples with the highest concentrations. In general, there was no relationship between root growth in the *A. tenuis* bioassay used and tree growth in the forest: in fact there was an inverse (non-significant) correlation. A positive correlation would be expected if a phytotoxic soil factor was responsible for restricting tree growth. The absence of such a relationship thus suggests that there is no generally toxic soil factor. One limitation of the *Agrostis* bioassay is that Sitka spruce roots are normally ectomycorrhizas, whereas *Agrostis* roots are not (Walker, 1987). This should not invalidate the present analysis, however.

Regression analysis appears to show that growth of Sitka spruce is most closely related to copper concentrations. However, the copper concentrations measured are not high : they are lower than those recommended by Hewitt (1966) in many hydroponic nutrient solutions, even before allowance is made for organic complexation. Zinc appears as a significant correlate of reduced growth in the simple regression analyses, but not conspicuously in the stepwise. Godbold *et al.* (1985) proposed that comparable Zn concentrations might affect Norway spruce growth. In contrast, ESSs from Leith Hill in Surrey (Skeffington, unpublished results) had somewhat higher Zn concentrations in soil beneath trees with no obvious growth or nutritional problems. Concentrations of S, B and Na, the other elements which have an apparent negative relationship with growth, are not high enough to be expected to cause problems (Bowen, 1979). Caution is required in interpreting statistical analysis in a complex, multi-variate situation where many of the variables show strong mutual correlations. Other variables, unconsidered in this analysis, affect growth. Sites differed considerably in planting date, planting method, exposure, water relations and so on. Other measures of growth are also possible and would perhaps give different results. However, the analyses presented here do strongly suggest that the problems at Afan 1 are not a simple question of soil toxicity, and there is little to suggest that toxicity is involved in the syndrome.

Acknowledgements

This work was performed at the Central Electricity Research Laboratories and is published by permission of National Power plc. A.M. Graham was a work experience trainee.

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Chapter 9

A tree-ring-based study of Sitka spruce growth in Afan Forest, South Wales: ring-width, wood density and chemical analysis

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Introduction

This chapter describes some of the results of a one-year study carried out in 1986/7 to examine the potential for using chemical analyses of tree rings to monitor relatively long-term changes in the atmospheric or soil environments. The study was carried out in Forestry Commission experiment Afan 1, South Wales, in a region with patches of poor tree growth (see Chapter 1).

The study included the production and analysis of a number of ring-width, wood-density and wood-chemistry records extending over several decades, aimed at elucidating relationships which exist between these variables while at the same time placing recent tree-growth changes in a longer time frame. The trees were far from ideal in this regard because their relatively young age restricts the scope for assessing the long-term significance of recent growth changes and for gauging the importance of the internal translocation of trace metals.

Descriptions of study sites

Two study sites (numbers 14 and 15) were selected from the 20 sites in Forestry Commission experiment Afan 1 (see Chapter 5). These sites are referred to as B and A respectively. Though both sites were planted at the same time (1960), and are less than 1 km apart (Figure 9.1), the trees showed contrasting apparent general health. Trees at site B were growing well, above average in terms of general growth on the coalfield and in terms of general yield class. Trees at site A were generally in poor condition and showed a much greater variation in stem diameter than site B. Many small trees were dead and many dominants showed severe signs of dieback and bent top. There was widespread chlorosis in older needles and some occurrence

of what appeared to be necrotic spots (see Chapter 1). Table 9.1 summarises a number of site tree-growth characteristics for sites A and B and for two additional sites.

One of these additional sites (C, planted in 1949) is located near Margam immediately adjacent to the Port Talbot Steel complex (see Figure 9.1). It has been subject to significant inputs of atmospheric pollution but the trees showed no signs of dieback. The final site (D) was selected as an unpolluted control site and is about 130 km north of the coalfield in Dovey Forest, Machynlleth (Figure 9.1 inset). The trees were planted in 1942 and have been growing well.

Tree-ring analyses

Background and description of parameters

Ring-widths were measured along radii of trunk sections cut at about 1.3 m above the ground. The samples yielded continuous time series of annual measurements with a precision of better than 0.01 mm. Absolute dating of all individual rings was accomplished by extensive cross-dating of individual series, within and between trees at the same site and between trees from different sites. This ensures that locally-absent rings are identified and allows individual series to be averaged to produce tree, site or regional chronologies. Such chronologies better exhibit the growth characteristics common among all of the series incorporated in the chronology. For further details, see Stokes and Smiley (1968), Fritts (1976) and Phipps (1985).

Besides ring-widths, densitometric parameter time series can be produced representing differences in the intra- and inter-annual structure

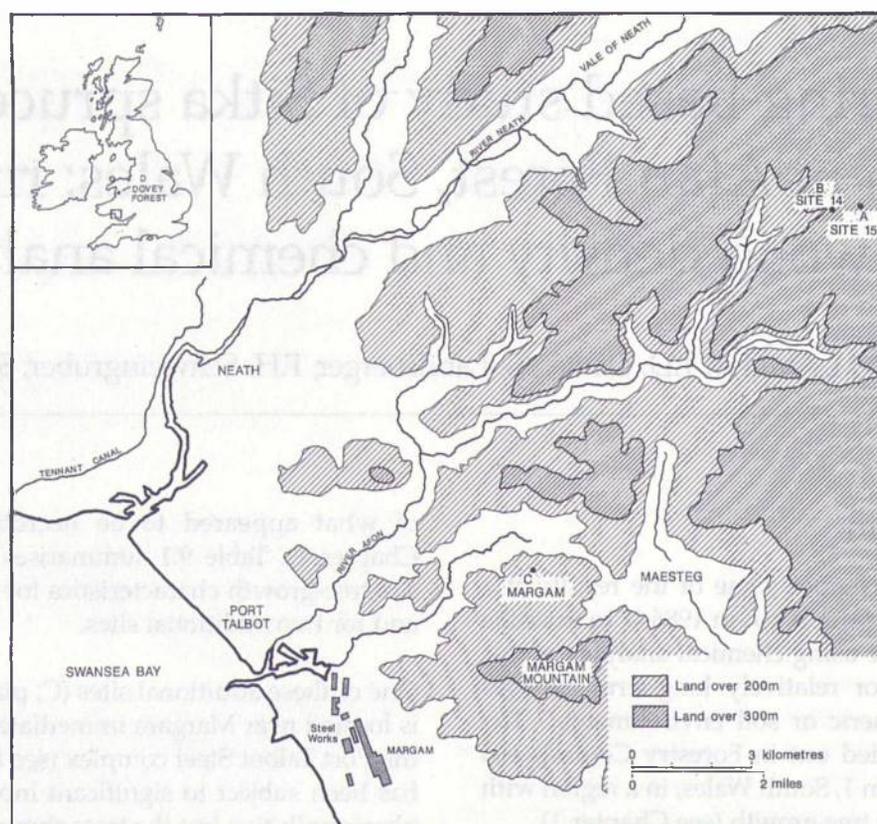


Figure 9.1 The Afan 1 area showing the locations of the study sites.

Table 9.1 Identification and general description of site details for areas included in this investigation

Site identifier for report	Site name ^a	OS grid reference	Altitude (m)	Planting date	Aspect	Exposure	Slope (%)	Stocking density ^b	Soil	General tree health ^c
A	Afan 1/15	SN 903 002	515	1960	W	Exposed	4.5	1.8	Peat to 60 cm	Very poor (5)
B	Afan 1/14	SN 896 002	460	1960	SW	Moderate	7.0	1.8	Peaty gley 20-25 cm	Relatively good (2)
C	Margam	SS 822 913	260	1949	N	Moderate	5.0	1.6	Brown earth	Relatively good
D	Dovey	SH 815 105	300	1942	NE	Moderate	5.0	1.6	Upland brown earth some gleying	Good

^a Afan 1 numbers refer to site numbers in Forestry Commission Project 584 (Coutts, 1986).

^b Distance in metres between individuals.

^c Numbers in brackets refer to growth condition as described by Corcoran (personal communication) in the range from 1 = very good growth for site to 5 = advanced state of bent top.

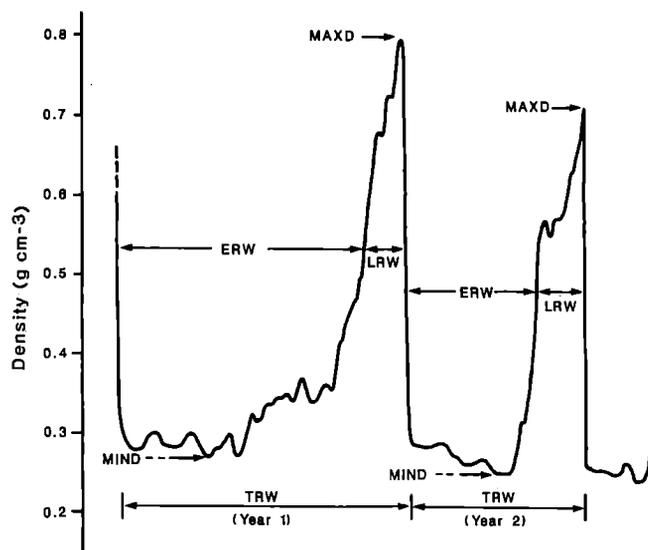


Figure 9.2 A schematic representation of a section of the density trace across two annual rings of a Sitka spruce radial section. The major ring-width and densitometric parameters are indicated. TRW: total ring-width; ERW: earlywood width; LRW: latewood width; MAXD: maximum density; MIND: minimum density

of the wood (see Schweingruber *et al.*, 1978; Schweingruber, 1988). An example of part of a raw density trace is given in Figure 9.2. This illustrates how a number of densitometric (and ring-width) parameters are defined. The only parameters used in this study are the total ring-width (TRW) and the maximum latewood density (MAXD).

Ring-width and basal area increment data

At each site, relatively large and small trees were selected, and two radii from opposite directions were measured, one facing towards the north-east. For the good tree-growth sites (B, C and D) there is little variation in tree size and character. At the poor growth site (A) size and apparent health of the trees is much more variable, and poor overall. For this site we grouped the relatively large trees and small trees into separate chronologies, i.e. A-poor and A-well (though even the 'well' trees are inferior in comparison to those at the other sites).

Annual basal areas (B_t) were calculated according to

$$B_t = \pi r_t^2 - \pi r_{t-1}^2$$

where r_t is the tree radius in year t by summing ring-widths (TRW) up to and including that for year t . For the first year of growth, r_{t-1} is zero. This method is valid because the sampled trees were straight grown with concentric annual rings.

The basal area data (Figure 9.3) show the differences in tree vigour within the poor-growth (A) site and between sites. Note that here (and for other parameters) the date of the

first value is not the same as the planting date (cf. Table 9.1) since it takes several years for seedlings to reach the sampling height of about 1.3 m. Planting date/first year differences vary from 5 to 7 years, except at D where it is only 3 years because samples here were taken at a lower level.

The basal area curves (Figure 9.3) all show the characteristic shape for even-aged stand data: a roughly exponential increase initially, then levelling off, with site differences in timing. At site A, all trees reach a constant basal area increment about 10 years after the planting date, at $\sim 5 \text{ cm}^2 \text{ yr}^{-1}$ for the 'poor' trees and $7.5 \text{ cm}^2 \text{ yr}^{-1}$ for the comparatively better growing trees. These values are much less than those at the nearby, 'healthy' B site, viz. $17\text{-}18 \text{ cm}^2 \text{ yr}^{-1}$. At site C, constant growth is not reached for about 15 years and stabilises at about $22\text{-}23 \text{ cm}^2 \text{ yr}^{-1}$. At the off-coalfield site D, annual basal area increment also increases exponentially for about 15 years. It then continues to increase linearly for a further 10 years from $25 \text{ cm}^2 \text{ yr}^{-1}$ to a peak of about 45 cm^2 about 25 years after planting. After another 8 years it falls back to achieve a stable annual value of around $25 \text{ cm}^2 \text{ yr}^{-1}$.

A value of 15 years for a stand to reach a roughly constant level of basal area increment accords with the 14 years quoted by Ford (1979) as the stage at which the production of needles in a young Scottish plantation of Sitka spruce reached a constant. In that case, annual basal area increment averaged over all tree sizes was about $25 \text{ cm}^2 \text{ yr}^{-1}$ (cf. sites D and C). The continued increase in basal area increment at D is probably due to management practices. Thinning at this site probably occurred first

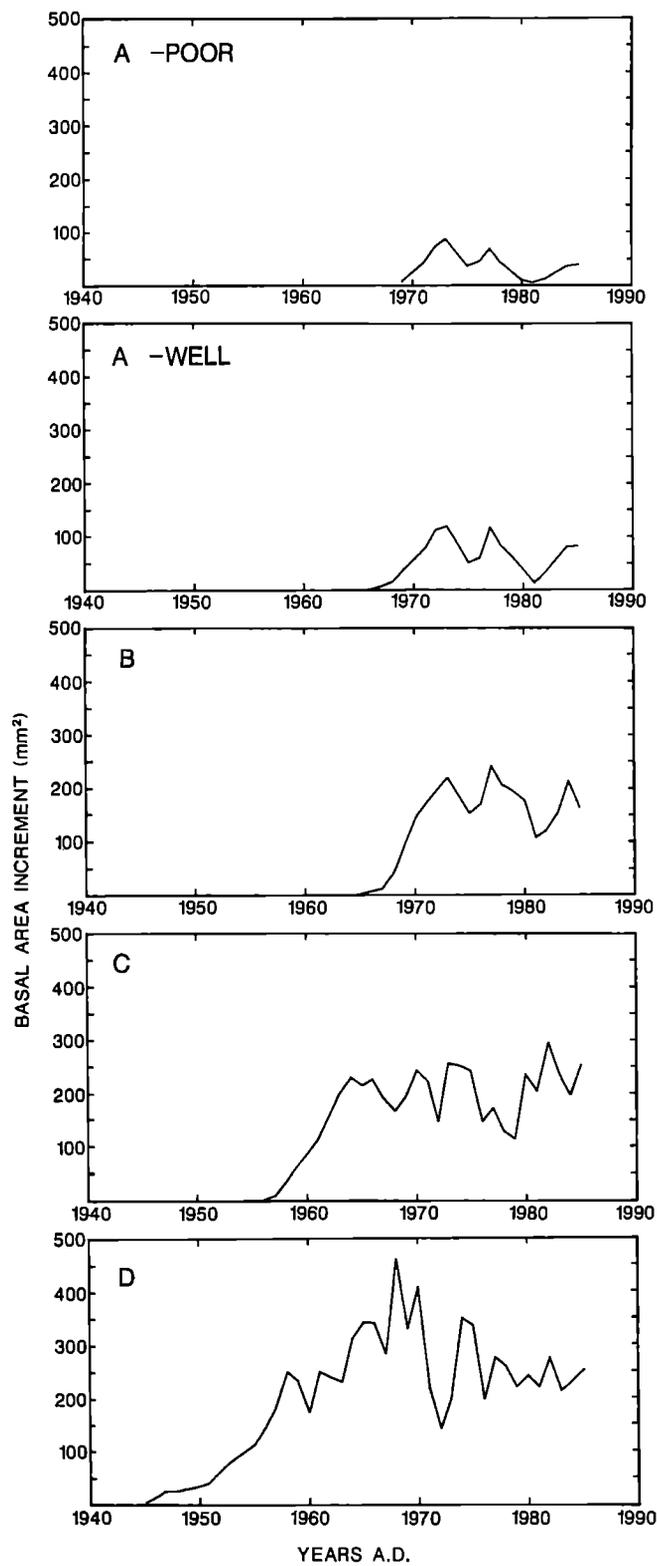


Figure 9.3 Basal area increment averaged across a number of trees at each of the sites investigated.

when the trees were about 20 years old (i.e. around 1962) and would have continued at 3 to 5-year intervals to the end of the 1970s (S. Corcoran, personal communication). This would have given the dominant trees an initial release from competition at the time when basal area growth was levelling off. The additional growth

would subsequently stabilise as the trees once again came under the influence of increasing competition. Trees at A and B differ from those at sites C and D because the former have never been thinned and their stocking density is slightly lower. Basal area increment is arrested earlier and at relatively low levels at A and B.

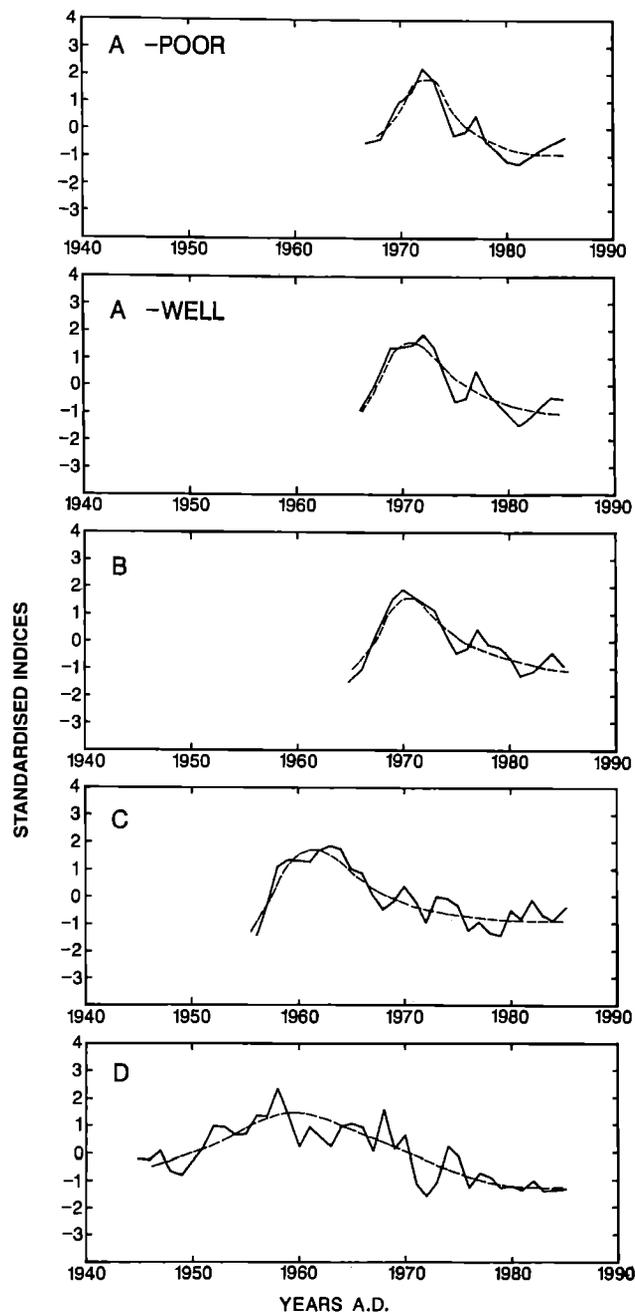


Figure 9.4 Indices of total ring-widths representing year-to-year growth at each of the study sites. The dotted lines indicate longer timescale changes associated with tree ageing and competition.

