FORESTRY COMMISSION
OCCASIONAL PAPER 35

Forestry Expansion – a study of technical, economic and ecological factors

International Environmental Impacts: Acid Rain and the Greenhouse Effect

M. Cannell and J. Cape
Institute of Terrestrial Ecology

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INTRODUCTION

The main international considerations concerning forests are those which involve the atmosphere. Forests affect the composition of the atmosphere, and forests are affected by changes in atmospheric composition that occur internationally. The two main considerations are atmospheric pollutants that produce 'acid rain' (including other types of pollutant deposition) and increases in amounts of CO_2 and other greenhouse gases which may affect tree growth both directly and indirectly by changing the climate.

Composition of the atmosphere

The earth's atmosphere has evolved over millenia to its present composition of approximately four-fifths nitrogen and one-fifth oxygen. The minor constituents, carbon dioxide (CO_2), water vapour, methane (CH_4) and nitrous oxide (N_2O) are intimately linked with biological activity and play a major role in controlling the chemical reactions that occur in the lower and upper atmosphere. Apart from the inert gases (argon, neon etc.) which are present in relatively large concentrations, the chemically active trace gases include carbon monoxide (CO), nitric oxide (NO) and ozone (O_3). These interact with each other, and with other biologically produced gases such as dimethylsulphide (from marine plankton) to produce, even in clear air, the gases which are usually associated with air pollution – sulphur dioxide and nitrogen dioxide. Typical concentrations of these gases are given in Table 1 for 'polluted' and 'unpolluted' regions.

The earth's atmosphere is changing owing to man's activity. Concentrations of carbon dioxide are increasing by about 1.5 p.p.m.v. per year and are thought to be 20% greater now than they were last century. Methane concentrations are also rising at 1.5% per year. Ozone concentrations in the lower atmosphere appear to have doubled in the last hundred years, but are being depleted in the upper atmosphere as a result of chemical reactions involving man-made chlorofluorocarbons. Changes to the composition of the earth's atmosphere have become the subject of increased scientific interest and public debate as 'acid rain', the 'greenhouse effect' and the 'ozone hole'.

Table 1 Composition of the atmosphere at sea-level

	Mole fraction	
Nitrogen	0.78	
Oxygen	0.21	
Argon	0.009	
Carbon dioxide	3.5×10^{-4}	
Neon	1.8×10^{-5}	
Helium	5.2×10^{-6}	
Krypton	1.0×10^{-6}	
Water vapour	0.006-0.06 (saturated at 0-40^{0}C)	
Nitrous oxide	0.3×10^{-6}	
Methane	1×10^{6}	
	Unpolluted	*Polluted*
Nitric oxide	10^{-11}	10^{-7}
Nitrogen oxide	10^{-11}	10^{-7}
Sulphur dioxide	10^{-9}	10^{-7}
Ozone	3×10^{-8}	10^{-7}

ACID RAIN

Pollutants from fossil fuels

'Acid rain' has come to be used as a term describing the range of pollutants derived from the combustion of fossil fuels. However, it is not only the combustion of fossil fuels which may cause air pollution. Emission of methane (natural gas) and volatile organic compounds (liquid fuels, solvents etc.) affect the subsequent chemistry of the products of fossil fuel combustion.

The most important gases released directly by the combustion of coal, oil or natural gas include sulphur dioxide (SO_2), nitric oxide (NO), nitrogen dioxide (NO_2) and hydrochloric acid (HC_l). These primary pollutants may originate from constituents of the fuel (e.g. sulphur or chlorine in coal) or from the combustion process itself. Although some of the nitrogen oxides ($NO_X = NO + NO_2$) are produced from nitrogen compounds in fuels, most come from the direct combination of oxygen and nitrogen at the high temperatures found in flames. This means that even 'clean' fuels like hydrogen or natural gas produce nitrogen oxides when burned in air. These primary pollutants may have environmental effects themselves, or may react in the atmosphere to produce secondary pollutants, over a period of hours or days.

The most important secondary pollutants are ozone and peroxyacetylnitrate or PAN (components of photochemical smog) and 'acid rain' in the strict sense – acids formed or incorporated in cloud and rain. Ozone is a natural constituent of the lower atmosphere, diffusing down from the upper atmosphere, and is also produced in warm, sunny weather by chemical reactions involving nitrogen oxides and volatile organic compounds. It is only one of a number of oxidising chemicals, produced by the action of sunlight, which are responsible for the conversion of sulphur dioxide and the nitrogen oxides (NO and NO_2) into sulphuric acid and nitric acid (Calvert *et al.*, 1985). Because these chemical reactions take time (hours to days), secondary pollutants may be found many hundreds of kilometres from their original sources. The oxidation reactions may occur in the gas phase, converting primary pollutants into acidic gases or particles which dissolve in cloud or rain, or may occur in cloud droplets directly. Emissions of primary pollutants in the UK from fossil fuel combustion are given in Table 2.

Table 2 UK emissions of gaseous pollutants (x 10^6 t yr^{-1}) in 1987

SO_2	3.9
NO_X	2.3 (expressed as NO_2 equivalent)
CO	5.3
CO_2	627.0
Hydrocarbons	2.4

Source: Digest of Environmental Protection and Water Statistics No 11. Anon (1988).

The one remaining gas which is important in determining rainfall acidity is ammonia (NH_3), which is emitted largely as a result of agricultural practice, both from crop production and animal husbandry. In areas of intensive stock rearing; as in the Netherlands, this gas has become a primary pollutant, leading to marked changes in vegetation type over the past decade.

Although most primary pollutants are derived from the combustion of fossil fuels, there are other sources, both man-made and natural. Biomass burning, whether straw, moorland or savannah, releases large quantities of smoke (particles) and nitrogen oxides into the atmosphere. In Britain, it has been estimated that straw burning may account for about 1% of annual NO_X (NO + NO_2) emissions (Fowler *et al.*, 1985), but in the tropics biomass burning may be the major source of nitrogen oxides. Soils may also be a source of nitric oxide (NO) through microbial activity, but soil emissions in Britain are thought to be small in relation to other sources. Natural biological processes may give rise to substantial amounts of sulphur-containing gases which ultimately are converted in the atmosphere to sulphuric acid. Estimates for western Europe suggest that 15% of atmospheric sulphur is derived from natural processes (Möller, 1984a, b). The contribution of natural processes to emissions of nitrogen compounds is not known, but is likely to be small compared with man-made emissions in industrial regions.