High frequency variability of tree growth

Inter-annual variability of ring-widths and wood density was highlighted using standardised departures. Series were standardised prior to averaging by subtracting the mean of the whole series from each value and dividing by the standard deviation also calculated over the whole

series length. In the ring-width chronologies (Figure 9.4), the low-frequency curves (dotted lines) represent the combined effects of long-term ageing and competition at each site. The years in which growth falls below the dotted line are those most likely to be influenced by factors adversely affecting growth over and above the general fertility of each site. The maximum density series are shown in Figure 9.5.

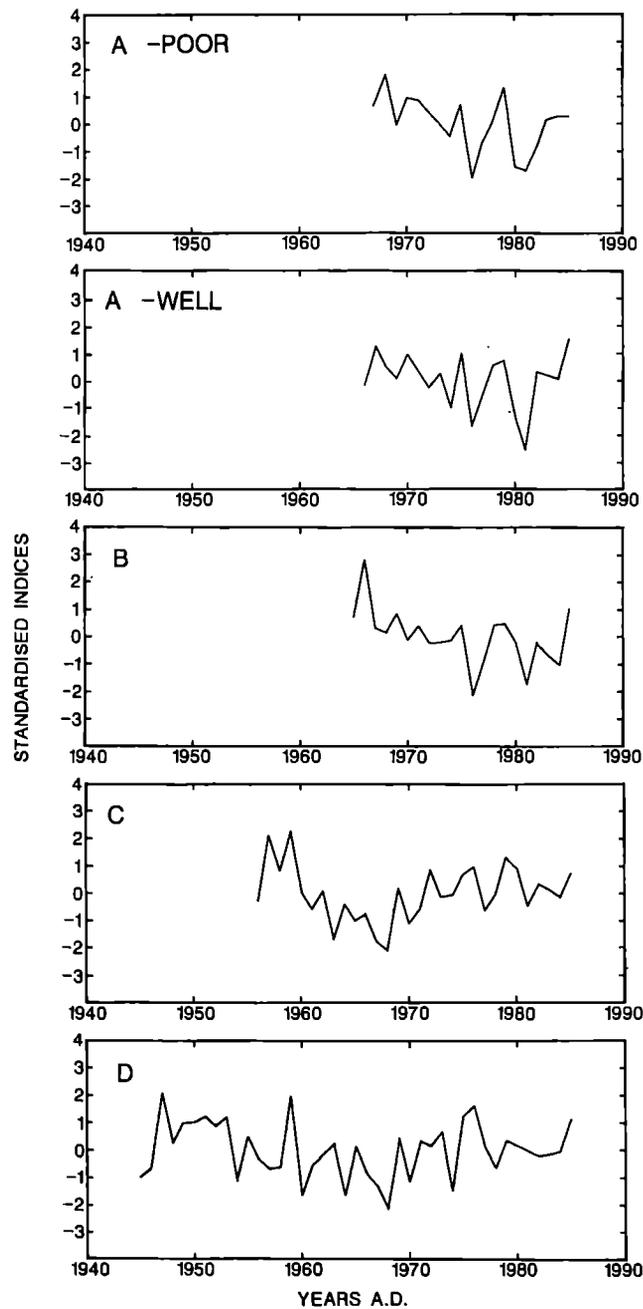


Figure 9.5 Indices of annual changes in the maximum latewood density of the trees at each of the study sites.

The years of particularly poor growth are different at different sites. At A, both well and poor trees show very similar ring-width patterns (Figure 9.4). Reduced growth is shown in 1975 and 1976 (though this may have begun in 1974), and 1980, 1981 and 1982 (this growth decline appears to have begun in 1979 in the relatively small trees). At nearby site B there is a similar pattern of slow growth in 1974 and 1975, and in 1981 and 1982. Unlike site A, however, growth

was normal in 1980. The slow growth at both sites around 1980 accords with observations of poor tree growth on the coalfield at this time (see Coutts and Corcoran, Chapter 4). The bad growth years at site C were in 1968, 1972 and for several years continuously from 1976 to 1979. There are two periods of slow growth at site D, 1960 to 1963 and 1971 to 1973. At C and D there is no evidence of the poor growth around 1980 shown in sites A and B.

Climate influence on tree growth

The nearest place for which we could obtain daily climate data was Swansea, for 1961 to 1987 inclusive. Seasonal and annual anomalies of temperature and rainfall are shown in Figures 9.6 and 9.7.

Temperature

The mean annual temperature at Swansea is 10.6°C. Monthly means are lowest in January (5.3°C) and highest in August (16.5°C). Afan 1 values based on a lapse rate of 0.65°C per 100 m would therefore be: annual mean, 7.6°C; January, 2.3°C; August, 13.5°C. The provenance of the Sitka spruce planted at Afan 1 is Queen Charlotte Islands (QCI). The mean annual temperature (1951-60) at Sandspit on the east of Moresby Island, QCI (53.3°N; 131.8°W) is 8°C (2.2°C in January, 14.8°C in August). Temperatures at Afan 1 and QCI are therefore very similar.

Temperature data (Figure 9.6), when compared visually with poor growth (Figure 9.4), indicate that the role of seasonal temperature variability in determining tree growth is minimal. Years with unusually cold or warm seasons do not figure strongly among the years with notably below-average ring-widths.

Precipitation

Over 1961 to 1987, mean monthly precipitation at Swansea has a minimum of about 70 mm in June and a maximum of about 140 mm in November. Annual precipitation for this period is about 1070 mm. Precipitation totals are higher at the higher altitude sites and our sites are among the wetter parts of Great Britain (Royal Meteorological Society, 1926). The mean annual rainfall for England and Wales (1931-85) is about 920 mm (Wigley and Jones, 1987) and at Sandspit, QCI, it is about 1250 mm. Although the annual cycle of precipitation at Sandspit is somewhat more marked than in South Wales, ranging from 44 mm in May to 188 mm in November (1951-60) the two locations are well matched.

Movements of soil water can, however, be rapid and relatively large in the peat soil of the Afan Forest (see Pyatt, Chapter 3) and it is feasible that summer drought may have a strong influence on tree growth. Such effects should be clearest in 1976 and 1984. Drought was more severe in 1976 because the winter of 1975/76 was very dry. The summer of 1976 was also warm and this would have aggravated any problem of soil moisture deficit.

The ring-width series show no obvious effect of the 1984 drought. Furthermore, the A and B ring-width chronologies (Figure 9.4) show growth in 1976 to be below average but not remarkably so; it is less in 1975. Growth in 1980 and 1981 is also very poor. At site C, 1968, 1972, 1978 and 1979 are all equally poor. At D, two prolonged periods of poor growth from 1960 to 1963 and from 1971 to 1973 are worse than 1976. Thus, the effect of drought is far from clear.

We also examined a number of other climate variables such as spring frost (Briffa *et al.*, 1989), obtaining generally negative results. On this evidence, it seems unlikely that climate is a major contributory factor in explaining years of poor growth in general, or the more prolonged poor growth at site A.

The influence of the green spruce aphid

The green spruce aphid (*Elatobium abietinum*) is known to be a significant pest on Sitka spruce throughout Britain (Carter and Nichols, 1988). The evidence for the influence of *Elatobium* at Afan 1 is pervasive but largely anecdotal. Coutts (1986) lists years of apparently bad outbreaks as 1949, 1950, 1957, 1961, 1968, 1970/71, 1973 and 1980. Innes and Neumann (1989) list years with high aphid numbers in south-west England as 1971, 1975, 1976, 1978, 1980, 1981, 1983, 1985 and 1987. Coutts (1986) states that, at Afan 1, 'striking reductions in growth were often associated with known outbreaks of *Elatobium*'. *Elatobium* causes defoliation, and sudden reductions in wood density and ring-width can give indications of defoliation events. This is illustrated in Figures 9.8 and 9.9. Figure 9.8 shows data from the poor-growth A site, from two relatively small trees (Figures 9.8(a) and (b)) and from larger, better-growing trees (Figures 9.8(c) and (d)). Figure 9.9 shows data for trees of contrasted sizes on site B and for relatively large trees at sites C and D.

Certain years stand out as likely years of defoliation. In two large trees from site A (Figures 9.8(c) and (d)) reduced density occurred in 1980 and 1981. The tree in Figure 9.8(c) also shows a slight density reduction in 1975. In both trees, growth recovery seems to have occurred rapidly after an infestation. For two smaller trees from site A (Figures 9.8(a) and (b)), the 1975 event is not recorded but both trees were severely affected in 1980/81. All the trees at this site show a marked slowdown of radial expansion at about 1974 or 1975, most likely the result of canopy closure though aphid infestation could be a contributory factor.

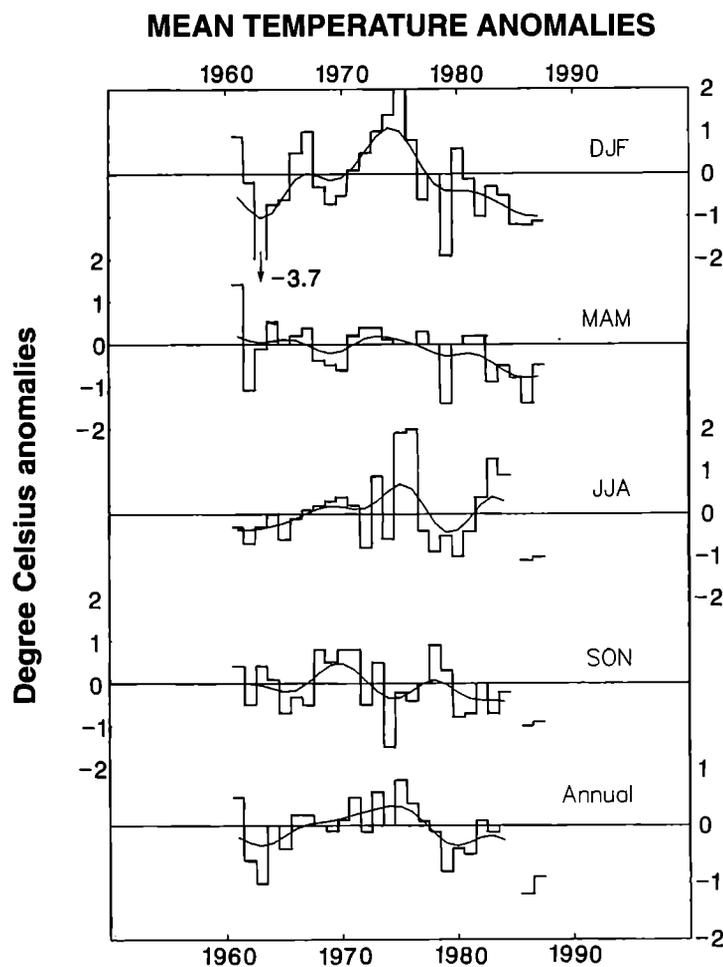


Figure 9.6 Seasonal and annual mean temperature variations at Swansea. The values shown are degree Celsius anomalies with respect to the mean for 1961-1987. The smoothed line represents 10-year low-pass filtered values.

These plots also show the effects of the 1976 drought: a characteristic flat-topped curve indicating a low amount of early wood formation and a sharp and early occurrence of thicker-walled latewood-type cells. Growth after 1976 shows that the overall effects of this drought were small and that it was the severe 1980/81 aphid infestation which produced the most dramatic growth limitation, especially in the 'poorer' trees.

This conclusion is supported by the plots for two trees at site B (Figures 9.9(a) and (b)). The larger tree (Figure 9.9(b)) shows no evidence of damage apart from a slight reduction in MAXD in 1981. The small tree (Figure 9.9(a)) clearly shows reduced ring-widths in 1974/75 and reduced growth and density in 1980/81. The tree from site C (Figure 9.9(c)) shows no evidence of damage but the tree from site D shown in Figure

9.9(d) produced a very narrow ring in 1971. Sites C and D were apparently not affected by aphids in 1975 and 1980.

Figures 9.8 and 9.9 suggest that *Elatobium* can have a strong influence on tree growth when heavy infestations occur. The same density data also clearly show that the occurrence and level of infestation is extremely variable both within and between sites, as stated by Coutts (1986). Nonetheless, widespread infestation at a site is likely to be registered as a narrow ring in any well-replicated ring-width chronology.

We conclude that *Elatobium* is an important control on the relatively high-frequency variability of tree-growth on the coalfield in general, and may be a significant factor in the poor overall growth of the trees at site A.

Chemical analysis of tree rings

For wood chemistry, two techniques were used, Neutron Activation Analysis (NAA) and Proton Induced X-ray Emission (PIXE), to establish within-tree, within-site and between-site concentrations of a range of cations. Some 99 time series, representing both methods and measuring up to 13 elements, were produced. Details are given in Briffa *et al.* (1989). Here we show only the results for manganese as these suggest a link between anomalously low concentrations of this element and poor growth at site A.

Results

A total of 12 concentration time series for Mn are shown (Figure 9.10). There is a general pattern of declining Mn in all trees from the oldest to the youngest rings, with little year to year scatter. Within-tree data and between-tree trends are in good agreement.

The data for the different sites reveal significant and systematic differences. Absolute levels are highest at the remote site D, followed by C, B and A. Representative ranges of the values (ppm) at these sites are: D, 100-170; C, 20-75; B, 20-50; A, 5-20. Thus, at the 'poor-growth' A site, mean Mn levels are about 15 times lower than the average at the D site. At A, values for the bigger trees are below the lowest values (in the smaller trees) at the other sites.

Comparison with published data

The evidence from the literature suggests that Mn concentrations are very variable both within and between species. Mn concentrations over the late 1800s to the early 1970s in unpolluted and urban shortleaf pines at Knoxville fell from relatively constant heartwood concentrations around 100 ppm to recent levels of around 50 ppm (Ricci, 1975). A similar picture is shown by Baes *et al.* (1984).

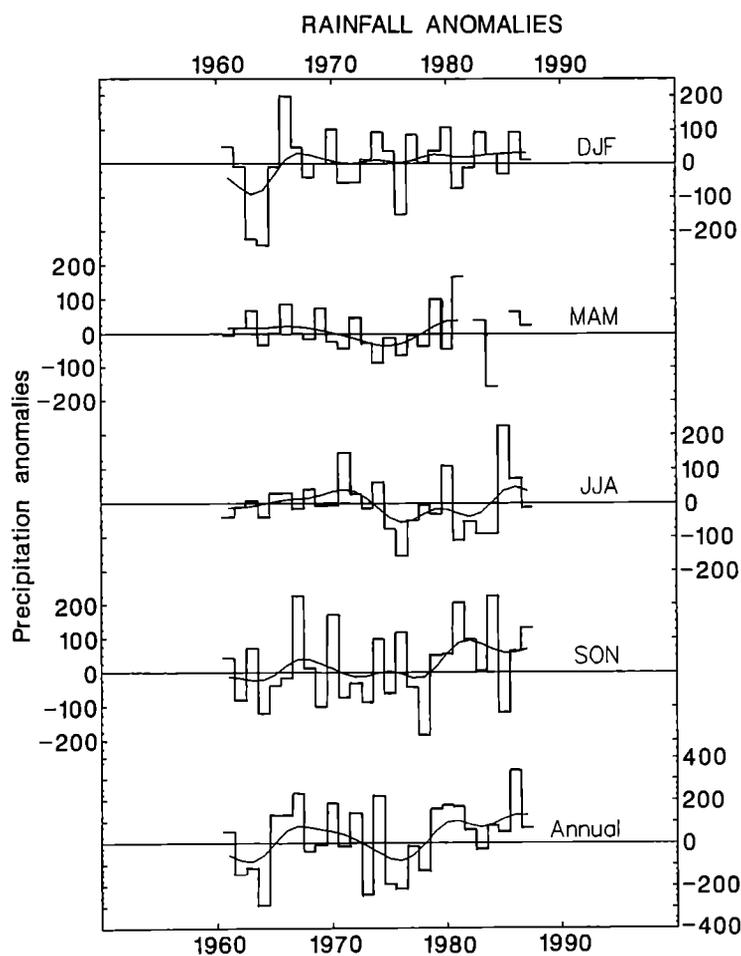


Figure 9.7 Seasonal and annual totals of precipitation at Swansea. The values are anomalies with respect to the mean for 1961-1987.

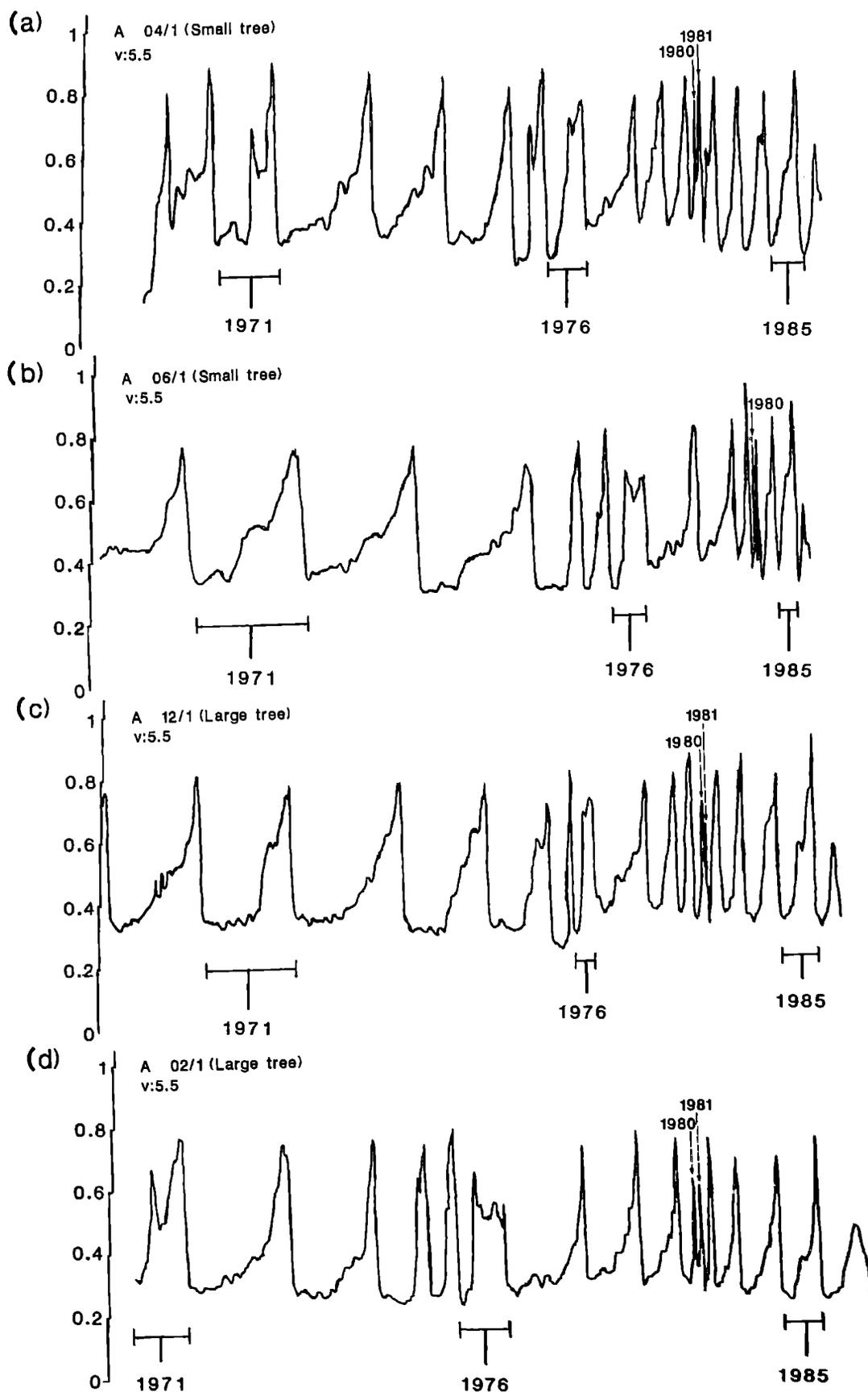


Figure 9.8(a),(b),(c),(d) The density profiles for recently formed growth rings of four trees growing at the site A (note that the ring for 1986 is not completely formed). The rings for 1971, 1976 and 1985 are indicated as reference points on each profile. Note the acute suppression of growth after 1980 in tree A 06. The ring for 1981 cannot be discerned.

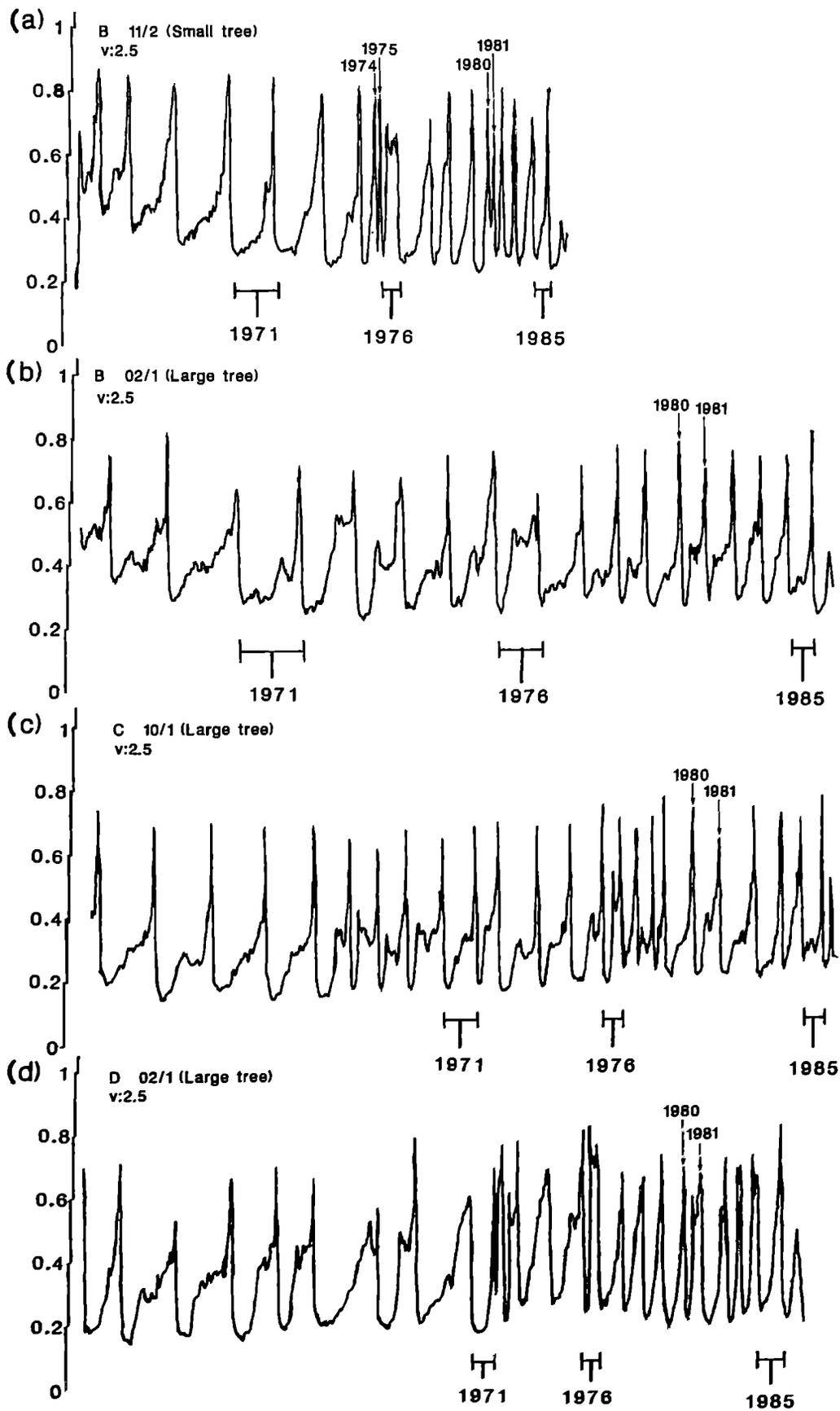


Figure 9.9(a),(b),(c),(d) The density profiles for the recent ends of trees at site B (two trees), C and the D control site. The rings for 1971, 1976 and 1985 are indicated as reference points.

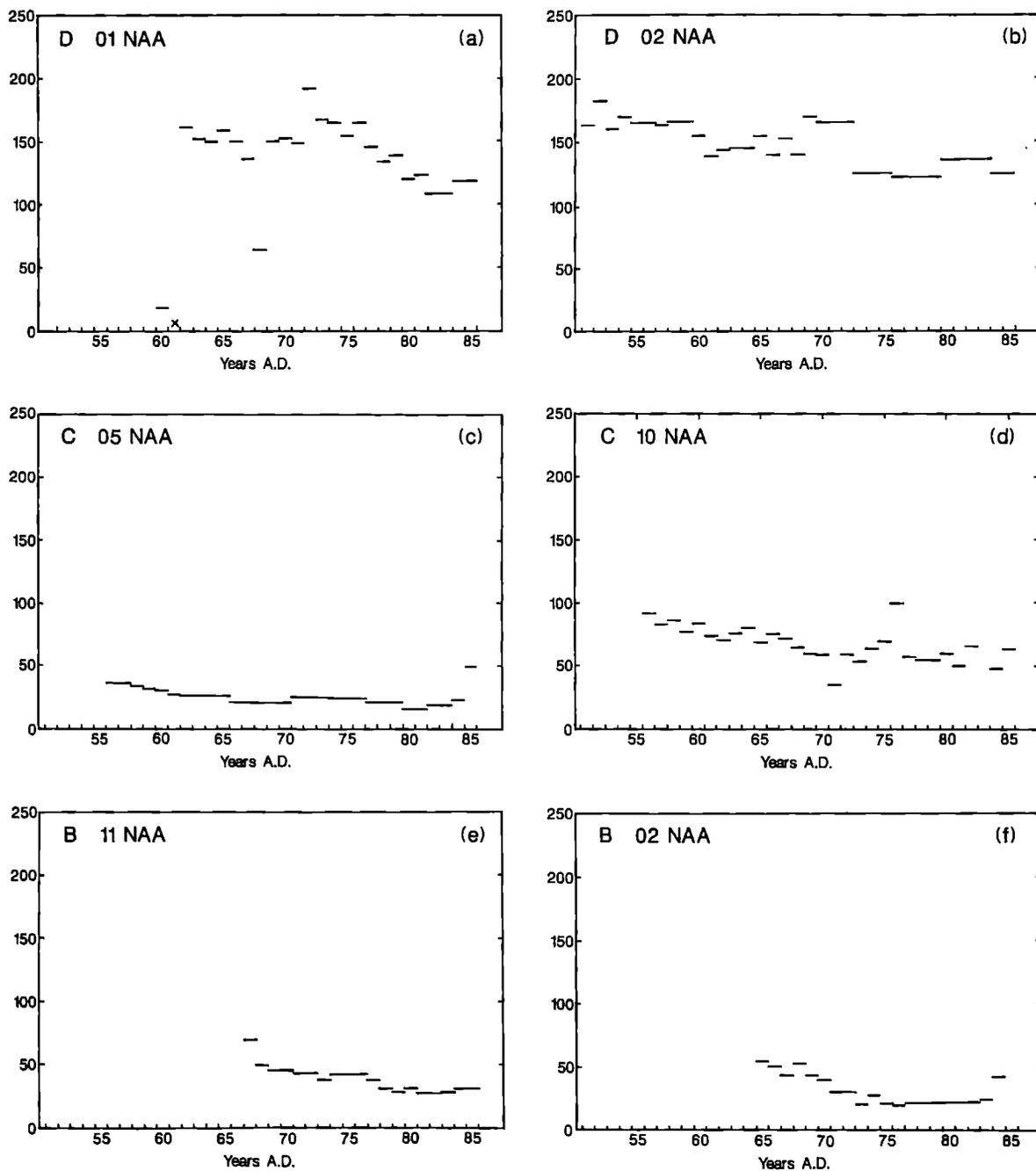


Figure 9.10 Concentrations (ppm) of manganese in individual rings or small groups of rings in selected trees at the various study sites: (a), (c), (e) and (g) are from relatively small trees while (b), (d), (f), (h), (i), (j), (k) and (l) are from larger trees. NAA indicates analysis by Neutron Activation Analysis, PIXE by Proton Induced X-ray Emission. NE and SW refer to north-east and south-west aspects of the tree. A small cross above the horizontal axis indicates that the level was below the detection limit.

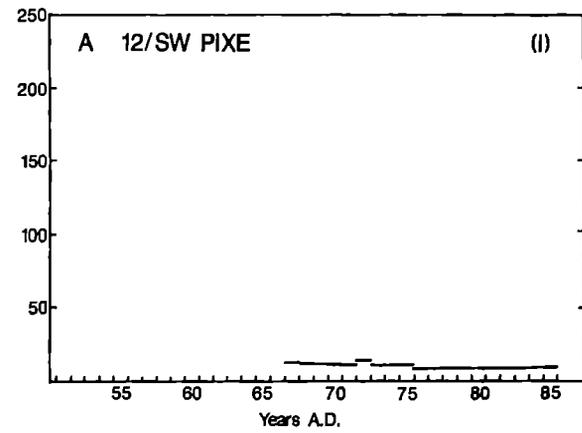
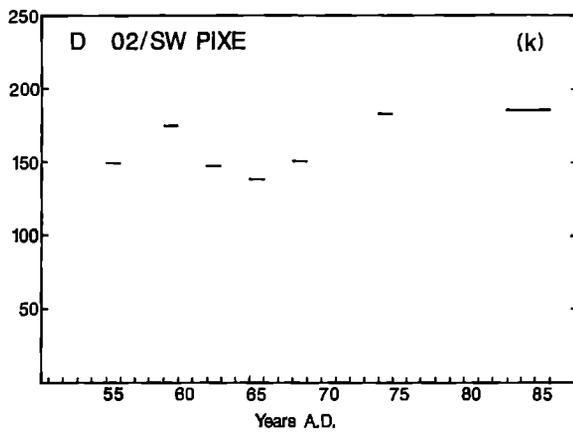
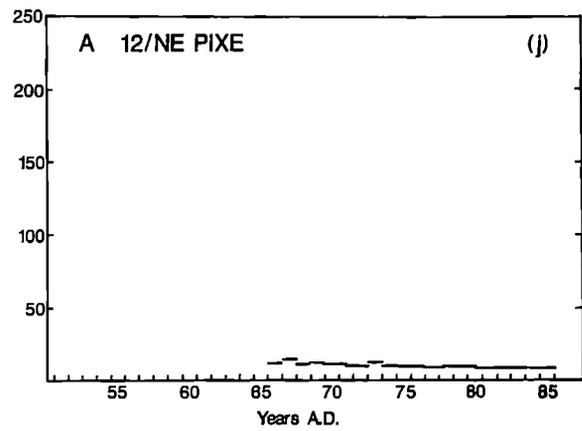
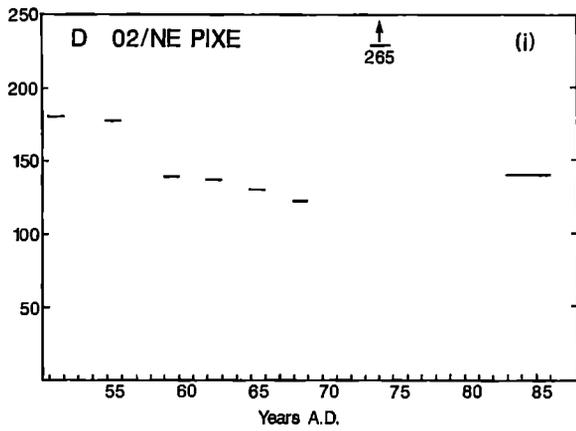
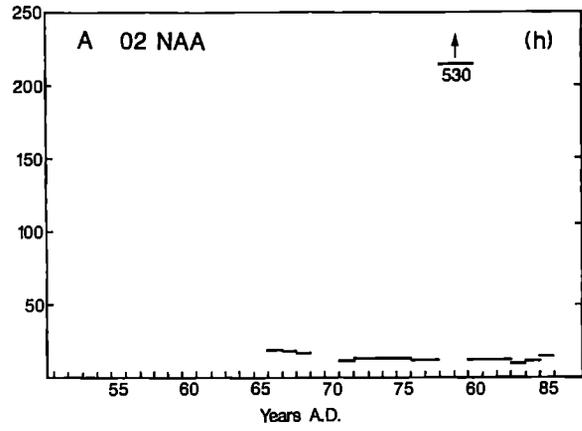
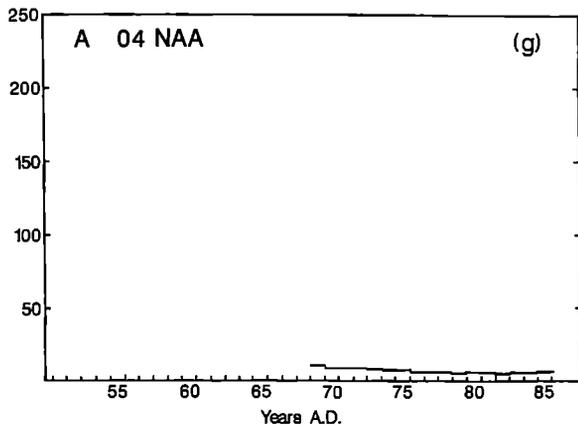


Figure 9.10 continued.

Gradually decreasing concentrations from pith to bark are also seen in the results of Legge *et al.* (1984) for Canadian hybrid lodgepole-Jack pine (1955-80) from two sites subject to acidic deposition and for one site that was not. At polluted and non-polluted sites, Mn concentrations decreased steadily from values around 300 ppm in older wood to recent values around 70-100 ppm.