Deposition of pollutants

Primary and secondary pollutants exist as gases and particles, and as solutes in cloud and rain. The mechanisms responsible for depositing pollutants at the earth's surface vary, depending upon the form in which they are found. The deposition of gaseous pollutants by atmospheric turbulence is known as <u>dry deposition</u>, and is dependent on meteorological conditions, vegetation structure and the physiological status of the plant. Particulate pollutants are predominantly in the sub-micron size range, and are very inefficiently deposited at the earth's surface. The direct and very efficient deposition of large cloud droplets by atmospheric turbulence is known as <u>occult deposition</u>. The nature of the receiving surface has little effect on the deposition of raindrops under gravity (<u>wet deposition</u>), but the pattern of water and solute deposition below a vegetation canopy is altered as rain is distributed between canopy drip and stemflow. The redistribution of water below a canopy leads to a redistribution of the pathways by which water passes to freshwaters, and has implications for patterns of solute transfer within forest soils.

Pollution climate

The distribution of primary and secondary pollutants in the atmosphere is a complex function of emission rate, atmospheric chemistry and weather type. Concentrations of primary pollutant gases are greatest close to sources (industrial areas), but concentrations and deposition rates of secondary pollutants may be greatest in areas remote from sources. The statistical distribution of hourly or daily concentrations of pollutant gases is approximately log-normal (Smith *et al.*, 1989). This means that for most of the time, concentrations are relatively small, with occasional episodes of large concentrations. The same type of behaviour is shown for pollutants in rain; daily mean concentrations and deposition are characterised by log-normal distributions, with a few events contributing a large proportion of the total annual deposition (Fowler and Cape, 1984).

The pollution climate of a particular site is characterised by the mixture of pollutants and the temporal variation and co-variation in relation to weather patterns. In general, pollutants do not occur singly. The interactions between different pollutants and the statistical distributions of multiple pollutants are only beginning to be explored. There are also site-dependent characteristic variations in average gas concentrations during the day (Figure 1). At any site, the pollution climate is dependent on topography, altitude, distance from source, and climate (rainfall amount, cloud duration, sunshine hours, temperature).

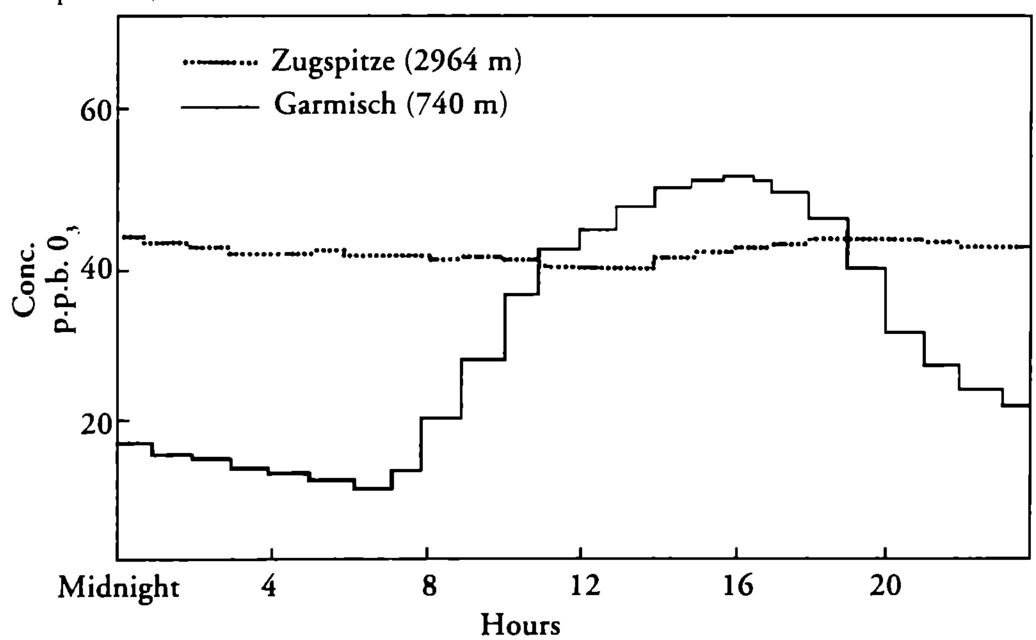


Figure 1 Differences in diurnal patterns of summer ozone concentrations at an adjacent mountain top (Zugspitze) and valley (Garmisch) site in Germany (after Reiter and Kanter, 1982).

It is convenient to classify pollution climates in Europe to distinguish regions exposed to different patterns of pollutants. Figure 2 illustrates three regions, which may be subdivided on the basis of altitude or topography, where primary or secondary pollutants dominate the pollution climate. When addressing potential effects of pollutants, it is important to know which type of pollutant stress may be influencing a particular area. One difficulty in defining such regions of pollution climate is the lack of high quality monitoring in rural areas.

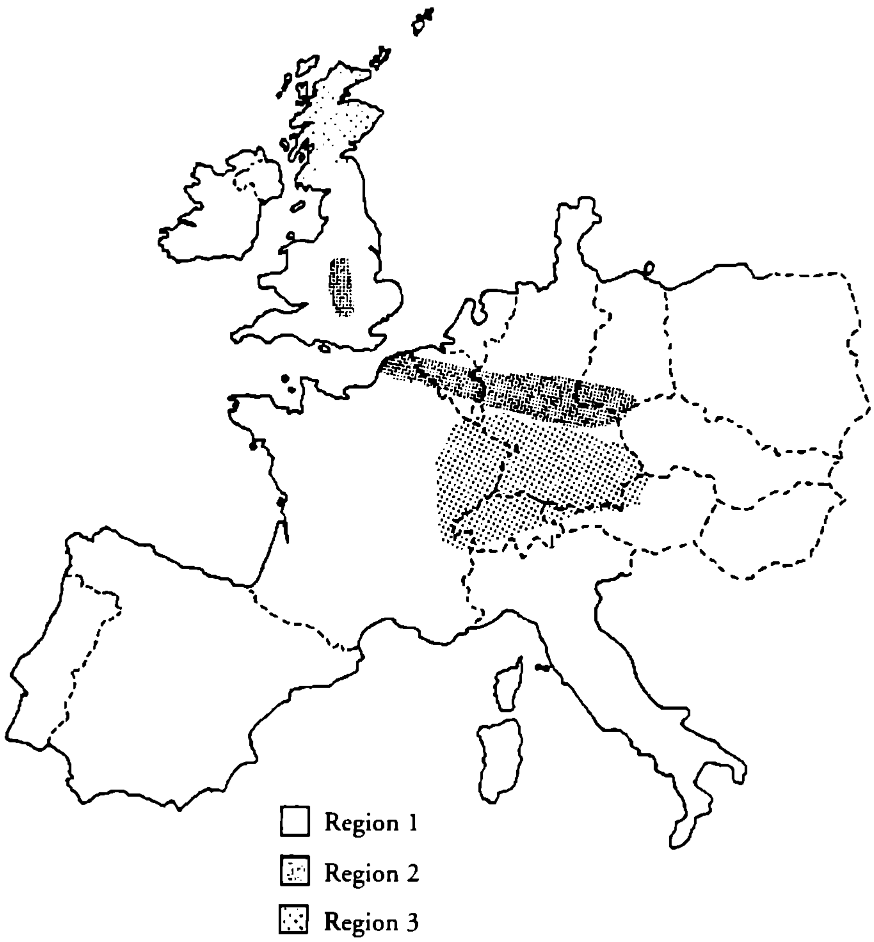


Figure 2 Regions of western Europe with different characteristic pollutant climates.