Hincman *et al.* (1978) is an exception to the above general pattern. In white pine from seven locations in New England, all sites showed a general trend of *increasing* Mn concentrations from older to younger rings. At three supposedly clean-air sites average Mn concentrations rise steadily from about 35 ppm to over 70 ppm (1940-70). The same pattern is seen at four more polluted sites. Increasing Mn in younger rings has also been reported by Guyette and McGinnes (1987) in western red cedar from Missouri in rings dated from 1650 to 1930. Their Mn concentrations are extremely low, almost constant at around 1.7 ppm until about 1850, then rising to about 2.6 ppm. McClenahan *et al.* (1987) give mean values for Mn in tulip trees of about 17-18 ppm for rings formed over 1955 to 1980. Tout *et al.* (1977) give multi-ring values for single elm and cedar trees growing in England. In the cedar the sapwood mean is 12 ppm but the heartwood mean is only 1.3 ppm. For two elm trees sapwood means are 0.7 and 2.2 ppm, while heartwood means are 1.0 and 1.5 ppm. Overall, our Mn data are in general agreement with most of those in the literature.

Foliar analyses

First-year needles were taken in August 1988 from the lower branches of four randomly selected trees from each site and analysed using NAA.

The results for seven elements are summarised in Table 9.2 and compared with data from a 1985 Forestry Commission Survey (FCS) (Binns *et al.*, 1986; Innes and Boswell, personal communication) and an earlier (1975) survey of Scottish Sitka spruce (J. M. MacKenzie, unpublished results).

Sodium

The off-coalfield site, D, has levels towards the higher end of the range in the FCS. For the two

coalfield sites with comparatively healthy trees (B and C), mean concentrations agree well with the FCS. The poor-growth site (A) has a mean only half that of the other coalfield sites, but this value is still within the FCS range.

Potassium

The means at our sites agree well with FCS. Within-site variability is quite high and no clear between-site relationships can be discerned.

Chlorine

All sites show values near the low end of FCS values, but within the FCS range. There is a suggestion of slightly higher values at the poor-growth site.

Calcium

The relatively good-growth coalfield sites (B and C) have means close to the mean FCS value. The remote site (D) which also has apparently healthy trees, has a value of only one-third of the FCS mean (i.e. half the FCS minimum). The poor-growth site (A) has a value considerably less than this, below 700 ppm.

Magnesium

There is no clear pattern in the data. The FCS range encompasses all of our results. The lowest value in our data was at the apparently healthy 'control' site (D).

Manganese

Concentrations at all four of our sites are below the mean of the FCS (see also Figure 9.11(a)). Site D has the highest levels (mean near 560 ppm, cf. FCS mean of ~800 ppm). Mean levels at the B and C sites are only half of this (~300 to 350 ppm) which puts them just above the extreme minimum value found in FCS (~260 ppm). Foliar Mn levels at the poor-growth site A are low, 35 ppm. This is much lower than the mean and minimum values in the FCS and indicates the possibility of Mn deficiency in the coalfield. Values for sites A and B are lower than those shown for the same sites in Chapter 5. The discrepancy may be accounted for by the difference in the branch whorls sampled (this study, lower branches; their study, top whorl).

(a) Mn (ppm dry weight)

(b) N (% dry weight)

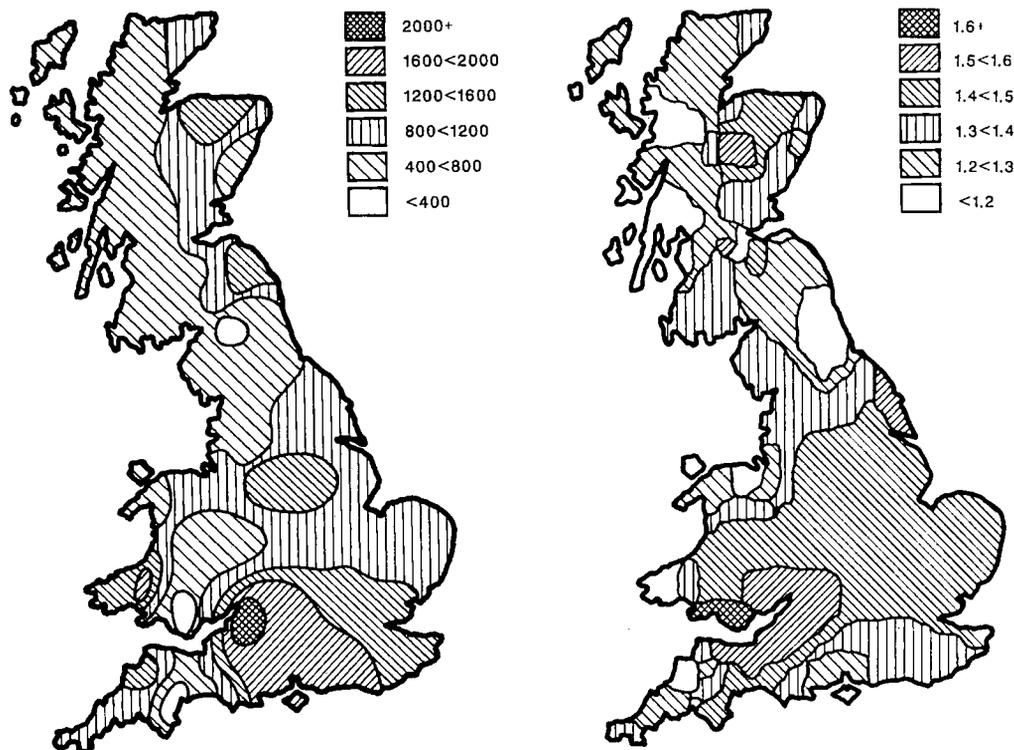


Figure 9.11 Sitka spruce first year needles 1985: (a) manganese (ppm) dry weight, (b) % nitrogen dry weight.

Vanadium

There is no obvious pattern in the values. Tree-to-tree variations differ widely between sites, with particularly high variability at the off-coalfield site (A).

The most significant finding of our foliar analyses is that levels of Ca, Mn and Na are low

at the poor-growth site, both in relation to our other sites and (for Ca and Mn) to FCS. The mean level of Ca at site A is less than a quarter of that for the wider survey and only a third of the lowest levels recorded anywhere. The situation is even more pronounced for Mn. The A site mean is many times lower than any of our other sites and seven times lower than the minimum FCS value.

Table 9.2 The mean elemental concentration values for the Sitka foliar analyses of the South Wales sites compared with those from 7th whorl samples of trees from sites throughout Great Britain surveyed in 1985 and the results of a smaller survey of top whorl needles (and twigs, not shown) from Scottish sites surveyed in 1975. All values are in ppm dry weight except for V which are in ppb dry weight

This study							
	Na	K	Cl	Ca	Mg	Mn	V
A	31.9	7625	837	676	665	34	0.13
B	63.7	10075	582	2517	970	289	0.20
C	62.1	8200	636	3098	685	355	0.31
D	128.3	7050	575	1015	543	568	0.29
Forestry Commission 1985 survey results ^a							
	Na	K	Cl	Ca	Mg	Mn	V
Max	151	12700	2300	5000	1450	2270	–
Mean	65	9900	1300	3200	880	807	–
Min	23	7300	500	2000	550	260	–
Forestry Commission 1975 survey results ^b							
	Na	K	Cl	Ca	Mg	Mn	V ^c
Mean	89	8790	–	2539	892	587	~0.6
S.D.	73	2030	–	985	150	342	0.6

^a Binns *et al.*, 1986; Innes and Boswell, personal communication.

^b J.M. MacKenzie, unpublished results.

^c In the original list these values were given as ppm dry weight but were presumably meant to be ppb.

Hypothesis to explain low manganese concentrations in trees on the coalfield

Leaching of certain cations from the soil (in the context of increasing precipitation acidity) has been proposed as a factor in forest damage in Europe, particularly for Mg²⁺ (e.g. Zöttl, 1985; Zech *et al.*, 1985; Zöttl and Hüttl, 1986), but also potentially for Mn²⁺ (Zöttl and Hüttl, 1986).

Manganese concentrations were lowest in wood and leaves of trees growing at the poor-growth site and were higher in the trees at the best-

growth site remote from the South Wales coalfield. Intermediate Mn levels were found in the trees growing in the better-growth coalfield sites. Also, at any one site, bigger trees contained greater concentrations of Mn in their rings than smaller trees. Compared with some of the published data (none of which is for Sitka spruce), the general level of Mn in the coalfield trees is low. Soil data at our sites (not described in this chapter: see Briffa *et al.*, 1989) show that Mn is close to or below deficiency levels. Extensive leaching of Mn, especially in the surface layers of the soils on the coalfield, is to be expected since mobilisation of Mn²⁺ due to low pH would be exacerbated by the relatively

high rainfall in the area. It is possible, therefore, that a deficiency of Mn may be contributing to the general decline of the Sitka spruce evident at many of the study sites in the Afan 1 Forest.

Manganese deficiency is a recognised problem for both trees (e.g. Leeper, 1947; Ingestad, 1958) and agricultural crops. In crops, deficiency is most often recognised on calcareous soils with high pH and large amounts of organic matter (Farley and Draycott, 1973) but low pH may also induce Mn deficiency if the soils are subject to moisture extremes and/or have relatively high levels of iron (Kabata-Pendias and Pendias, 1984, Table 28). Examples of Mn deficiency in trees on acid soils have been reviewed by Leeper (1947). At Afan 1, soil pH values range from 3.5 to 5.0 (Graham, 1986), moisture levels vary widely in time and iron levels are high.

Atmospheric input of Mn into the biochemical cycle of woodland is generally low, but its magnitude is unknown in the Afan 1 area. In general, trees depend on an efficient recycling of this metal with possible replenishment from the soil through the weathering of soil minerals. In acidic soils, however, leaching losses will probably exceed weathering gains, as shown for example by Heinrichs and Mayer (1977, 1980) in the acid soils of the Solling area of Germany. Here, the net balance of Mn is negative, with the soil constantly losing Mn in seepage water. Significant leaching from the rooting zone could have led to the current low level of Mn availability to the trees. Site-to-site differences in tree health may reflect differences in Mn availability and in the degree of leaching of each soil as well as variations in the degree of root development of the trees.

Foliar Mn levels at the poor-growth site, which are about 30 ppm, are similar to the levels commonly associated with Mn deficiency. Deficiency thresholds for crops have been given variously as: 12-25 ppm (Kabata-Pendias and Kabata, 1984); about 20 ppm (Kreutzer, 1970; Zech, 1970; Thornton and Webb, 1980); and 30 ppm (Knezek and Ellis, 1980; Farley and Draycott, 1973). Farley and Draycott (1973) state that, in sugar beet, concentrations below 15 ppm would produce severe problems. Leeper (1947) considers 15 ppm to be a reasonable dividing line between sick and healthy oat plants, but he notes that sick plants have been reported containing 29 ppm (McLachland, 1941) and even 36 ppm (Sherman *et al.*, 1942).

The most relevant reference to Mn deficiency in trees is Ingestad (1958). He examined chlorotic spruce (*Picea abies*) and birch (*Betula verrucosa*) growing on a lime-rich fen in Gotland and established that the chlorotic trees generally contained less than 20 ppm Mn. Fertilisation with $MnCl_2$ reversed the chlorosis.

There are a number of aspects of plant growth where Mn plays a significant role and through which Mn deficiencies may cause detrimental effects, in photosynthesis and in the control of auxin activity. In photosynthesis, Mn is important because it is a component of the enzyme phosphotransferase and because many of the enzymes in the citric acid cycle require Mn for their optimal functioning. While Mg can substitute for Mn in many of these enzymes this is only at the cost of significant loss of efficiency. Chloroplasts are very sensitive to low Mn and show rapid structural impairment when it is limited. The most immediate response to a deficiency of Mn is therefore likely to be a severe reduction in chlorophyll, leading to a reduction in net photosynthesis and consequently a reduction in dry matter production (though apparently respiration and translocation are largely unaffected) (Ohki *et al.*, 1979, 1981). Thus, leaf yellowing could result from, or be consistent with, Mn deficiency. While not a prominent symptom in the Afan 1 Forest, leaf yellowing has been recognised, especially in older needles (see Chapter 1).

In the control of plant auxin activity, Mn deficient leaves are known to exhibit very high indoleacetic acid (IAA) oxidase activity (see references in Marschner, 1986, and Rains, 1976). Mn catalyses the destruction of IAA inhibitor. Hence, a reduction of Mn leads to an increase in the enzyme which breaks down IAA, resulting in a loss of apical dominance and perhaps to an increase in the formation of epicormic shoots. The occurrence of such a phenomenon in the Afan 1 Forest, along with the dramatic bent top symptom characteristic of the trees, is consistent with the possibility that Mn deficiency might be playing some role.

In summary, the wood and foliar chemistry results presented here, along with current knowledge of the role of, and response to, deficiencies of Mn in plants, form a *strong circumstantial* case for considering Mn as an important contributor to the phenomenon of Sitka spruce decline at Afan 1.

Conclusions

Our dendroecological approach has shown that inter-annual climate variability is unlikely to be a significant direct factor in causing years of poor growth. The data do, however, lend strong support to the theory that infestations of the green spruce aphid are linked to markedly reduced net productivity at both the individual tree and site level.

Comparisons of the results of chemical analyses of the wood and current-year foliage at each of the four sites examined suggest that a deficiency in Mn may be involved in poor tree growth.

Acknowledgements

This work was supported by NERC (through grant GR3/6403A). We particularly acknowledge the encouragement and co-operation of Mike Coutts, Forestry Commission (Northern Research Station) and Stan Corcoran and Simon Mead, Forestry Commission (Brecon) who carried out the sampling of the timber, leaves and soil. John Innes (Alice Holt Lodge) gave advice and kindly supplied unpublished data on the chemical analyses of Sitka spruce foliage throughout Great Britain. Soil analyses (not presented here) were undertaken by Pete Abrahams, Institute of Earth Studies at the University College of Wales. Densitometric analyses were carried out in Fritz Schweingruber's laboratory by P. Nogler, while the PIXE analyses at the Lund Institute of Technology were the work of E. M. Johansson.

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Chapter 10

The green spruce aphid, spruce root aphids and tree growth in Afan Forest

C. Carter

Introduction

Where Sitka spruce afforestation has taken place on peat or peaty-gley soils in Wales (such as Afan Forest) both the green spruce aphid (*Elatobium abietinum* Walker) and a spruce root aphid (*Pachypappa vesicalis* Koch) have been found to occur frequently. This chapter aims to describe the complex life cycles of these two introduced aphids as they occur in Britain and show how they have been influenced by environmental factors at Afan during this 5-year study. In outbreak years, *Elatobium* can cause severe browning and almost total loss of old needles on Sitka spruce even on established trees. Such affected trees do not die, but as subsequent new foliage gradually masks the bare shoots of previous attacks the impact of the aphid tends to be forgotten. Since this study commenced, a root aphid (*P. vesicalis*) previously unrecorded in Britain has been found to be well established in parts of Afan Forest, especially in the places where fine surface roots ramify over periodically waterlogged peaty soils. Both of these aphid species are thought to contribute to depressed tree growth, and the interaction between host plant growth and the abundance of aphids is discussed.

The green spruce aphid: *Elatobium abietinum*

In Europe, this aphid is endemic, occurring on Norway spruce, probably throughout its range where possibly some coevolution of the aphid and its host plant has occurred. Norway spruce and other Eurasian species appear to be more resistant to attack than any of the North American species (Nichols, 1987). In North America the green spruce aphid (*Elatobium abietinum*) has only been known to occur on Sitka spruce since 1916 (Holms and Ruth, 1968). There

are a few species closely related to the green spruce aphid but most are specific to plants of other families in eastern Asia. Eastern Asia is the centre of speciation for the genus *Picea* (Wright, 1955). By inference it seems likely that Norway spruce or one of its close relatives is the original host plant of *Elatobium* across Europe and beyond.

The mild winter climate of Britain and those coastal regions of Europe favoured by the gulf stream enable *Elatobium* (as viviparous virginoparae) to continue to feed and breed during the winter months. Furthermore, since feeding sites are available, there is no obligation to pass the winter in a resting egg stage. The situation is different in mainland Europe and northern Scandinavia since the freezing temperatures in most winters then become a limiting factor. Therefore the appearance of males and females in the autumn is an essential part of the life cycle for the production of overwintering eggs. These eggs remain unhatched for several months (von Scheller, 1963; see Figure 10.1).

In Britain, the combination of growing an exotic North American host-plant (Sitka spruce) that is very susceptible to the green spruce aphid, and mild winter weather enabling this aphid to reproduce parthenogenetically throughout the winter, will inevitably result in severe defoliation from time to time. The green spruce aphid is therefore the major background pest of Sitka spruce in Britain.