Region 1: small SO_2 and NO_X concentrations; large summer ozone concentrations.

Region 2: large SO_2 and NO_2 concentrations; wet deposition relatively small.

Region 3: small SO_2 and NO_X concentrations; wet deposition relatively small.

(Last *et al.*, 1986.)

Current pollution in Britain

Air quality in Britain has markedly improved over the past decade. Although there are few rural measurements of gaseous air pollutants, data for sulphur dioxide show a consistent decrease in annual average air concentrations (Figure 3). Recent measurements in rural areas have provided a better knowledge of the spatial distribution of both sulphur dioxide and nitrogen dioxide (Figures 4a and b).

Rural areas in the central and southern Pennines which, 20 years ago, had sulphur dioxide concentrations that inhibited the growth of Scots pine, now have relatively clean air (Farrar *et al.*, 1977; Lines, 1981). Increasing pollution by nitrogen oxides and ammonia may even improve the prospects for forestry on better quality soils in lowland areas, although excessive atmospheric deposition of nitrogen to forests growing on poor soils may exacerbate soil and freshwater acidification and lead to nutrient deficiencies (Nihlgard, 1985).

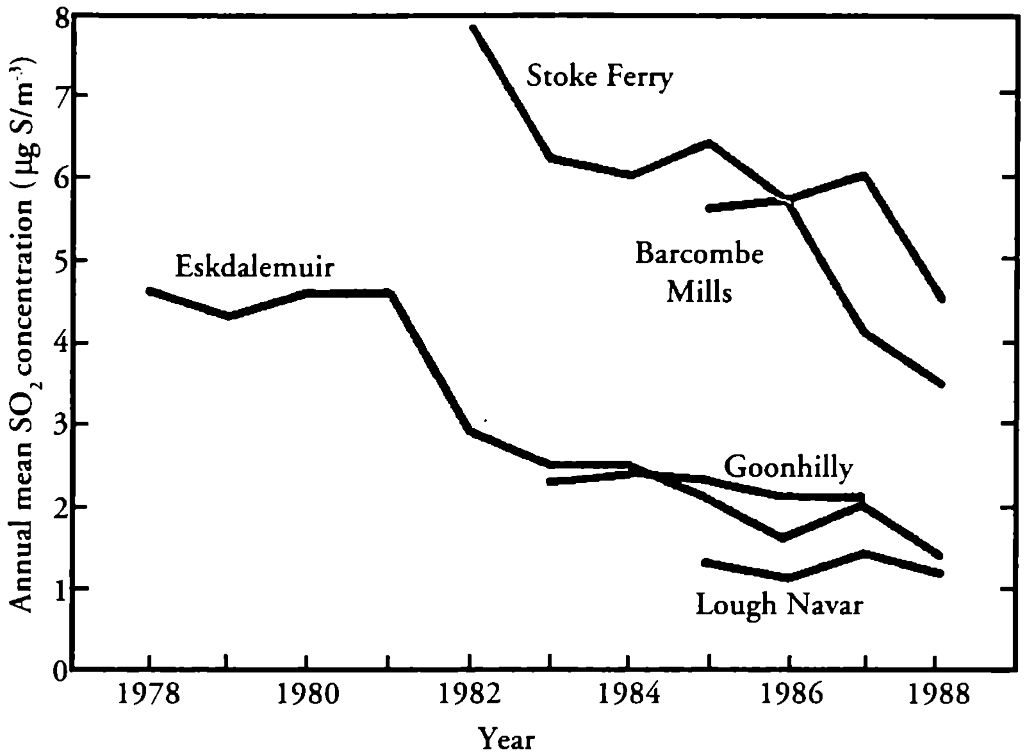


Figure 3 Annual average concentrations of sulphur dioxide in rural areas of Britain (Irwin, personal communication).

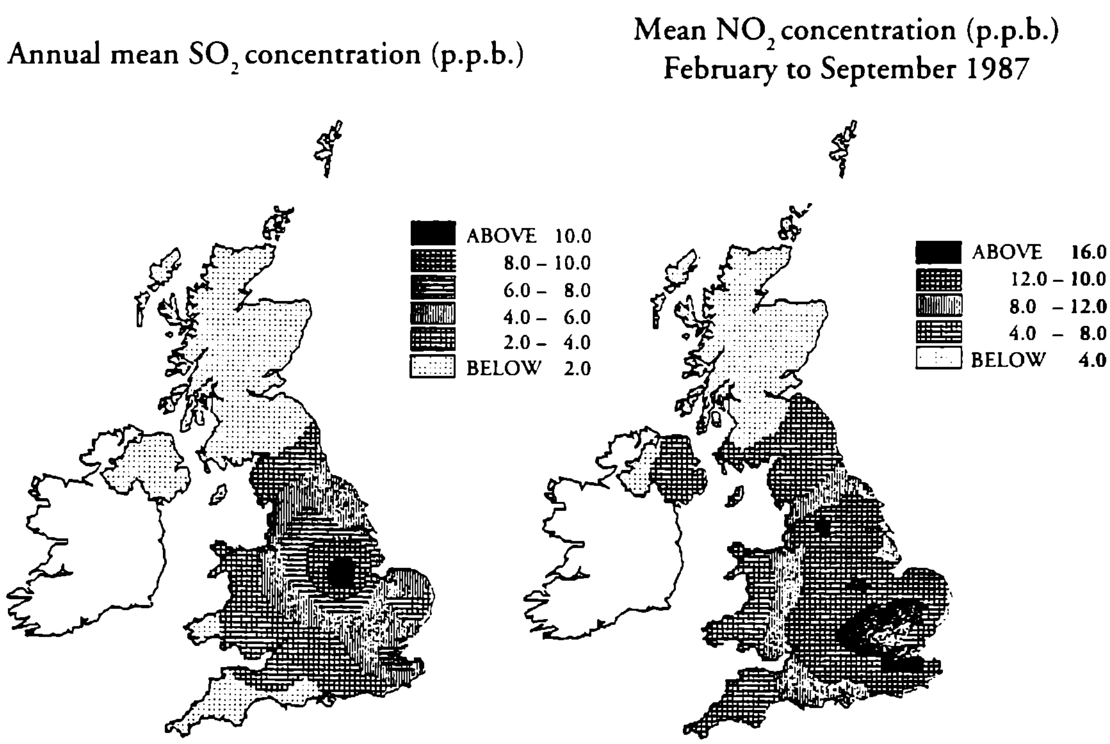


Figure 4 a. Distribution of sulphur dioxide concentrations in rural Britain (annual average, 1987).

b. Distribution of nitrogen dioxide concentrations in rural Britain (Feb-Sept, 1987).

(Williams *et al.*, 1989; Metcalfe *et al.*, 1988).

Wet deposition of pollutants has also changed in the last decade, with significant decreases in concentrations of acidity and non-marine sulphate over much of Scotland and northern England (Figure 5). Data for the rest of Britain are sparse, but apart from the English Midlands the trend seems to be similar (Barret *et al.*, 1987). Set against this is a small rise in wet deposition of nitrogen.

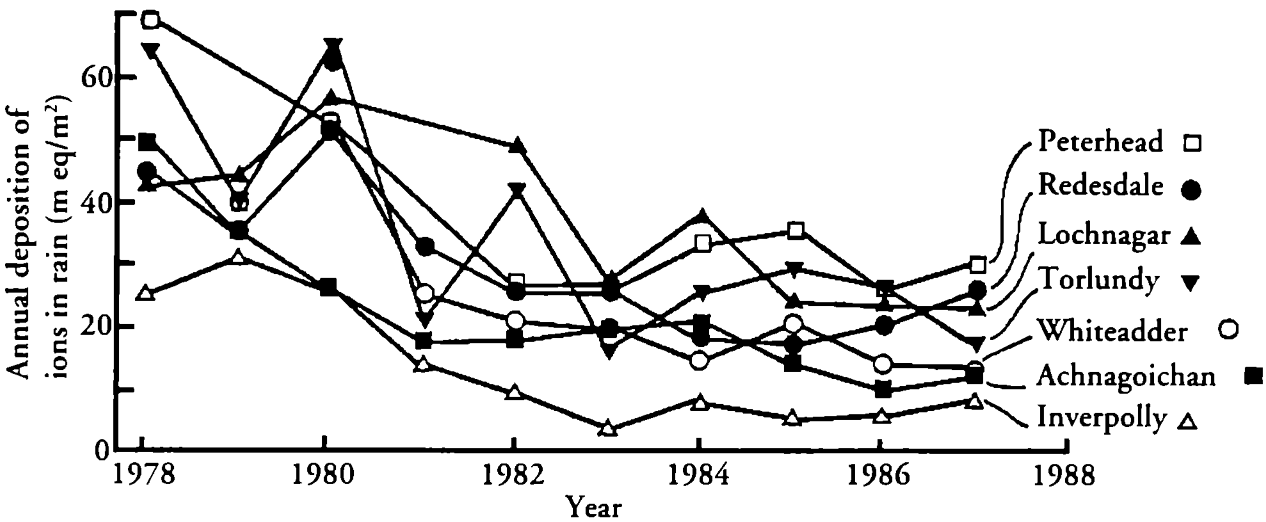


Figure 5 Change in the annual acid deposition in rain at 7 sites in N. Britain since 1978.

The present pattern of acid deposition is shown in Figures 6a and b, which have been derived from average rainfall data and measured concentrations at 67 sites (Campbell *et al.*, 1989). Patterns for deposition of sulphate, nitrate and ammonium are similar to those for acidity, with largest concentrations in the east, but largest wet deposition in the west. The concentrations of pollutants in rain are unlikely to cause direct damage to trees, but may result in long-term soil acidification in sensitive upland areas.

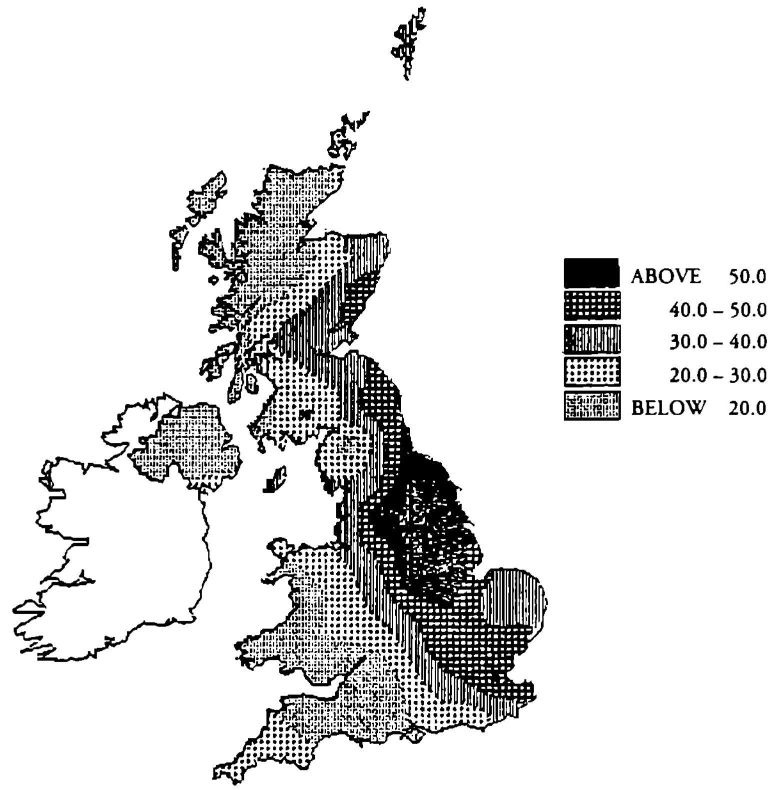
Recent data suggest that previous estimates of wet deposition to hills have been underestimated (Fowler *et al.*, 1988). Concentrations of acidic pollutants in clouds may, on occasion, be high enough to cause direct damage, or may interact with other stress factors such as frost, rendering trees more susceptible to natural climatic extremes (Fowler *et al.*, 1989).

Future patterns of emission

Although it is not expected that the patterns of pollutant exposure over Europe will markedly change in the next decade, international agreements such as the EC directive on large combustion sources will lead to further reduction in emissions of primary pollutants, and should result in decreases in the amounts and concentrations of air pollutants over the whole of Europe. However, current understanding of the processes underlying pollutant transport and chemical reactions in the atmosphere is not sufficiently advanced, nor are current models sufficiently detailed, to allow quantitative predictions to be made of changes in pollutant deposition in areas remote from sources.