Influence of *Elatobium* on foliage and tree growth

During the dormant season of the tree, *Elatobium* may be found in small colonies on any of the green foliage, but there seems to be a preference

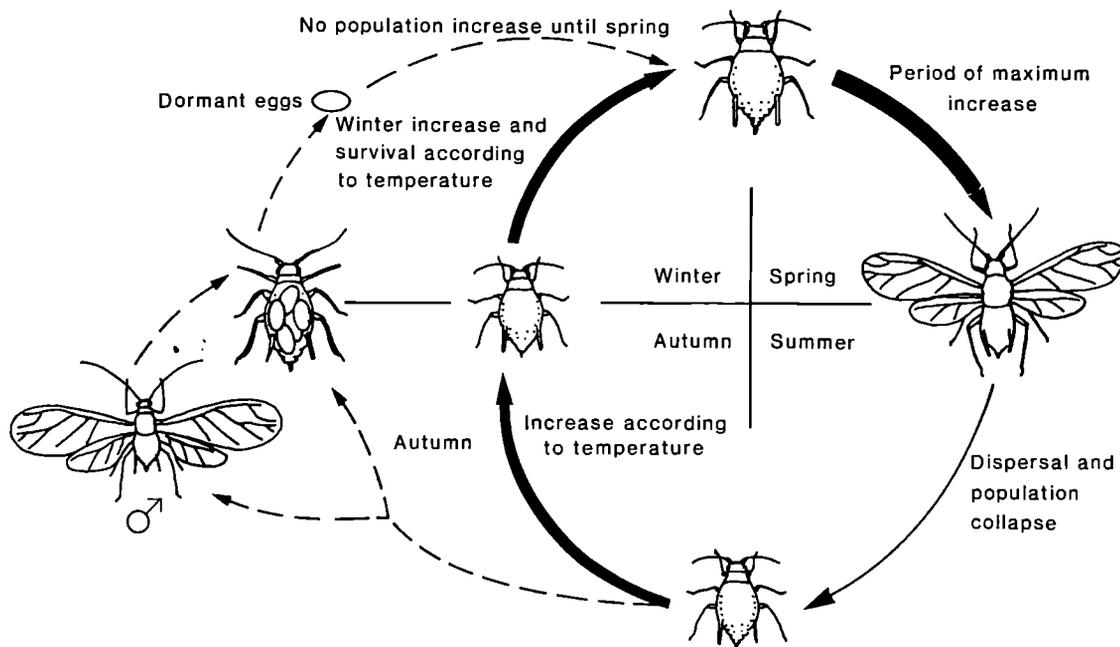


Figure 10.1 Life cycle of *Elatobium abietinum*. Spruce is the only host plant for this aphid. The broken line includes the complete holocycle which occurs in regions with a severe winter climate; in Britain and other mild areas this aphid is anholocyclic as shown by the line.

for, and most damage to, the oldest foliage. When new foliage appears in the spring it may become colonised, but aphids are usually only to be found there if no other older foliage is available. In such cases of very heavy attack the basal needles of the current year's shoots may become yellow, then wither and fall away, but this is not thought to be a direct result of aphids feeding on those needles. After such a heavy attack, a small, previously well-foliated tree gives the appearance of being 'hollowed-out' as the only green needles will be retained on the current year's shoots on the periphery of the crown.

In some seasons, especially in upland situations, the spring *Elatobium* attack may be only light and may continue to exist at a low level well into the summer. Under these circumstances, the current year's needles may start to become infested at the end of August, by which time the foliage will have matured and shoot growth ceased.

In common with most other aphids, *Elatobium* feeds on phloem sap, in this case from the phloem within the endodermal ring of cells within the needle. The aphid gains entry by passing its filamentous stylets through the stomata. During this process salivary substances pass into the needle and after a few days a

yellow colour appears around this entry point. In the case of Sitka spruce, this area increases until the whole needle changes colour and subsequently falls. Throughout the feeding period the aphid gives birth to a further generation of about 10 virginoparae which repeat the process on other needles nearby. The generation time is about 20 days, so parthenogenetic reproduction under favourable mild conditions (15°C) enables their numbers and the extent of the damage to increase rapidly.

There are, therefore, three possible ways in which *Elatobium* can affect tree growth:

1. By removing soluble substances directly from the phloem in the needles, denying the plant photosynthate and other metabolites.
2. By introducing salivary enzymes causing needle tissue necrosis, and weakening new growth, e.g. new needles in the lower crown.
3. By depleting the tree of its photosynthetic tissue, which could be all but the current year's needles. This would have a further influence on photosynthesis in subsequent years until the tree had become reclothed in its full complement of photosynthesising needles.

A comparison of subsequent height growth of defoliated and undefoliated 6-year-old trees showed that *Elatobium* brought about a 61% loss in the year of attack and a similar loss the following year (Carter, 1977). Further detailed studies on smaller trees demonstrated significant losses in potential growth expressed as dry-matter production throughout the whole tree including the root system. After experiencing some sporadic late autumn/early winter attacks in the mid 1970s, it became apparent that early winter defoliation was more debilitating than the usual springtime event, so that terminal buds of the leader and lateral whorls failed to open the next year.

With trees 10 m tall, it seems as if the reverse is the case. The leader and the upper part of the crown generally escape the severity of attack and the interior foliage and lower part of the live crown are attacked the most. It is thought that attacked trees of this age would consequently show more of a loss in radial increment in the year of attack than a loss in height. The loss in potential radial increment on intermediate sized trees (3-5 m) after an attack by *Elatobium* in 1985 at Afan Forest near site 11 (Chapter 5) was measured by comparing the growth of adjacent attacked and unattacked trees through the following growing season. Increments were measured from girth bands at 2 to 4-week intervals through the growing season (Figure 10.2(a)). The attacked and unattacked trees showed a highly significant difference in growth up to 28 August; the period between mid June and early July showed the greatest mean difference (Figure 10.2(b)); the cumulative loss in the increment of the attacked trees by the end of the summer averaged 44% (Figure 10.2(c)).

The frequency of attack

Records of attack years on Norway spruce go back to the last century. Since the more widespread planting of Sitka spruce in the 1950s, records for that species have become more comprehensive. Outbreaks have occurred irregularly, on average every 5 to 8 years; more frequently in the mildest parts of Britain. Sometimes two successive years may occur, starting usually with a lesser attack followed by a major one (e.g. 1970/71 in Scotland, and 1979/80 in Wales) but a third successive year in one place is probably a rare event.

One of the major regulating factors curtailing a serious attack is a sudden change from mild winter weather when the air temperature falls

below -8°C for some hours (Carter, 1972). The aphid is relatively hardy, and can tolerate dry frosts down to this temperature without appreciable mortality on account of its waxy covering (Bevan and Carter, 1980). However, the freezing of fog droplets which come into contact with cold foliage causing the growth of rime ice crystals markedly increases the mortality of aphids at the same or even at higher sub-zero temperatures (Carter and Nichols, 1989).

Elatobium studies on the South Wales coalfield plateau (Afan 1)

There is probably quite a long history of damage to spruce by *Elatobium* in mild areas of South Wales, but possibly, on account of the sudden collapse of the aphid population after a damaging attack, the presence of the aphid has been overlooked and the resultant growth loss confounded with other adverse issues such as pollution and site factors in the area.

A severe outbreak occurred in 1980 and its subsequent impact on the P74 IUFRO provenance collection of Sitka spruce has been monitored (Carter and Nichols, 1988). In the growing season immediately following that attack, there was a significant reduction in leader growth. The reduction in potential growth continued for at least another year, but the reduction was greatest in the smaller northern provenances than the taller southern ones.

At the conception of the Afan 1 experiment (Chapter 2) it was decided to eliminate *Elatobium* from some of the trees where detailed growth measurements and studies on soil water conditions were being made. At the 20 sites throughout the forest, 4 of the 8 trees were sprayed with insecticide using a high volume drench; 4 matching trees, a short distance away remained as unsprayed controls. Spraying in 1985, 1986 and 1987 was carried out in late August, a time after all winged immigrants would have arrived yet before population increase was known to take place. In the two subsequent years, the spraying date was determined by the presence of aphids after conducting a pilot survey.

Foliage sampling for the green spruce aphid

The purpose of the sampling was twofold: firstly to establish the aphid load at the peak time of year, and secondly to run a check that the insecticide treated trees were aphid free.

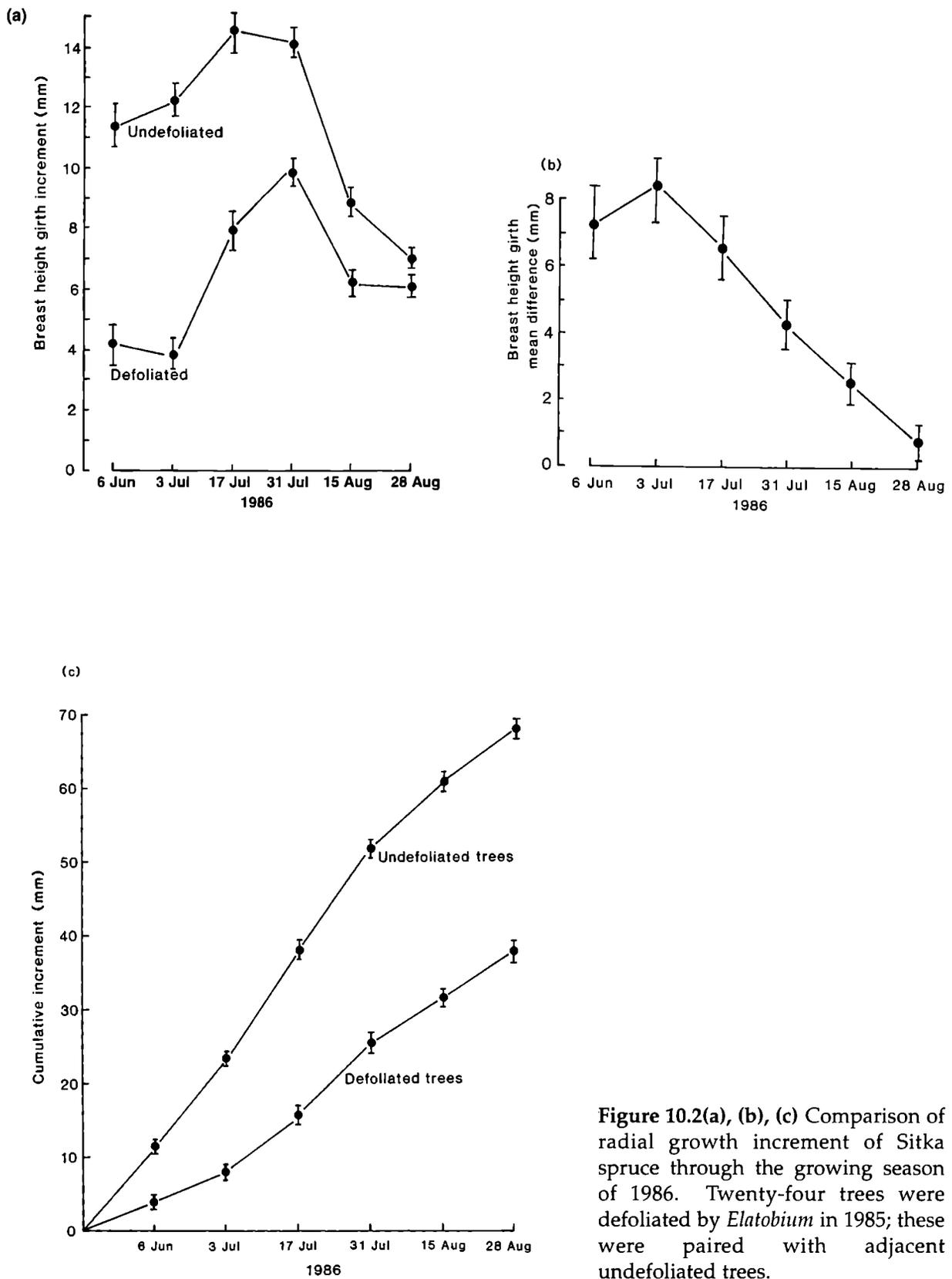


Figure 10.2(a), (b), (c) Comparison of radial growth increment of Sitka spruce through the growing season of 1986. Twenty-four trees were defoliated by *Elatobium* in 1985; these were paired with adjacent undefoliated trees.

From 1985 to 1989 inclusive, sprayed and unsprayed trees were sampled. On each occasion a shoot was cut from each of three aspects of the live crown using a high pruning sampler. This comprised a set of interconnecting lightweight aluminium poles and a pruning cutter with a sample grip, the cutter being operated with a long cord from the ground. The shoots were placed in polythene bags and put into cool insulated boxes while being transported to the laboratory. The next day, individual shoots were put in modified Tullgren funnels and the aphids collected in 80% alcohol so that they could be counted.

Summary of results

1985. The sampling at the population peak (21 May) only revealed aphids at four sites. Site 3 showed the highest numbers and was resampled on 30 July when aphids were still found to be present. Another comprehensive sampling was repeated on 9 October, well after the summer migration of alate was completed. At this time 15 sites had small numbers of aphids present.

1986. Intensive sampling was made at site 4 on 12 March where aphid activity had been seen but revealed low numbers. A comprehensive sampling was carried out on 13 May (the expected population peak) but it produced no aphids. So all the sites supporting aphids the previous autumn must have experienced some severe weather by the spring sampling date. Sites 4, 11 and 13 had a few aphids present again on 25 June, i.e. after the alate migration, but numbers dwindled over the next 4 months.

1987. Spot checks were made of all sites during the early part of 1987 but no aphids were found in these locations. A comprehensive sampling of all sites was carried out on 17 August after the alate migration and 10 sites were then found to have small numbers of aphids.

1988. Five sites, thought by now to be particularly favourable for aphids (sites 4, 6, 9, 11, 13) were sampled intensively on 18 January; all these sites had aphids present except site 4. Sites 9 and 11 were sampled intensively on 29 March and 27 April, but the numbers were far too low for this time of year (approaching population peak) to be of any significance. After the alate migration on 23 August, 15 of the sites

had aphids present as in the autumn of 1985 but marginally more abundant. Further intensive sampling at three sites on 31 October and 30 November confirmed a slight increase in their numbers.

1989. An early spring extensive sampling on 19 April confirmed good survival of aphids through the winter; the numbers averaged at 10-fold increase over any previous year. The two sites with the greatest numbers (sites 3 and 12), when sampled intensively on 27 April and again on 18 May, showed that the high numbers had been maintained and a widespread moderate defoliation then occurred at all sites. Intensive sampling at sites 3 and 6 on 20 September failed to reveal the presence of any aphids.

Over the period of observation in experiment Afan 1, only moderate defoliation by aphids occurred and it was confined to a single year, and then in only 2 out of the 20 sites. It is not surprising, therefore, that no significant effects on growth were found between sprayed and unsprayed trees (Chapter 2).

The effect of low air temperatures in preventing spring attacks

The complete absence of any aphids in the May 1986 sample could be accounted for by the very low air minimum temperature of -16°C (recorded at site 3) in the preceding winter months. Similarly, the winter of 1986/87 had very low air minimum temperatures down to -18°C which were sufficient to bring about significant mortality of the overwintering aphids. In contrast, the next three winters were warmer enabling some aphids to survive; -8°C is the temperature at which 50% mortality could be expected (Table 10.1).

The spring of 1989 with the highest numbers from the sampling was noticeably mild, allowing good survival and marked population increase by the middle of April. However, it is notable that there were virtually no aphids in the area in 1990 in spite of the mild winter weather. Such a sequence has been observed elsewhere, but the absence of aphids in the samples taken in September 1989 and the depletion of feeding sites by previous defoliation are likely to be significant factors.

Table 10.1 Air minimum temperatures (winter extremes) recorded at Afan 1 site 3

Month of reading	Position of thermometers (both at 1 m)	
	Fence post, open °C	Tree stem, inside spruce crop °C
2/85	-17	-15
12/85 3/86	-15 -18	-13 -16
12/86 2/87	-6 -21	-4 -18
12/87 1/88	-8 -10	-5 -8
11/88 to 3/89	-11	-8
11/89 to 5/90	-10	-8

Spruce root aphids: *Pachypappa vesicalis* and *Pachypappella lactea*

The widespread occurrence of root aphids and their associated white wax-wool secretions in masses round the fine roots has been very notable in Afan Forest. This phenomenon has been seen in other parts of Britain in the past, but only on nursery plants has any serious impact been noted (Carter, 1962; Hochmut, 1966). During the first two seasons of this field study at Afan Forest, small differences in tree growth on certain sites were found between sprayed and unsprayed trees although the *Elatobium* populations had been negligible. A pilot sampling (using a soil coring tool) of the rooting zone under sprayed and unsprayed trees for the abundance of root aphids suggested that the insecticidal drench from spraying the foliage at sites 8 and 9 may have had some controlling effect on root aphids (Table 10.2). This would seem feasible since many of the fine roots are within the top 10 cm of the soil surface.

Table 10.2 Comparison of the numbers of the root aphids present in soil samples from under sprayed and unsprayed trees (24 November 1986)

Site number	Sprayed trees	Unsprayed trees
5	12	26
6	127	136
8	1	31
9	1	120

Note These results are from two 10 cm diameter litter cores taken from the top 15 cm of litter and soil below each of the four sprayed and four unsprayed trees at each site. The apparent lack of effect from the insecticide spraying at site 6 could be accounted for by the different size of trees and the angle of application. Here the trees were smaller than the other three sites and the spray was applied horizontally. In contrast, the trees at the other sites were taller, the jet of spray was at a steeper angle to the crown foliage which would in turn intercept a greater volume of spray.

Identity and life cycle of the spruce root aphids

There have been difficulties in unravelling the appropriate name for spruce root aphids in Britain. The most significant recent account has been that of Stroyan (1975) who pieced together the life cycle of one species (*Pachypappa tremulae* (L.)) that alternates between two host plants (Norway spruce roots and galled Aspen leaves) by winged migration. Since then, Danielsson (1990) has found morphological features and differences of the gall-making generation on *Populus* to distinguish two other species, namely *Pachypappa vesicalis* Koch, and *Pachypappella lactea* (Tullgren). An account of their discovery and occurrence in Britain is given by Carter and Danielsson (1991). These three species are present in Wales, but it is probably only the latter two that need to be considered at Afan.

A simplified representation of the life cycle of the most abundant species *P. vesicalis*, is shown in Figure 10.3, but it is important to take into account the absence of the poplar hosts in the coalfield plateau which was treeless *Molinia* moorland before afforestation. The aphid colonies have been found to exist anholocyclicly on roots throughout the year in Afan forest. How *P. vesicalis* disperses, if the poplar host is not present, is a matter of current investigation. But as this species is known to occur on nursery stock, it is quite possible that they were brought into the forest on transplants and have now become well established.

Seasonal fluctuation in abundance and the distribution on roots

Periodic sampling of roots to 10 cm deep from August 1989 to January 1991 has revealed an abundance of aphids during October and the fewest during the early months of the year. Throughout the whole of this period apterous virginoparae were present in small colonies on the fine roots. During late September to October, winged aphids (sexuparae) were produced, especially in those places where the fine roots were at (or near) the surface especially on the sides of drainage ditches. There have been no other winged forms found (such as winged virginoparae) that could transfer from spruce roots to spruce roots.

During the late summer drought of 1990 there were no flourishing colonies on a deep peat

study area in site 3. By early September the bases of plough furrows between the planting lines were very dry and wide cracks had appeared in the peat; it was only in the moister places that aphid colonies were active. By mid-October, following a period of wet weather, new root growth was conspicuous and dense colonies were again found. Sampling the same site in late October revealed extensive aphid colonies on the banks of drains and among fine branching tree roots within suppressed *Molinia* tussocks. These more conspicuous colonies with flocculent wax wool around them were of the larger of the two species, *Pachypappa vesicalis*. In the summer drought, the planting ridges were much drier and fewer aphids were found in this zone. However, smaller, discreet greyish white specks of wax wool (about 3 mm diameter) were present just under the layer of dead needles. These woolly specks enclosed a cell-like pocket over a small root and were the sites where the other species (*Pachypappella lactea*) fed.

Both rooting zones, from the more freely drained ridges to the wet furrows, can be colonised by one or other of these root aphids. The copious wax production by *P. vesicalis* is likely to protect the aphids from temporary periods of saturated soil conditions. Such a protection has been recorded in the case of a closely related aphid (*Pemphigus trehernei* Foster) that survives periods of inundation while living on plants growing in tidal salt marshes (Foster, 1976).

Feeding and production of secretions

From observation, *Pachypappa vesicalis* grows larger and possibly at a more rapid rate than *Pachypappella lactea*. While feeding, the aphids remove from the roots amino acids and carbohydrates that the plant requires for growth. During this process, *P. vesicalis* produces conspicuous honeydew droplets which can be seen as liquid spheres coated with wax particles; this coating prevents the aphids from being fouled-up and is an advantage since ants, the usual exploiters of honeydew, have not been found in these aphid colonies. This water-repellent wax secretion also surrounds the young active roots so it may impair their efficiency by creating a hydrophobic barrier for the uptake of water and soil nutrients. How the aphids interact with mycorrhizae and how much they influence root anatomy in this actively growing zone is under investigation.

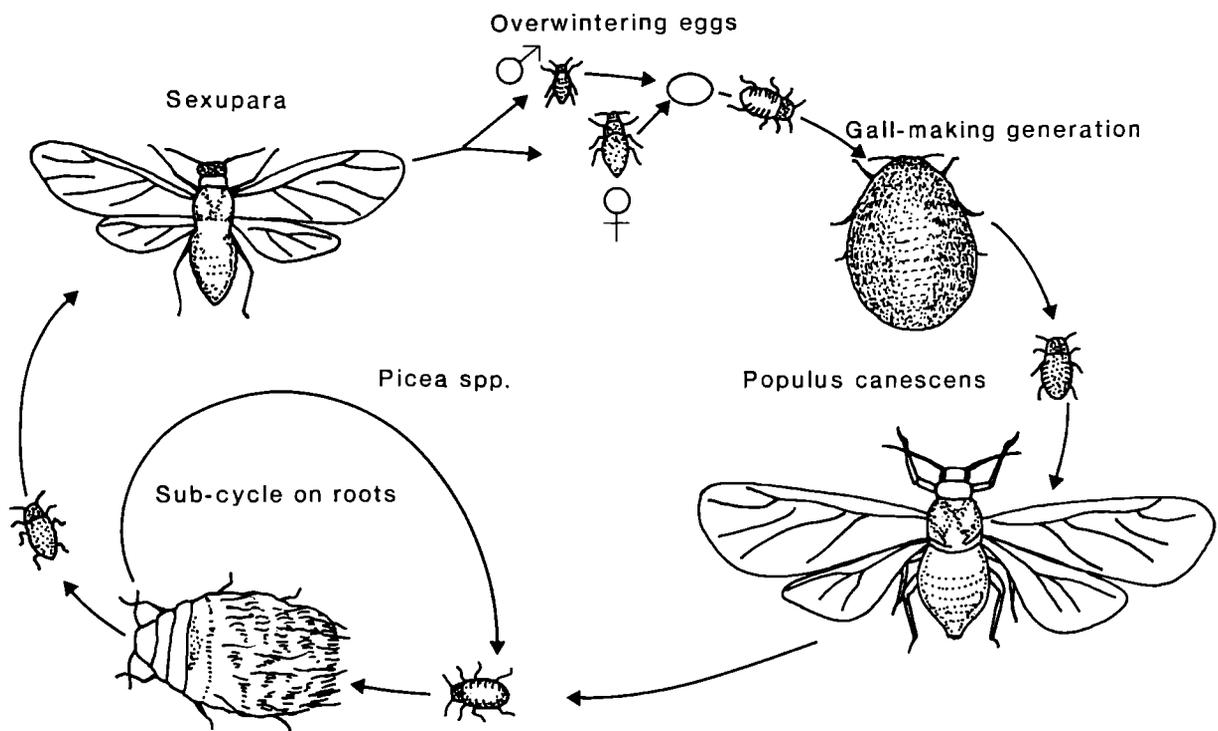


Figure 10.3 Life cycle of *Pachypappa vesicalis*. The alate forms from *Populus canescens* leaf galls migrate to spruce roots in early summer. Apterous forms occur throughout the year on spruce roots. The alate sexupara form migrates from spruce roots to *Populus canescens* in the late autumn and gives birth to minute males and females that pair to produce a single overwintering egg.

Concluding remarks

That a loss of increment from *Elatobium* does occur has been clearly demonstrated by Carter and Nichols (1988) and in this present study. It seems doubtful if the losses can ever be made up in subsequent seasons. The decrease in photo-synthetic area from a defoliation results in a change to a more open crown climate. *Elatobium* defoliation also leads to a reduction in root growth (Carter, 1977). A combination of these new conditions could result in increased transpiration demands by the remaining foliage and root waterlogging. If the root aphids are present throughout the year, they could respond to periods of seasonal root growth and take advantage of mild winter weather. So, in combination with *Elatobium* they may be significant contributors to a forest decline syndrome such as has been experienced in Afan Forest.

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Chapter 11

Infection of Sitka spruce needles by endophytic fungi

M.K. Smith and N. Magan

Introduction

Symptoms of declining Sitka spruce on the South Wales coalfield are described by Coutts and Danby in Chapter 1, and mention is made of the possible role of needle fungi in bringing about the symptoms of needle discoloration and premature defoliation that are common on the affected trees at Afan.

Lophodermium species cause needle cast on several conifers, including pines and spruces. Spores of *Lophodermium* are usually released in damp humid conditions and deposited on needles to which they adhere. They germinate under favourable environmental conditions forming germ tubes and appresoria from which infection pegs penetrate the epidermis (Millar, 1981). *Lophodermium pinastri* has been the most often quoted species in the literature causing characteristic banding on needles. However, studies by Minter and Millar (1980) showed that on Scots pine needles *L. seditiosum* caused a serious disease in young plantations; *L. pinastri* colonised senescing needles; and *L. conigenum* fruited mainly on needles of damaged trees and branches. Other work has shown that apparently healthy pine needles are often already colonised by *Lophodermium* spp. which cause inconspicuous chlorotic to necrotic flecks in the needle epidermis (Costonis and Sinclair, 1967; Lanier, 1968; Miller, 1981). In Germany and Sweden *L. piceae* (Fuck.) Höhn. has been found to be predominant in green needles of Norway spruce (Butin and Wagner, 1985; Suske and Acker, 1987a,b) although it was found to be more common in young healthy stands than stressed diseased ones in Sweden (Barklund, 1987). *Lophodermium piceae* has been described as a weak parasite or saprophyte (Darker, 1932) but Butin (1983) described it as an aggressive pathogen.

Another fungus isolated from needles of conifer trees has been *Rhizosphaera kalkhoffii* Bubák. This fungus has been isolated from both green and brown needles (Butin, 1983; Rehfuess and Rodenkirchen, 1984) and has been demonstrated to cause a needle blight of Japanese red pine in the 1960s (Chiba and Tanaka, 1968). Usually infection occurs via pycnidiospores. After infection, mycelium grows within the tissue forming a hyphal mass which forms the outer layer of the pycnidial wall in which the pycnidiospores are later produced on the needle surface (Kobayashi, 1967). It has been suggested that trees under water stress may be particularly susceptible to infection by *R. kalkhoffii* (Tanaka, 1980). Sulphur dioxide fumigation has also been shown to facilitate the spread of *R. kalkhoffii* within needles rather than predisposing them to infection. Pycnidiospores of this fungus had no effect on seedlings until exposed to atmospheric pollutants. Tanaka (1980) suggested that *R. kalkhoffii* was a weak parasite which infected needles under environmental stress.

Both these fungi have been considered to be endophytes, defined as fungi that cause unapparent, asymptomatic infections entirely within the plant tissue (Petrini, 1986; Carroll, 1986). However, endophytes can become pathogenic, causing symptoms on the host if previously exposed to nutrient and environmental stress (Carroll, 1986).

There has recently been considerable discussion about the possible role of fungal infection of needles in the development of forest decline in parts of Europe. Rehfuess and Rodenkirchen (1984) isolated both *L. piceae* and *R. kalkhoffii* from spruce needles in Germany and suggested that they together caused needle-reddening disease (Nadelrote). However, after detailed sampling of spruce stands Butin and Wagner (1985)

suggested that both *L. piceae* and *R. kalkhoffii* were only early colonisers of dying or dead needles and not implicated in needle-reddening disease. Recently, Suske and Acker (1989) demonstrated that *L. piceae* was present in the tissues of green, symptomless needles. In both Scotland and northern England premature loss of needles from Sitka spruce plantations was accompanied by a high level of colonisation by *R. kalkhoffii* and *L. piceae* (Gregory and Redfern, 1987). Furthermore, needles collected from Sitka spruce trees in the poor growth sites in South Wales (Tywi and Afan) in 1986/87 showed that some of the green and yellow needles were predominantly colonised by *L. piceae*, while brown needles were colonised by *R. kalkhoffii* (D.B. Redfern, personal communication).

Objectives and methods

The objectives of this study were therefore to determine the patterns of colonisation of Sitka spruce needles by these two fungi in an intensively studied poor growth site in Afan and compare this with their behaviour in a good growth site at Mynydd Du in the Black Mountains of East Powys. It was also decided to compare the level of colonisation by these two fungi in a replicated fertiliser experiment in the poor growth site and under the influence of a pesticide treatment designed to control the green spruce aphid (*Elatobium abietinum* Walker).

Table 11.1 Comparison of the percentage isolation of *Lophodermium piceae* and *Rhizosphaera kalkhoffii* from green Sitka spruce needles in experiment Afan 2 and at Mynydd Du

Percentage occurrence on needle segments						
<i>L. piceae</i>						
Needle age class	1987		1988		1989	
Site sampled	Afan 2	M. Du	Afan 2	M. Du	Afan 2	M. Du
April 1989	0.4	1.3	1.3	0.4	–	–
September 1989	0	0	2.1	0	–	0
December 1989	1.7	5.0	2.1	1.7	0.8	3.3
March 1990	0.8	0	0.8	0	0.2	0
June 1990	0.4	0	0.2	0	0	0
September 1990	np	np	1.7	0.8	0.09	0
<i>R. kalkhoffii</i>						
Needle age class	1987		1988		1989	
Site sampled	Afan 2	M. Du	Afan 2	M. Du	Afan 2	M. Du
April 1989	10.8	0.4	1.7	0	np	np
September 1989	0.4	0	1.3	1.7	0	0
December 1989	13.3	1.7	0.8	1.7	0.4	0.8
March 1990	4.6	0.8	2.9	0	0.2	0
June 1990	np	np	1.4	0	0.2	0
September 1990	np	np	6.9	0	3.5	1.7

np: needles not present.

Table 11.2 Comparison of the occurrence of *Lophodermium piceae* and *Rhizosphaera kalkhoffii* on green Sitka spruce needles in experiment Afan 1, site 12, untreated and treated with pesticide

Mean percentage colonisation of needles						
<i>L. piceae</i>						
Needle age class	1987		1988		1989	
Treatment	Control	Spray	Control	Spray	Control	Spray
April 1989	1.2	0	0	0.4	0	0
September 1989	0	0	5.0	0	0.7	0
December 1989	11.2	2.2	0	1.3	0	0
March 1990	3.9	0.4	2.1	0	0.9	0
June 1990	np	np	3.3	0	1.5	4.2
September 1990	np	np	2.1	0	0	0.8
<i>R. kalkhoffii</i>						
Needle age class	1987		1988		1989	
Treatment	Control	Spray	Control	Spray	Control	Spray
April 1989	4.7	1.4	1.3	0.4	0	0
September 1989	0	0	7.5	8.1	0	0.8
December 1989	13.3	1.7	5.0	3.3	1.7	0.4
March 1990	6.1	2.1	3.9	1.3	0.6	0.4
June 1990	np	np	3.3	1.3	0.9	0
September 1990	np	np	9.7	0	0.7	1.7

^aSpray: pesticide application in April 1989.

Trees from both the poor growth Afan 2 site (Chapter 6) (four trees in 1989 and eight in 1990), the good growth Mynydd Du site (four trees), and plots in experiment Afan 1, site 12 (Chapter 5) (four trees, with and without pesticide application) were sampled. Branches with current and at least two previous years' needles were removed from an upper whorl, at a height of about 4 m. However, at Mynydd Du, because of the height of the trees, samples taken at 4 m were from within the canopy. Branches were either placed in labelled plastic bags and removed to the laboratory for further separation or the needle year classes removed and immediately placed in labelled sterile Universal

bottles. Branches and needles were stored at 4°C until detailed mycological examination could be carried out.

Green needles from the three year classes were then surface-sterilised in 20 ml sodium hypochlorite solution (7.5% available chlorine) which also contained a 1:100 solution of 95% ethanol to wet the needles (adapted from Carroll and Carroll, 1978; Petrini, 1986). The Universal bottles containing needles and sterilising solution were agitated with a whirlimix for 30s and left for 4.5 min. The sterilising solution was decanted and the needles placed between sheets of 9 cm diameter filter paper (Whatman No. 1) and

blotted dry. The needles were cut aseptically into 5 mm segments and plated on 1% malt extract agar (pH 4.0). Twelve segments per plate and five replicate plates per year class were set up for each tree (total of 240 segments per age class). Plates were incubated at 20°C and examined weekly for up to 4 weeks before identification and assessment of colonisation.

Results

Table 11.1 compares the percentage of needle segments from which *L. piceae* and *R. kalkhoffii*

were isolated at the poor growth and good growth sites. *Rhizosphaera kalkhoffii* was generally more abundant than *L. piceae*, particularly on the poor growth site. Regardless of needle age, *L. piceae* was present on a low percentage of green needles in both sites. Percentage colonisation of needles of the 1988 year class with *R. kalkhoffii* suggested an increase with sample time in the poor growth site. However, in the 1987 year class colonisation was greater than 10% on two sampling occasions but was not consistently high. Discoloured needles were not often present because of the severe nature of the defoliation.

Table 11.3 Comparison of the isolation of *Lophodermium piceae* and *Rhizosphaera kalkhoffii* from green needles of Sitka spruce in untreated plots and those receiving fertiliser in the Afan 2 site

Mean percentage occurrence on needles						
<i>L. piceae</i>						
Needle age class	1987		1988		1989	
Treatment	Control	Fert	Control	Fert	Control	Fert
April 1989	0.4	4.2	1.3	0	-	-
September 1989	0	3.8	2.1	1.3	0	2.1
December 1989	1.7	6.7	2.1	3.8	0.8	4.2
March 1990	0.8	1.3	0.8	0.4	0.2	0.8
June 1990	0.4	np	0.2	0	0	0.8
September 1990	np	np	1.7	0.4	0.09	0
<i>R. kalkhoffii</i>						
Needle age class	1987		1988		1989	
Treatment	Control	Fert	Control	Fert	Control	Fert
April 1989	10.8	5.9	1.7	0	np	np
September 1989	0.4	9.6	1.3	5.4	0	0
December 1989	13.3	4.2	0.8	2.1	0.4	0.8
March 1990	4.6	5.0	2.9	3.3	0.2	2.3
June 1990	np	np	1.4	2.0	0.2	0.4
September 1990	np	np	6.9	2.5	3.5	2.5

np: needles not present.

Fert: luxury fertiliser application.

The possible relationship between occurrence of *L. piceae*, *R. kalkhoffii* and green spruce aphids was studied in the pesticide trial on Afan 1 (Table 11.2). Needles of all classes receiving pesticides were found to have a marked reduction in colonisation, particularly by *R. kalkhoffii*. The high level of needle colonisation by *R. kalkhoffii* (see Table 11.1) on Afan 2 in April 1989 (on the 1987 year class needles) may have been due to the outbreak of *Elatobium* in this site in March of that year. Previously, work by Skarmoutsos and Millar (1982) with *Adelges* aphids on *Larix eurolepis* showed that a number of species of fungi, including *Lophodermium* spp., could be isolated from needles attacked by the aphid. They also found marked differences in the endophytic mycoflora between the feeding points of the aphids, unattacked parts of needles and naturally senescent needles. These observations suggest that the action of feeding aphids may play a role in the ecology of needle pathogens. Unfortunately, in the Afan sites, no large outbreak of aphids occurred in 1990 or 1991.