Whereas emissions of primary pollutants in western Europe and North America are expected to decrease, emissions in the developing world are expected to increase rapidly as industrialisation proceeds. Urban air pollution is already severe in large cities such as Sao Paulo and Mexico City, and in the absence of controls will continue to increase.

a. Precipitation weighted annual mean hydrogen ion concentration ($\mu eq\ l^{-1}$), 1987



b. Wet deposited hydrogen ion ($g\ H\ m^{-2}$), 1987

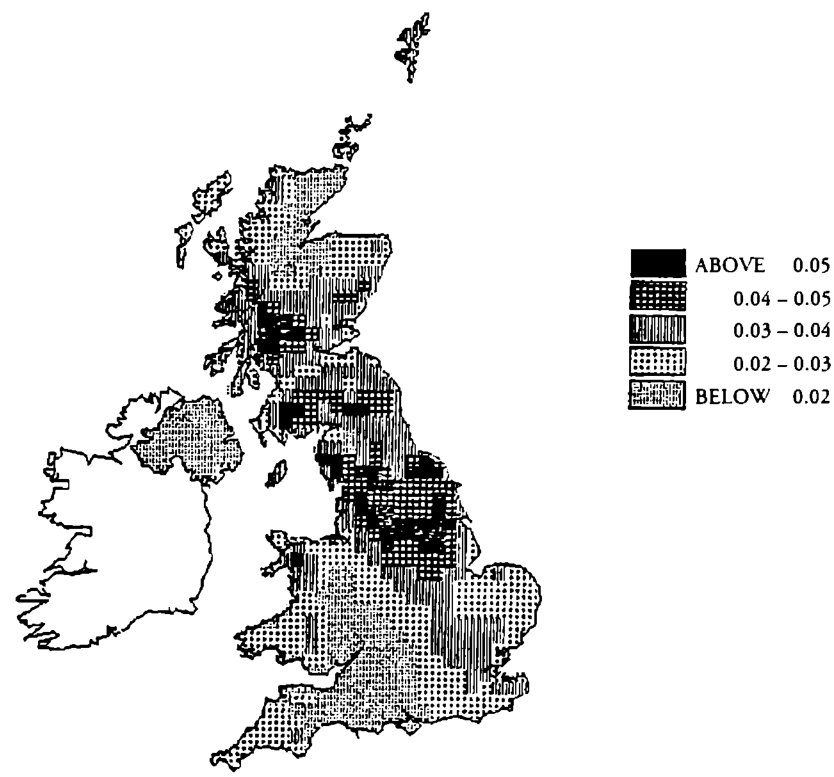


Figure 6 **a.** Distribution of concentrations of acidity in rain (annual average 1987).

b. Distribution of deposition of acidity in rain in 1987 (Campbell *et al.*, 1989).

Consumption of fossil fuels in developing countries currently amounts to about one quarter of world consumption (Varhelyi, 1985). Pollutants are also emitted by fuelwood burning and by agricultural practices. In rural areas, 'slash and burn' agriculture emits nitrogen oxides and volatile hydrocarbons which react to give ozone and other photochemical oxidants.

Effects on trees

All of the major pollutants are known to be harmful to trees if present at large enough concentrations. Visible damage may be shown (as leaf lesions or necrosis) in response to exposure to large concentrations close to pollutant sources. Exposure to smaller concentrations may also cause visible symptoms. More difficult to assess are effects of air pollutants on tree growth and development, or on the response of trees to other stresses such as drought, frost or insect attack. In areas exposed to pollution from a point source of primary pollutants, transect studies may show the 'hidden' effects of low-level air pollution, but this type of study is not generally possible with secondary pollutants, which may be widely spread over a large area. As trees are long-lived, the likelihood of subtle effects is enhanced, especially if these involve interaction with occasional biotic or abiotic stresses.

Experiments with single pollutant gases or acid mist/rain have demonstrated that air pollutants can have <u>direct</u> effects on trees by affecting gas exchange (photosynthesis and water relations), biochemical pathways (e.g. production of antioxidants) and sensitivity to frost. However, it is very difficult to extrapolate from experimental studies, usually involving seedlings or saplings, to mature trees growing in an established forest. Numerous mechanisms have been investigated whereby pollutants may affect trees, and many hypotheses have been put forward to explain observed declines in tree health in the field (Krause, 1988).

Air pollutants may also <u>indirectly</u> affect tree health by modifying soil chemistry and the availability of essential nutrients. Nutrient deficiency is the known cause of 'Type I' forest decline in Europe (associated with magnesium deficiency in the mature foliage) but the mechanisms whereby the deficiency is induced are not known (Roberts *et al.*, 1989). Available data, however, show that some forest soils have become more acid, presumably through wet and dry deposition of acidic pollutants over the last half century (Tamm and Hallbäcken, 1986). This soil acidification leads to enhanced leaching of nutrient cations and increases in concentrations of free aluminium ions in soil, both processes which are likely to inhibit the availability of nutrients. Although many of the stages of these indirect effects can be demonstrated in the laboratory and in the field, direct cause-effect relationships cannot yet be proved.

Recent surveys of forest health in Britain (e.g. Innes and Boswell, 1989) show patterns of crown density and discoloration which are probably related to climate, rather than to any effects of air pollutants. Such surveys cannot demonstrate whether air pollutants affect British forests positively (by supplying nutrients) or negatively (by impairing physiological processes). More experimental work on mature forest trees, using realistic exposure treatments, may indicate the likelihood of significant effects under given conditions, but a quantitative expression of direct and indirect pollution effects on forests is unlikely in the foreseeable future. Potential diagnostic indicators of tree health are being developed to quantify the extent of visible and latent forest damage (Cape, 1988), but whether such tests can identify specific pollutants as casual agents remains to be seen. The extent of air pollution effects (if any) on British forests is unlikely to change over the next decade, given the expected improvements in air quality. In the longer term, increases in CO_2 are likely to mitigate any direct effects of pollutants on trees.

Interactions between forests and pollutant deposition

In addition to the possible effects of air pollutants on trees, forests influence the pathways of pollutant deposition to soils and freshwaters, as noted above. Moreover, the aerodynamically rough surface of a forest enhances the deposition of reactive gases and cloud droplets. Calculations for Kielder Forest suggest that deposition rates for sulphur pollutants may have increased by 30%, and for nitrogen pollutants may have doubled, as a result of planting trees (Fowler *et al.*, 1989).

Consequently, planting forests increases the potential acidifying influence of air pollution on sensitive upland freshwaters, and can lead to marked differences in chemistry and biology between moorland and forested catchments (Hornung and Adamson, 1991).

The concept that pollutant deposition above some threshold value may have deleterious effects on ecosystems has been expressed in terms of <u>critical loads</u>. Discussions on appropriate critical loads for 'sensitive' ecosystems now form the basis for strategy discussions on emission control in Europe. A critical load is defined as 'a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge' (Nilsson and Grennfelt, 1988). The critical load of acidity for forests is given as 20 kg $H^+ km^{-2} yr^{-1}$, implying a requirement for 80-90% reduction in acidifying pollutant emissions in Europe if long-term chemical change to sensitive forest soils is to be avoided. Similarly, critical loads have been defined for nitrogen input to forest ecosystems (Table 3). However, such simple concepts cannot account for the complexity of pollutant exposure and vegetation interactions, and are best regarded as only crude estimates of the extent of possible pollutant effects.

Table 3 Critical loads for deposition of nitrogen to production forests on well drained sites assuming whole tree harvest (Nilsson and Grennfelt, 1988).

Forest productivity	*Nitrogen* ($kg\ ha^{-1} yr^{-1}$)
Low, net N mineralisation	0*
Low, net N immobilisation	3-11
High, net N mineralisation	0*
High, net N immobilisation	7-20

* Any N input will delay recovery

The whole concept of critical loads, and their use in strategic planning of emission reductions, is an area which is surrounded by scientific controversy. Although it is a convenient framework for describing potential pollutant effects on forestry, the practicalities of assigning 'critical loads' to any particular forest ecosystems have yet to be resolved.

'ground: greenhouse gases the carbon budget

The earth's atmosphere contains several gases that are transparent to incoming short-wave radiation received from the sun but together absorb about 40% of the long-wave infrared radiation emitted by the earth. In the absence of these greenhouse gases the average surface temperature of the earth would be -18°C instead of the present +15°C. If we ignore water vapour, then carbon dioxide (CO_2) accounts for about half of the warming effect, and methane (CH_4), nitrous oxide (N_2O), ozone (O_3) and chlorofluorocarbons (CFCs) together account for the other half (Figure 7). Each of these gases absorbs infrared radiation at particular wavelengths. Carbon dioxide already absorbs much of the infrared radiation within its particular wavelength, but the other greenhouse gases do not. Mainly for this reason, the relative temperature increase per molecule increase in CO_2 is less than the increase per molecule of the other greenhouse gases, by factors of 90 200 and about 6000 for CH_4, N_2O and CFCs, respectively (Ramanathan *et al.*, 1985). Carbon dioxide generated by burning methane has about 5% of the greenhouse effect of the unburned methane.

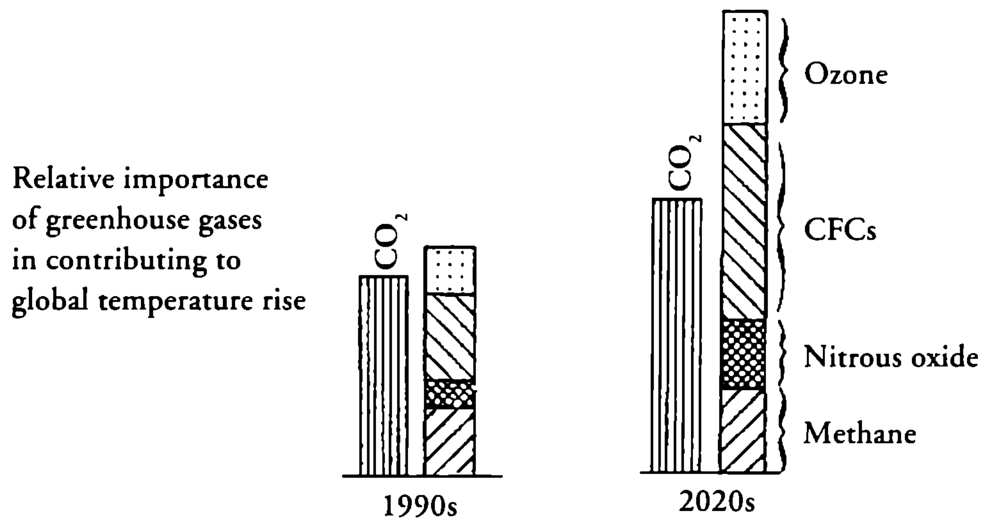


Figure 7 Relative contribution of different greenhouse gases to global warming. Taken from McElroy (1988).

The concentration of methane is expected to double in about 50 years. The main sources are rice paddies, wetlands, the digestive tracts of ruminants, waste disposal, oil recovery and possibly termites. Nitrous oxide is formed in the soil by bacterial denitrification and also in combustion processes. It is increasing at about 0.3% per year, for unknown reasons. The future of CFCs in the atmosphere depends on the implementation of the Montreal Protocol of 1988. However, the emissions of CFCs are likely to remain close to current values because the protocol does not apply worldwide. Also, CFCs F11and F12 have atmospheric lifetimes of 80 and 140 years, respectively. In general, the greenhouse effect of non-CO_2 gases is expected to increase relative to CO_2 in the next 50 years (McElroy, 1988).

The rate at which $C0_2$ levels increase in the atmosphere in future years depends upon how much is emitted and how much remains in the atmosphere. Looking forward to 2050 AD, there is at least a four-fold uncertainty in the predicted global emissions of $C0_2$ and a 20-50% uncertainty in the proportion that will remain in the atmosphere (Bolin, 1986). The level of future $C0_2$ emissions depends mainly on the extent of fossil fuel burning and the mix of fuels used (coal, oil or gas), which in turn depends upon economic growth, especially in developing countries, policy decisions, fuel prices, and technical developments in energy use efficiency. Coal emits 70% more $C0_2$ per unit of energy released than gas. Also, countries differ by up to an order of magnitude in economic growth per unit of energy consumed. At present, fossil fuel burning puts about 5×10^{15} g C (one thousand million tonnes of carbon) into the atmosphere each year. This could conceivably fall to 2×10^{15} g C yr^{-1} or increase to 25×10^{15} g C yr^{-1}, with huge consequences for the rate of $C0_2$ doubling (Figure 8) (Bolin, 1976).