The addition of luxury amounts of fertiliser to plots at the Afan 2 site resulted in different patterns of colonisation of needles by *L. piceae* and *R. kalkhoffii* (Table 11.3). *Lophodermium piceae* was isolated from a higher percentage of needles found in both 1987 and 1989 in the fertilised plots than the control unfertilised plots. However, isolation of *R. kalkhoffii* from needle segments from plots receiving a fertiliser remained similar or were slightly reduced when compared to controls. Needle retention was similar in the two treatments although trees receiving the fertiliser appeared greener and healthier. The increase in *L. piceae* may partially have been due to an increase in nutrient availability in the needles in the fertiliser plots.

This work suggests that colonisation by endophytic fungi, particularly *R. kalkhoffii*, may increase in Sitka spruce trees with poor vigour and thus contribute to premature senescence of needles. However, complex interactions may occur with aphid infestation and other environmental factors, and at this stage it is difficult to evaluate the role of endophytic fungi in the decline of Sitka spruce in South Wales.

Acknowledgements

We are very grateful to Dr John Gibbs for advice, Neville Danby and his staff for their valuable help with sampling and to the NERC for financial support.

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Chapter 12

Assessment of the role of physiological response to sulphur dioxide in Sitka spruce

P.H. Freer-Smith and M.C. Dobson

Introduction

It has long been recognised that sulphur dioxide (SO₂) in high concentrations can have detrimental effects on tree growth. For example, during the 1950s and 1960s Scots pine, Sitka spruce and other species grew badly in the industrial Pennines of Britain. Although this poor growth could not be attributed specifically to SO₂ episodes, the sulphur content of Scots pine needles was correlated with winter time SO₂ concentrations. Furthermore, significant improvements in growth occurred after the mid 1960s when pollutant concentrations declined (Lines, 1984) as a result of the Clean Air Acts of 1956 and 1968.

Large winter time concentrations and episodes of SO₂ occurred during the late 1970s when UK emissions were at their peak; however, even since the major emission reductions, maximum daily mean concentrations at rural sites have reached values of up to 120 nl l⁻¹ (Martin and Barber, 1980). Such concentrations would not generally be expected to cause visible injury but physiological effects might be detected in sensitive tree species. For example, Keller (1980) found reduced rates of photosynthesis in *Picea abies* fumigated with 50-200 nl l⁻¹ SO₂, which resulted in reduced cambial growth, while Garsed *et al.* (1979) found that 60 nl l⁻¹ decreased stem and needle elongation and caused premature leaf senescence.

The check of Sitka spruce in Afan Forest may result from the combined effects of a number of factors or stresses (Coutts *et al.*, 1985); these may include gaseous deposition of SO₂ from local sources (Chapter 2). Port Talbot, 15 miles (c. 20 km) from the edge of the forest has many heavy industries including steel works and oil

refineries. Other important factors may include exposure, frost, winter waterlogging, spring or summer drought, defoliation by the green spruce aphid (*Elatobium abietinum*), or other pollutants. The symptoms of decline described by Coutts *et al.* (1985), although not specific to SO₂, are similar to symptoms of damage to spruce from chronic exposure to SO₂. The work described in this chapter was conducted in order to assess the possible role of gaseous SO₂ in the problems that have arisen in some Sitka spruce stands in the Afan District.

In the checked stands large variation is evident between the vigour of individual trees (Chapter 4), with poorly growing and relatively vigorous trees found close together, indicating that some trees are more able to withstand the combination of stress factors than others. This is a common observation for forests suffering decline (e.g. Brenner *et al.*, 1988), and may result from genotypic differences which give strong variability in the tree response to the stress or combination of stresses responsible for the decline. In order to determine whether different susceptibility to SO₂ was responsible for such growth variations, cuttings were taken from seven pairs of trees, each pair consisting of a tree relatively tolerant of the conditions causing decline and a nearby tree in an advanced stage of decline. Experiments were conducted on the rooted cuttings of these 'good' and 'poor' trees in order to determine:

- Whether there were intrinsic differences in the photosynthetic and stomatal characteristics of the good and poor clones.
- Whether there were differences between good and poor clones in susceptibility to an SO₂ episode.

- Whether the uptake rate of SO_2 by the cuttings was significantly different for good and poor clones.

If clonal cuttings from trees growing poorly took up more SO_2 than those from trees growing well, and showed more physiological damage from exposure to it, this would suggest that genotypically controlled differences in sensitivity to SO_2 are among the factors responsible for poor growth in the Afan district.

Materials and Methods

In 1986 cuttings were taken from seven pairs of Sitka spruce (*Picea sitchensis* [Bong.] Carr.) trees, c. 26 years old. Each pair was made up of a tree tolerant to the conditions causing decline, which was relatively vigorous (good), and a nearby tree which was intolerant of the site conditions and in an advanced stage of decline (poor). Good trees were between 20% and 60% taller than poor trees and had between 61% and 80% greater diameter at breast height (dbh). The rooted cuttings from each pair of trees were grown out-of-doors in peat supplemented with 'Osmocote' slow release fertiliser (N:P:K, 8:11:10) and were sprayed with Pirimicarb once to control *Elatobium abietinum*. In December 1988 eight clonal cuttings (eight poor, eight good) from each of pairs 1, 5 and 6 were selected for experimental work and were brought into a polyhouse ventilated with charcoal filtered air.

Measurements of photosynthetic characteristics, stomatal responses and SO_2 flux were made between February and July 1989 using the system described by Dobson (1990). With this system the shoots of four individual cuttings were enclosed in single-plant chambers each day. The uptake or output of carbon dioxide (CO_2), water vapour (H_2O) and SO_2 from each plant was measured and net rates of photosynthesis, transpiration and SO_2 flux were then calculated. The fluxes of CO_2 , H_2O and SO_2 between the needle and air are controlled by the concentration gradient and the resistances between the source and sink. Mesophyll and stomatal conductances are conventionally used to quantify the magnitude of the stomatal and mesophyll resistances in the flux pathway. When gas exchange parameters are calculated according to the model proposed by von Caemmerer and Farquhar (1981) and measurements are made at different photosynthetic photon flux densities (PPFD) and CO_2 concentrations, parameters can be derived which describe the stomatal and biochemical charac-

teristics of the needle and the photosynthetic apparatus.

Measurements were made in clean, unpolluted air and in air containing $150 \text{ nl l}^{-1} \text{ SO}_2$ so that the effects of a SO_2 episode on stomatal and biochemical characteristics could be determined. The main parameters derived from measurements at different light levels were as follows:

- the apparent quantum yield (dA/dQ), which represents the number of moles of CO_2 taken up per quantum of light intercepted by the shoots;
- the light saturation rate of net photosynthesis (A_{max}), which is an indication of the photosynthetic capacity of the shoots;
- the light saturation values of transpiration (E_{max}) and stomatal conductance ($g_{\text{s max}}$).

The parameters derived from measurements at different CO_2 concentrations were carboxylation efficiency (dA/dC_i), which is indicative of the activity of the primary carboxylation enzyme Rubisco and the maximum rate of ribulose-1,5-bisphosphate regeneration (J_{max}), which is controlled by the rate of coupled photosynthetic electron transport.

During February and March 1989 the relationships between photosynthetic rate and CO_2 concentration were determined for eight trees per clone for pairs 1, 5 and 6. These trees were then placed in controlled environments where they completed leader extension in May, so that CO_2 response curves could be re-measured and the relationship between PPFD and photosynthetic rates determined in July. At the second set of measurements CO_2 and light response curves were determined in clean air on the first day and in $150 \text{ nl l}^{-1} \text{ SO}_2$ during the second day.

Results

Figure 12.1 shows the relationship between net photosynthetic rates and CO_2 concentration measured during dormancy for cuttings taken from the good and poor trees. Each curve is the mean for measurements made on eight trees. Analysis of variance of the initial slopes of the individual curves (dA/dC_i) revealed significantly lower carboxylation efficiency for the poor clones compared to the good clones of pair 5. These results thus confirm the observation from measurements made before budbreak

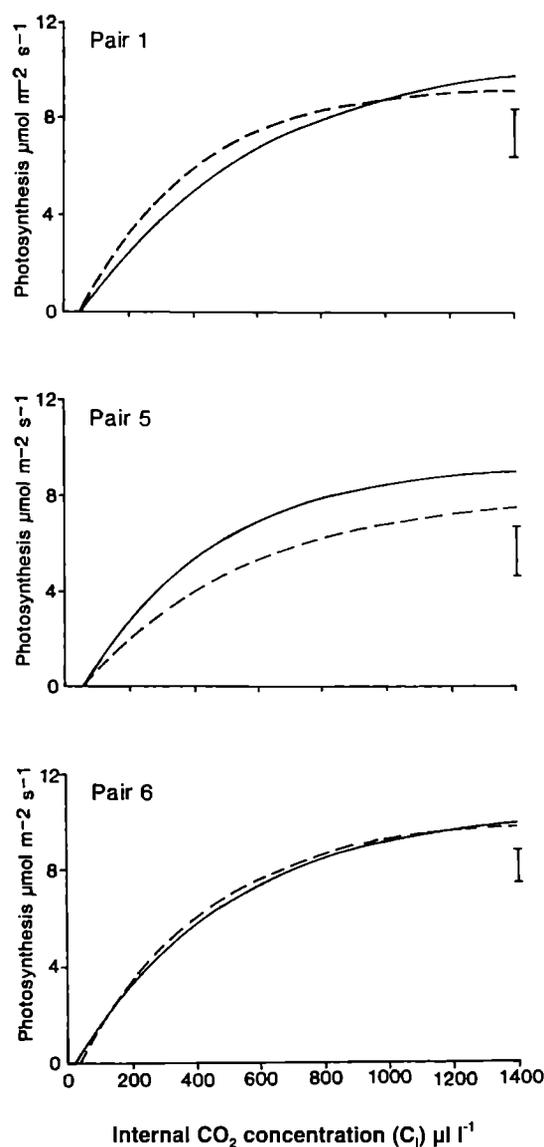


Figure 12.1 The effects of increasing internal CO_2 concentration on rates of net photosynthesis during dormancy for clones of *Picea sitchensis* taken from pairs of parent trees (1, 5 and 6) of visually poor (---) and good (—) appearance. Curves are means of 8 individually fitted curves. LSDs ($p < 0.05$) are shown for the highest CO_2 concentration.

that the poor clones tend to have less favourable photosynthetic performance in clean air than the good clones. Similarly, the parameters derived from the light-response curves also show lower values for the poor genotype of pair 5 (quantum yield, light saturated rates of photosynthesis and transpiration). There was also a suggestion of lower values of maximum rate of transpiration for the poor clones of pair 6.

Exposure to SO_2 for 5 h at 150 nl l^{-1} significantly decreased carboxylation efficiency of both poor and good clones of pair 6. For pair 1 the light saturated rate of photosynthesis was significantly depressed by SO_2 in both poor and good clones, and for pair 5 the maximum stomatal conductance values, maximum rates of photo-

synthesis and transpiration (A_{max} , E_{max} and $g_{s \text{ max}}$) were depressed by SO_2 for both poor and good clones. The maximum values of stomatal conductance ($g_{s \text{ max}}$) were also lower for cuttings of both poor and good clones exposed to SO_2 as compared to the values in clean air. On no occasion were there any statistically significant interactions in the effects of genotype and SO_2 .

Figures 12.2 and 12.3 show the SO_2 uptake rates, or flux, to the shoots of the cuttings measured during the determination of CO_2 -response and light-response curves respectively. The fluxes are plotted against stomatal conductance and it can be seen that as the stomata open SO_2 uptake increases. Linear regressions were fitted to describe the relationship between stomatal

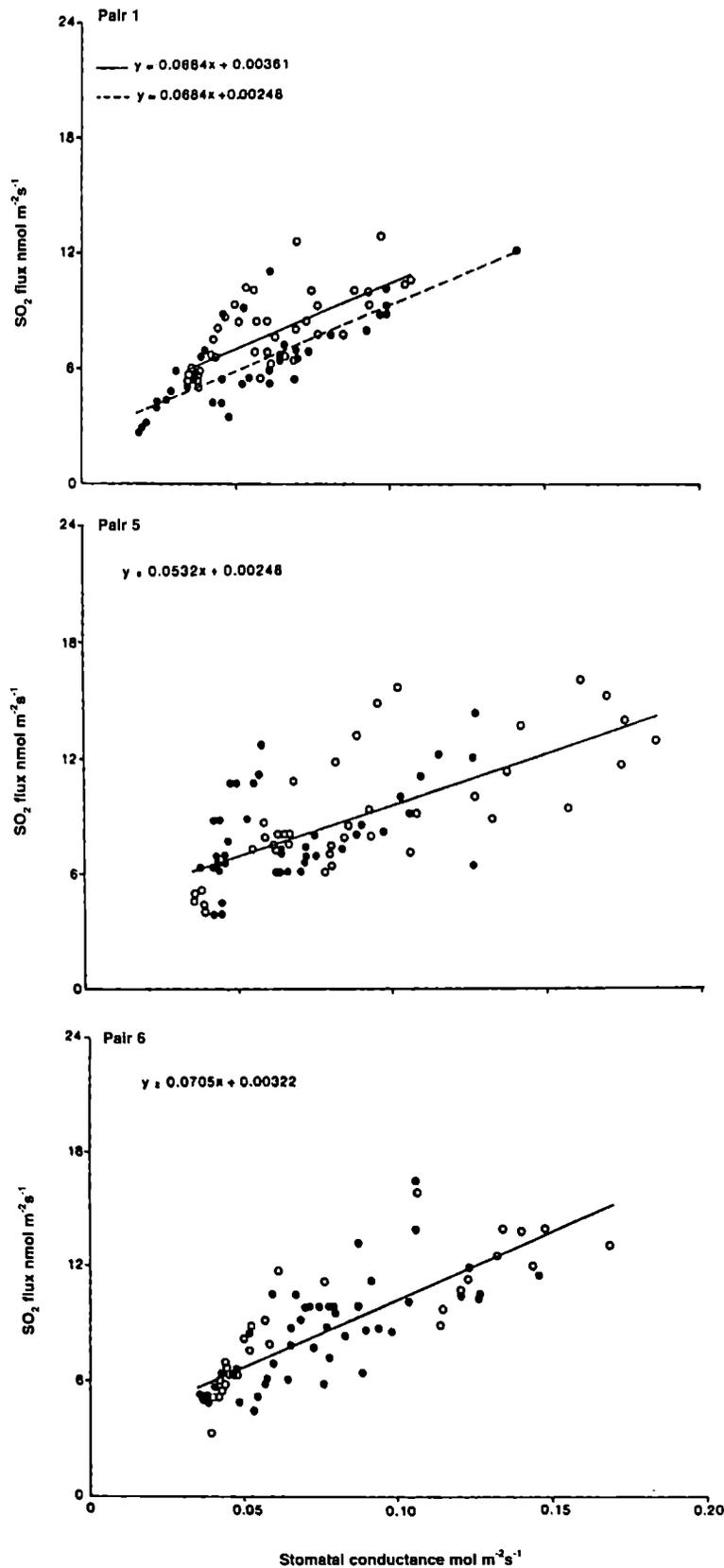


Figure 12.2 The effects of stomatal conductance on uptake rates of SO₂, after budbreak, for clones of *Picea sitchensis* taken from pairs of parent trees (1, 5 and 6) of visually poor (●) and good (○) appearance. Measurements of g_s and SO₂ flux were made during the determination of CO₂-response curves (Figure 12.1). Single regressions were calculated for the data set in each case except where Genstat indicated that calculating separate regressions would give a significant ($p < 0.05$) improvement in the 'goodness of fit'. The percentages of variance accounted for by the regressions for each pair were 62.3%, 45.3% and 64.6%, respectively.

conductance and SO₂ flux. Separate regression equations were fitted for poor and good cuttings only when this significantly ($p=0.05$) improved the percentage of variance accounted for by the regressions. For pair 5 the relationship between g_s and SO₂ flux was similar for cuttings from poor and good trees, but mean fluxes over all g_s values were marginally greater in cuttings taken from the trees showing good growth because stomatal conductances reached larger values (Figures 12.2 and 12.3). When SO₂ fluxes were measured during the determination of CO₂-response curves the good genotype of pair 1 showed larger fluxes at all stomatal conductances (Figure 12.2), and the same effect was detected for the good clone of pair 6 during the light-response curve (Figure 12.3). On no occasion did the cuttings from the poor trees of each pair take up more SO₂ than the good clones.

Discussion

Since all of the cuttings were rooted and grown under the same conditions, any differences in photosynthetic characteristics and responses to SO₂ can be attributed primarily to genotypic differences. The measurements of photosynthesis and stomatal conductance made both before and after budbreak generally show that cuttings taken from the poor parent trees had poorer photosynthetic performance than their good counterparts. For all three pairs there were indications of lower maximum values of A , E and g_s at light saturation for poor clones, and for pair 5, carboxylation efficiency and J_{max} , values were also significantly lower. As well as indicating, as would be expected, that genotype has an influence on photosynthetic characteristics, these data suggest that the physiological parameters which were measured have some influence on the ability of trees to survive the mixture of stressful factors experienced in the Afan Forest District. Thus, trees with poorer, genetically determined, photosynthetic characteristics appear to have grown less well in the forest. These less vigorous individuals may consequently be more susceptible to periodic stress caused by factors such as frost, drought or defoliation by *Elatobium*.

SO₂ episodes similar to those which have been experienced on the fringes of large industrial and urban areas (i.e. 150 nl l⁻¹ for 5 h) have been shown to influence the photosynthetic and stomatal responses of *P. sitchensis*. For pairs 1 and 5 maximum photosynthetic rates, stomatal

conductances and transpiration rates were depressed by SO₂ in both good and poor clones, while for pair 6 carboxylation efficiency was decreased by SO₂ for both sets of clones. These results suggest that for pairs 1 and 5 SO₂ may be influencing gas exchange through an effect on stomata, while for the clones of pair 6 effects may have been mediated through the action of SO₂ on the mesophyll. Both those mechanisms have been reported for herbaceous plants (Koziol and Whatley, 1984). Although these effects of SO₂ are important in that they indicate mechanisms by which SO₂ may be influencing needle biochemistry, the most significant finding is that there were no differences in the responses of good and poor clones to SO₂. Both genotype and exposure to SO₂ affected stomatal and photosynthetic performance, but there were no statistically significant interactions in the effects of these two factors. Both poor and good clones of all three pairs consistently responded to SO₂ in the same way, indicating that response to SO₂ is unlikely to have contributed to the phenotypic differences between the original parent trees. This finding casts doubt over the direct effect of SO₂ as a factor responsible for the check in growth of trees at Afan.