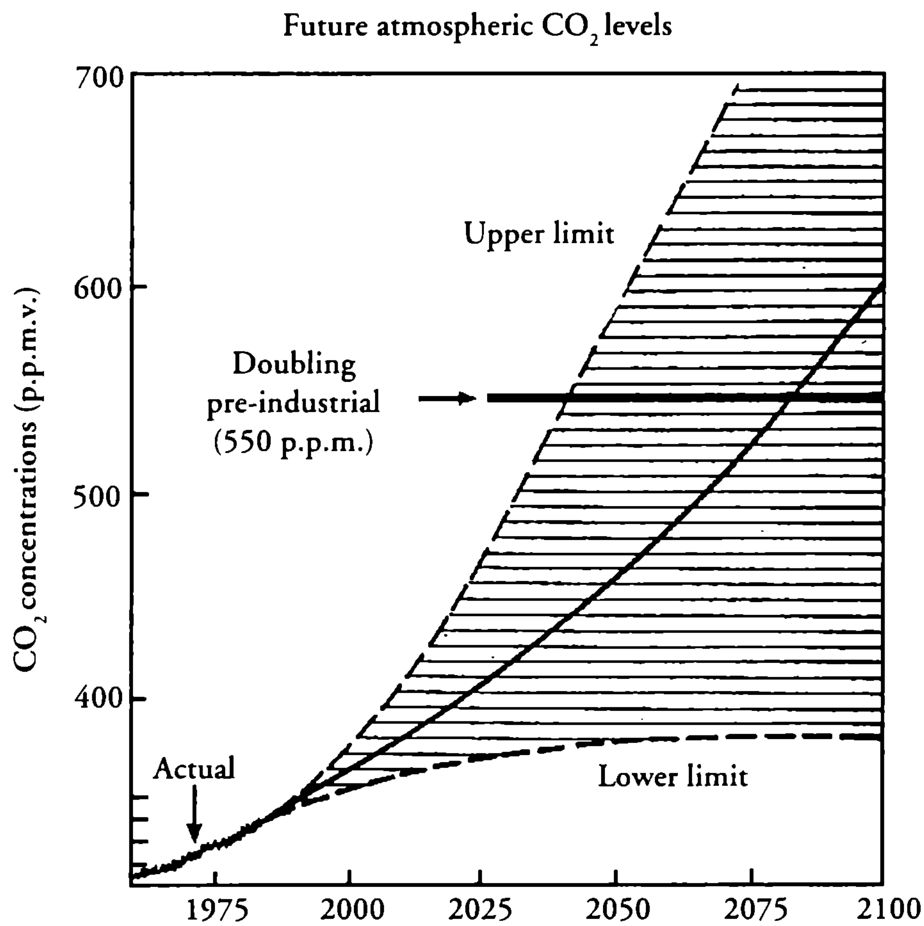


Figure 8 Possible scenarios for increasing atmospheric CO_2 levels. The actual increase corresponds to global emissions of about 6×10^{15} g C yr^{-1}; the upper limit corresponds to an increase to about 25×10^{15} g C yr^{-1}, the lower limit assumes decreased emissions to about 2×10^{15} g C yr^{-1}.

The other sources of $C0_2$ are the destruction of tropical forests and changes in land use that cause soil organic matter to decompose. The net emission from these sources lies somewhere in the range $0.5\text{-}2.5 \times 10^{5}$ g C yr^{-1}, and is probably now much less than it was in the period 1860-1920 (Peng *et al.*, 1983). Given that there is much new afforestation in the world and increasing $C0_2$ levels enhance growth, it is possible that the total next flux of carbon between the atmosphere and the terrestrial biosphere is close to zero.

Less than half of the CO_2 emitted into the atmosphere remains there. The other half is taken up mainly by the oceans, where some of the CO_2 that is absorbed by planktonic photosynthesis is fixed in carbonates that fall to the ocean bed and so is removed from the global circulation. CO_2 dissolves most readily at low water temperatures and when ocean mixing maintains a low concentration of dissolved organic carbon in the surface water.

The problem of the fate of CO_2 emitted into the atmosphere concerns the whole global carbon cycle (Figure 9). The amount of carbon in the atmosphere is small compared with the amounts in the oceans and soils (not to mention carbonate rocks), and the net emission of CO_2 from fossil fuels and the biosphere (about 5 and 1×10^{15} g C yr^{-1} respectively) are small compared with fluxes of around 100×10^{15} g C yr^{-1} between the atmosphere and both the oceans and biosphere. A small change in these large fluxes could have a large effect on the amount of CO_2 remaining in the atmosphere.

Global carbon flow (10^{15} g year)

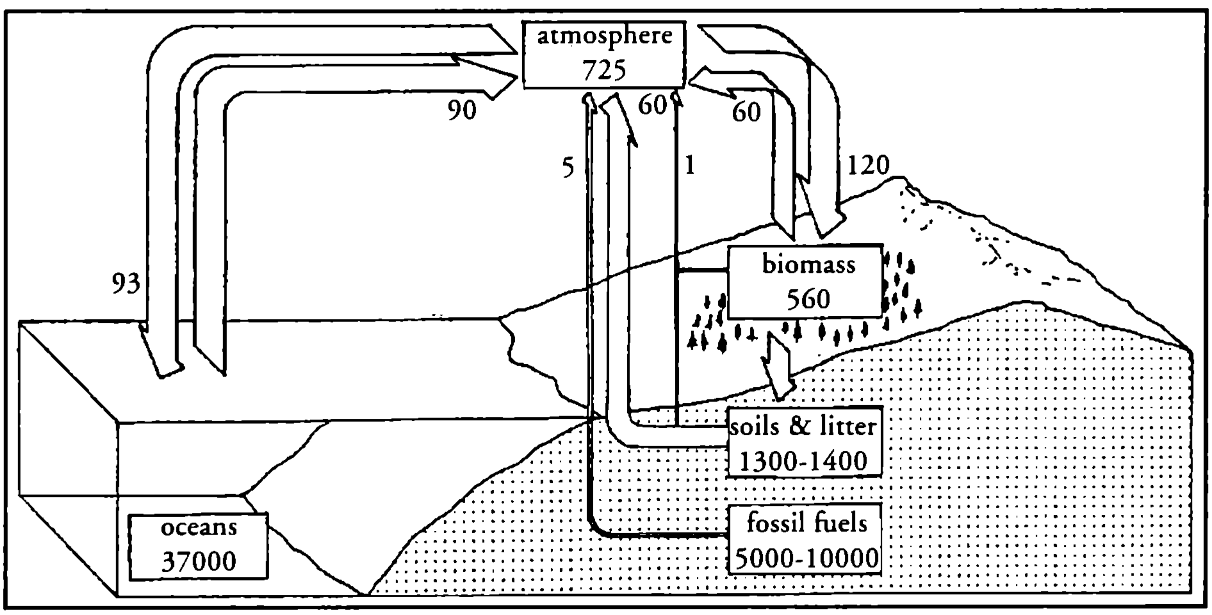


Figure 9 A simplified global carbon budget. The values in boxes indicate the sizes of the storage pools (10^{15} g C); the arrows indicate the fluxes. All values in the diagram are approximate; exact values are unknown.