There is no clear indication that the effects of SO₂ on physiology would be detrimental to growth in the long term. However, interactions of SO₂ episodes with other stress factors cannot be ruled out and the effects of sulphur on tree nutrition, soils and biotic agents such as *Elatobium abietinum* may well be important. For example, from observations made on trees fumigated over long periods with small concentrations of SO₂ (60 nl l⁻¹), Freer-Smith (1983) found that fumigated trees of *P. sitchensis* were able to support larger populations of *E. abietinum* than the clean-air controls.

The SO₂ flux data are of considerable interest and add further evidence against the hypothesis that direct SO₂ damage is responsible for the observed decline. SO₂ flux was shown to be linearly related to stomatal conductance and, as described above, SO₂ caused stomatal closure in all clones. This suggests the operation of an exclusion mechanism as has been suggested by Atkinson and Winner (1989), except that because of the more active physiology of the good clones, they showed generally larger values of stomatal conductance in clean air and in the presence of SO₂ (Table 12.1) and these resulted in greater SO₂ uptake (Figure 12.1).

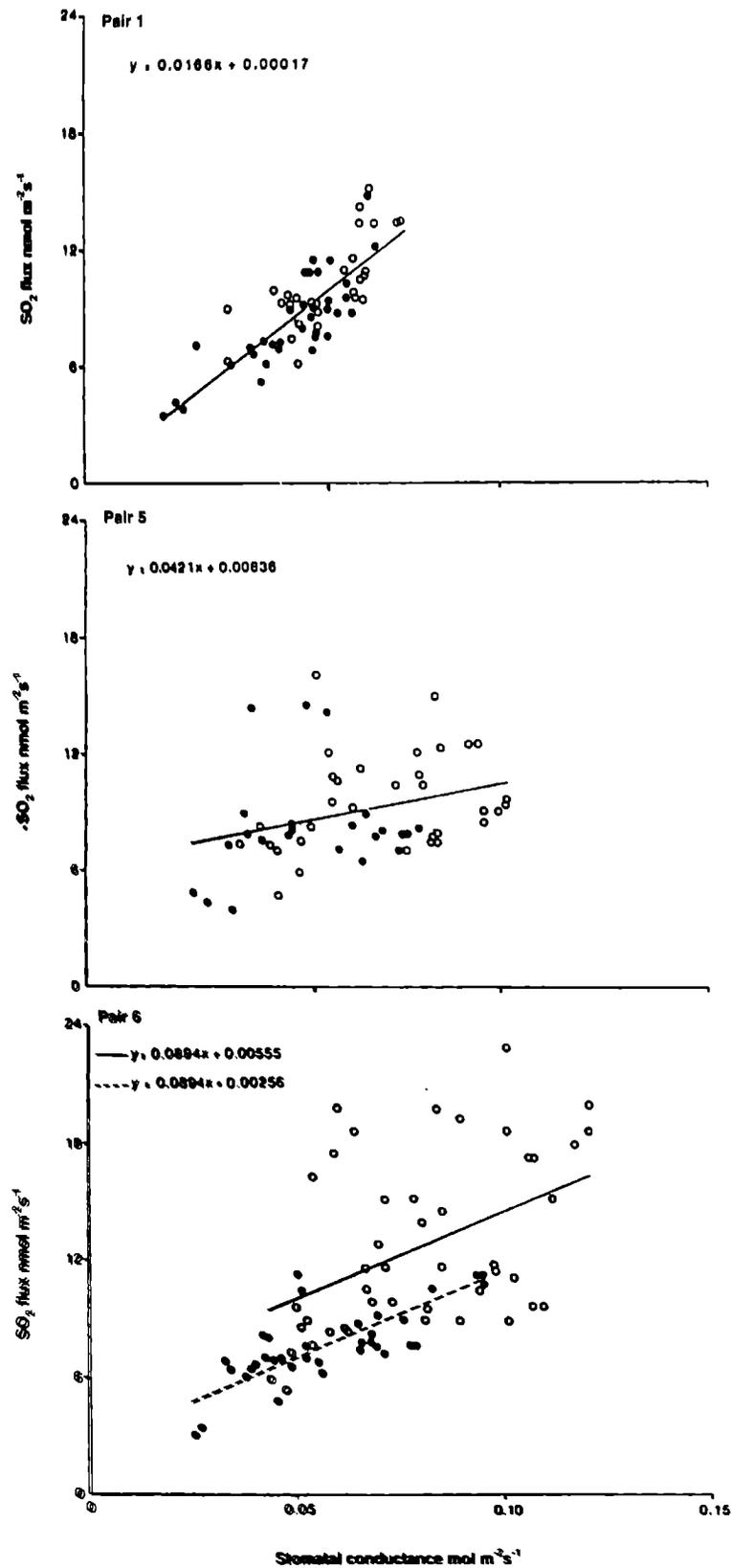


Figure 12.3 The effects of stomatal conductance on uptake rates of SO_2 , after budbreak, for clones of *Pinus sitchouensis* taken from pairs of parent trees (1, 5 and 6) of visually poor (•) and good (○) appearance. Measurements of g_s and SO_2 flux were made during the determination of light-response curves. Single regressions were calculated for the data set in each case except where Genstat indicated that calculating separate regressions would give a significant ($p < 0.05$) improvement in the 'goodness of fit'. The percentages of variance accounted for by the regressions for each pair were 66.3%, 8.8% and 47.2%, respectively.

Table 12.1 Effects of exposing clones of *Picea sitchensis*, from pairs of parent trees (1, 5 and 6) of visually poor (P) and good (G) appearance, to clean air for 5 h (-SO₂) and, on the following day, to air conditioned with 150 nl l⁻¹ SO₂ for 5 h (+SO₂). (a) Measurements were made of Rubisco regeneration capacity (J_{\max}) and carboxylation efficiency (dA/dC_i). (b) Measurements were made of quantum yield (dA/dQ), light saturated rate of photosynthesis (A_{\max}), and values of E (E_{\max}) and g_s ($g_{s\max}$) at a PPFD of 800 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Each value is the mean of four measurements. Significant effects are marked ** $p < 0.01$, * $p < 0.05$

(a)

Variate	Pair no.	Treatments				ANOVA			
		G-SO ₂	G+SO ₂	P-SO ₂	P+SO ₂	Clone	Pollution	Interaction	LSD $p < 0.05$
J_{\max} $\mu\text{mol m}^{-2} \text{s}^{-1}$	1	9.950	8.590	8.880	7.520	ns	ns	ns	2.73
	5	13.000	14.330	10.180	11.170	**	ns	ns	2.73
	6	8.180	8.030	10.000	10.470	*	ns	ns	2.30
dA/dC_i	1	0.0257	0.0249	0.0268	0.0241	ns	ns	ns	0.0130
	5	0.0403	0.0394	0.0325	0.0257	*	ns	ns	0.0139
	6	0.0423	0.0238	0.0365	0.0258	ns	**	ns	0.0119

(b)

Variate	Pair no.	Treatments				ANOVA			
		G-SO ₂	G+SO ₂	P-SO ₂	P+SO ₂	Clone	Pollution	Interaction	LSD $p < 0.05$
dA/dQ	1	0.0213	0.0202	0.0218	0.0213	ns	ns	ns	0.0060
	5	0.0233	0.0252	0.0181	0.0195	**	ns	ns	0.0038
	6	0.0216	0.0227	0.0237	0.0230	ns	ns	ns	0.0051
A_{\max} $\mu\text{mol m}^{-2} \text{s}^{-1}$	1	5.44	4.74	5.46	4.45	ns	*	ns	0.961
	5	6.57	5.65	5.72	4.65	**	**	ns	0.771
	6	5.82	5.56	5.75	5.44	ns	ns	ns	1.450
E_{\max} $\text{mmol m}^{-2} \text{s}^{-1}$	1	1.102	1.142	1.074	0.913	ns	ns	ns	0.283
	5	1.186	1.012	1.035	0.838	*	*	ns	0.209
	6	1.339	1.350	1.146	1.104	ns	ns	ns	0.353
$g_{s\max}$ $\text{mol m}^{-2} \text{s}^{-1}$	1	0.0858	0.0670	0.0744	0.0548	*	**	ns	0.0162
	5	0.1244	0.0895	0.0874	0.0659	**	*	ns	0.0274
	6	0.0931	0.0914	0.0877	0.0770	ns	ns	ns	0.0380

It has been shown that cuttings taken from trees of low vigour in South Wales had poorer photosynthetic performance than those taken from trees of greater vigour. This appears to be genetically controlled and may put trees at competitive disadvantage as they are likely to have lower reserves of carbohydrates and may be less resistant to stressful conditions. The physiology of both good and poor clones was affected by $150 \text{ nl l}^{-1} \text{ SO}_2$ but there was no evidence that poor clones were more susceptible to SO_2 . Furthermore, two of the good, more vigorous, clones took up more SO_2 than their less active paired clones. This suggests that direct responses to SO_2 are not a primary factor in *P. sitchensis* decline in this area, although SO_2 episodes may influence growth and survival through interacting effects on other environmental factors.

Acknowledgements

Dr M.C. Dobson wishes to thank the Department of the Environment for financial support during this work.

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Chapter 13

Conclusions

M.P. Coutts

The chapters in this Technical Paper describe work on different aspects of the decline phenomenon but do not fully explain the poor growth of Sitka spruce on the South Wales coalfield. This is not surprising considering the complexity of decline syndromes and the difficulties encountered in comparable and often much larger investigations in Europe and USA. In spite of the problems, the work has served to characterise certain aspects of the environment and the tree response. Stem analysis showed that decline commonly began at about the time of canopy closure, and growth frequently decreased to a low level over a period of about four years (Chapters 4 and 9). Canopy closure and the period just prior to this may be a time of particular stress for plantation crops; the amount of foliage is reaching a maximum during that time, with consequent demand on nutrients from the soil, and on wet sites the crop has not had time to exert much drying effect on the soil.

The history of decline did not appear to be related to any pattern of climatic conditions (Chapter 9) although the overall climate of high rainfall and warm winters may be important and the effects of late frosts on foliage produced in previous years deserves further study. Measurements of atmospheric pollution (Chapter 2) indicate that direct damage to trees by SO₂ is most improbable, in spite of large quantities of sulphur which were found in the needles. Atmospheric concentrations of NO₂ were likewise too low to be directly damaging.

The crops studied were mainly on three soil types, peaty ironpan, peaty gley and deep peat (Chapter 3). Although poor crops were present on all three types, the poorest were found on the waterlogged deep peats. On the peaty gleys and ironpan soils it was difficult to relate crop

conditions to soil characteristics because of variation in other factors such as crop age, but on the peaty gleys the poorest crops were generally on the wetter sites with high water-tables. Particularly large fluctuations in borehole water levels were found and under the high rainfall of the region high water-tables were common and could occur at any time of the year. 'Even in midsummer the water-table could be situated within 20 cm of the surface for periods of two or more weeks.' The variation in rooting depth encountered in the area (Chapter 5) will be mainly caused by differences in water-table depth. Sitka spruce roots are highly sensitive to waterlogging during the growing season, therefore high, and especially fluctuating, water-tables may cause significant periodic death of fine roots.

The studies on soil hydrology indicated that lower soil layers were more permeable than in gleys studied elsewhere in the UK. Periods of waterlogging, when conditions would have been anaerobic, together with the great throughput of water from the high rainfall, may have subjected the soils to a lot of leaching.

Although some relationships were found between excessive soil wetness and poor tree growth, an arrangement of sites on a scale of wetness (Chapter 3) did not accord particularly well with crop condition, suggesting that other factors such as mineral nutrition might be equally or more important. Measurements of the peat nutrient contents (Chapter 7) showed that N, P and K concentrations were comparable to those of peat on sites where Sitka spruce grows well, but mineral and readily mineralised nitrogen concentrations were low and comparable with those in poor, unflushed oligotrophic blanket peats. The coalfield peats were

particularly acid (pH 3.4-4.0) considering their high mineral content, a feature to which atmospherically borne sulphur may have contributed, and this acidity helps to explain the slow rate of mineralisation.

Foliar analyses in experiment Afan 1 showed that concentrations of nitrogen in the needles tended to be low (notwithstanding some NO₂ pollution in the area) and were correlated with basal area increment (Chapter 5). Foliar phosphorus was poorly correlated with growth but some crops had marginal or deficient levels. Foliar potassium was the strongest discriminator for growth rate although concentrations were above the 0.5% deficiency level accepted for younger crops. Calcium concentrations were normal in the leaves, although concentrations found in the peat were low. Magnesium concentrations in the leaves were also normal and were not related to tree condition, in contrast to some examples of decline of Norway spruce in Europe. Sulphur concentrations in the foliage were remarkably high, bearing witness to pollution in the area. However, foliar sulphur concentrations were positively correlated with tree growth, indicating that the high sulphur levels were not toxic. The correlation between growth and sulphur may be explained by the fact that sulphur concentrations were correlated with those of the major nutrient elements.

In 1986, NPK fertiliser, with or without lime or trace elements, was applied to a 20-year-old crop (Chapter 6). The treatments did produce some responses. Foliar concentrations of the major nutrients increased relative to the unfertilised controls but nutrient concentrations in most treated and control plots decreased for 2 years after the fertilisers were applied. The fertilisers have made the trees look healthier and appear to have reduced the occurrence of dieback of the type described in Chapter 1. Fertilisers also increased diameter and height growth. The increases were large in percentage terms compared with unfertilised controls but their economic value is difficult to assess. The small size of the trees necessitated making measurements that were non-standard in mensurational terms, and the longer term growth patterns of the fertilised and unfertilised crops are unknown.

It is too early to say whether the application of trace elements in the fertiliser experiment will affect growth in the long term but there was no statistically significant effect of this after 4 years. Manganese concentrations in trees on

the coalfield were shown to be low (Chapter 9), but foliar analysis in experiment Afan 1 (Chapter 5) indicated that they were above published deficiency levels in Norway spruce. The role of Mn deficiency in growth decline is still difficult to evaluate. No other trace elements examined appeared to be deficient in this experiment.

The possibility that heavy metals might be present at toxic concentrations in the soil solution was investigated (Chapter 8). Although concentrations of copper and zinc showed inverse relationships with tree growth, foliar analysis showed a positive relationship between foliar copper and growth, and no significant relationship with zinc. In the soil solution concentrations of inorganic aluminium were high, but there was no indication that aluminium: calcium ratios were damaging. In addition, if heavy metal toxicity had been a problem then the lime addition on Afan 2 (Chapter 6) would be expected to have improved growth as an increase in pH makes most heavy metals less available. Symptoms of toxicity to heavy metals are often expressed in the early seedling stage whereas tree decline on the coalfield occurred after a substantial period of acceptable growth. It is concluded that there is no evidence to implicate heavy metal toxicity in the decline phenomenon.

Defoliation by the green spruce aphid (*Elatobium abietinum*) has sometimes been severe on the coalfield and the outbreak in 1980/81 was associated with reduced tree growth and wood density (Chapters 4 and 9). Past defoliation by aphids has certainly caused severe dieback of the crowns of some trees. Unfortunately, the hypothesis in experiment Afan 1, that decline results from aphid defoliation of trees suffering from other stresses, was not effectively tested because significant defoliation did not occur during the period of observation. Additional defoliating agencies have been identified, namely the needle fungi *Lophodermium piceae* and *Rhizophaera kalkhoffii* (Chapter 11). Needles of the mid and lower crown region, which are attacked by aphids, appear to be favoured by these fungi, and the fungi undoubtedly cause some of the defoliation which had previously been attributed to aphids. In addition, two species of root aphids have been found on trees in the coalfield (Chapter 10) but their importance can not yet be assessed.

The evaluation of the several stress factors identified is rendered particularly difficult by

interactions between them. For example, defoliation will reduce transpiration and the interception of rainfall and thereby increase soil wetness, adding to root damage on some sites. Pollution favours *E. abietinum* and can therefore enhance defoliation. Defoliation increases air movement in forest stands thereby increasing the exposure of trees to pollution, and so on. Relationships between mineral nutrition and the ability of trees to recover from defoliation have also been mentioned (Chapters 5 and 6). During discussions about what has come to be known as 'the coal field problem' it has often been argued that such and such a stress cannot be important because the stress also occurs in areas where the trees are healthy. However, it must be remembered that the effects of a stress factor vary enormously with its timing and intensity, and are greatly complicated by other conditions.

Although a number of factors have now been examined at different levels of detail, resources

have not been available for investigating several potentially important aspects. Measurements of pollution have not included ozone or occult precipitation. The latter may well be important because the plateau area of the coalfield is often covered by cloud. Experiments on nutrition on the coalfield have yet to test the effects of applying individual nutrient elements rather than complete NPK fertilisers. Measurements of the tree crops have not included the biomass of leaves or fine roots. It is desirable to quantify the loss of needles and roots caused by different agencies and to clarify their role in disturbing the carbon budget. At the time of writing, work continues on effects of fertilisers, and on the performance of Sitka spruce clones originating from trees which have shown different responses to conditions on the South Wales coalfield, differences in response to atmospheric pollution having already been detected between clones under laboratory conditions (Chapter 12).

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