Consequently, there are large research efforts to determine factors affecting the atmosphere-oceans and atmosphere-biosphere carbon fluxes. For instance, a 1% decrease in ocean plankton, i.e. photosynthesis could increase atmospheric CO_2 levels by 2-7%. There are many uncertainties concerning the roles of forests including (1) the magnitude of net emissions from forest burning and changes in soil organic matter, and (2) the effect of CO_2 'fertilisation' (increasing photosynthesis) on the amount of carbon stored in forests and other vegetation globally (i.e. the standing crop).

Most researchers agree that it seems unlikely that atmospheric CO_2 concentrations will double until towards the end of the twenty-first century. However, the combined effect of CO_2 and the other greenhouse gases is likely to have a warming effect equivalent to CO_2 doubling by the middle of the twenty-first century or sooner.

Climatic change scenarios

The current level of CO_2 in the atmosphere, at 350 p.p.m., is already higher than that recorded in Antarctic ice bubbles dating back 160 000 years (Barnola *et al.*, 1987) and future warming by 2-3°C would be unprecedented in the earth's history over the same period (Harrington, 1987).

Global mean temperature has risen by 0.5°C (±0.2°C) in the past century, which is consistent with the rise in greenhouse gases but is still within normal variation. Northwestern Europe, including the UK, cooled by about 0.2°C in the period 1967-1980 (Jones *et al.*, 1987). Changes over the next 10-20 years in global and regional climates due to greenhouse gases will be small, slow and difficult to detect above natural fluctuations (due to effects of volcanoes, changes in the sun's luminosity, El Nino events and random factors). It is therefore necessary to rely on global circulation models (GCMs).

There are five major GCMs which have been used to predict the effect of doubling CO_2 levels on mean global surface temperatures and precipitation (Table 4). They all agree that the earth will become warmer and that the poles will warm more than equatorial regions. However, none of them accurately simulates the existing global climates and all include major uncertain feedbacks with the oceans and clouds. The 2 x CO_2 scenario given by the UK Meteorological Office GCM gives 1.2°C warming if no feedbacks are included, 2.2°C warming if water vapour and snow/ice are included, but anywhere between 2.0 and 6.0°C if cloud is included, depending upon the type of cloud (Mitchell, personal communications).

Table 4 Output of the five major General Circulation Models of the effect of double atmospheric CO_2 levels on global mean surface temperature and precipitation. (Taken from Hulme and Jones, 1988)

	Global change for 2 x CO_2 (equilibrium values)	
	Temp (°C)	Precipitation (%)
UK Met Office	+ 5.2	+ 15.0
Goddard Inst Space Studies	+ 4.2	+ 11.0
Geophysical Fluid Dynamic Lab	+ 3.5	+ 7.1
National Center Atm Res	+ 4.0	+ 8.7
Oregon State University	+ 2.8	-

It should be stressed that the 2 x CO_2 values for global warming are the 'equilibrium' values, obtained after a lag of 20-60 years when the oceans warm. The transient or actual rate of warming is only about half the equilibrium rate. Thus, for equilibrium warming by 2030 AD of 0.8-5.4°C, the corresponding transient warming is 0.6-3.1°C.

It may be noted that the predicted increases in temperature for a doubling in greenhouse gas are large compared with global climatic changes that have occurred over the last 120 000 years. Thus, the earth was only 0.5-1.0°C warmer during the Eemian Interglacial (before the last ice age, 120 000 BP) and during the hypsithermal (8000-4000 BP). Europe was only 0.5-1.0°C cooler during the Little Ice Age (1400-1800 AD) and 4-5°C cooler during the last glacial maximum (Harrington, 1987).

Turning to the UK climate, the five GCMs show a range of 2.9°C to 6.0°C equilibrium warming under doubled greenhouse gas concentrations. Autumn and winter show the greatest warming, and all models agree that warming over the UK will be slightly greater than the global average. The GCMs qualitatively agree that UK springs, autumns and winters will become wetter, but predictions for summer precipitation range from +79 mm to -35 mm.

Hulme and Jones (1988) reviewed the output of the five GCMs for the UK and compared the instrumental records for 20 cool and warm years in the past.

The predictions for the UK (with doubled concentration of greenhouse gases and at equilibrium) in which they had most confidence were as follows:

1. It will be annually warmer by 4.0-4.5°C, with autumns and winters showing the greatest warming.

2. The magnitude of the warming will be greatest in eastern UK.

3. It will be annually wetter by 20-200 mm, especially in autumn and especially in the south-west.

There is no indication that there will be more extreme events (winds, frosts or droughts), although the warming is likely to be irregular, especially locally, owing to natural variability. It is worth adding that warmer does not mean sunnier: in this respect, the climate of Britain will never be the same as that in south-western France.

Carbon storage in wood

Trees take CO_2 from the atmosphere and store it in perennial tissues. Forests may therefore be used to delay the buildup of CO_2 in the atmosphere and delay global warming. If the total emission of carbon into the atmosphere is 6×10^{15} g C yr^{-1}, and half of this is removed from circulation by the oceans, is it possible to plant forests to absorb the remaining 3×10^{15} g C yr^{-1}?

Sedjo (1989) estimated that one hectare of new forest on good sites in the Pacific Northwest and southern United States will sequester about 6×10^{6} g C yr^{-1}. At this rate of annual carbon fixation it would require about 470 million hectares of new plantation to be established immediately to sequester about 3×10^{15} g C yr^{-1}. This is 1.5 times the total forested area in the United States, or about 10% of the current area of forest worldwide. In other words, the present total industrial plantation effort worldwide of about 92 million hectares would have to be increased five or sixfold. The land area exists for such an expansion of forest plantations in the next half century or so, but at great cost and attendant problems of timber disposal.

An alternative would be to increase the growth rates of existing forests by genetic improvement, and by applying fertilisers and good silvicultural practices. Estimates of the increase required are 2.5 m^3 ha yr^{-1} above current levels for all 3000 million hectares of existing closed forest worldwide, or an increase of 50% in the net annual yield (Sedjo, 1989; Marland, 1988).

In the USA, Applied Energy Services of Arlington, Virginia (an independent power company) has estimated that planting 52 million trees in Guatemala over a period of 10 years will be sufficient to absorb the 15.5×10^{12} g C that will be emitted over 40 years from an 80 megawatt coal-fired plant it is building in Connecticut.

In the UK, our current total emissions of carbon as CO_2, CO and hydrocarbons is about 175×10^{12} g C yr^{-1} (171×10^{12} g C as CO_2). This is equivalent to about 3×10^6 g C (3 tonnes) per person per year.

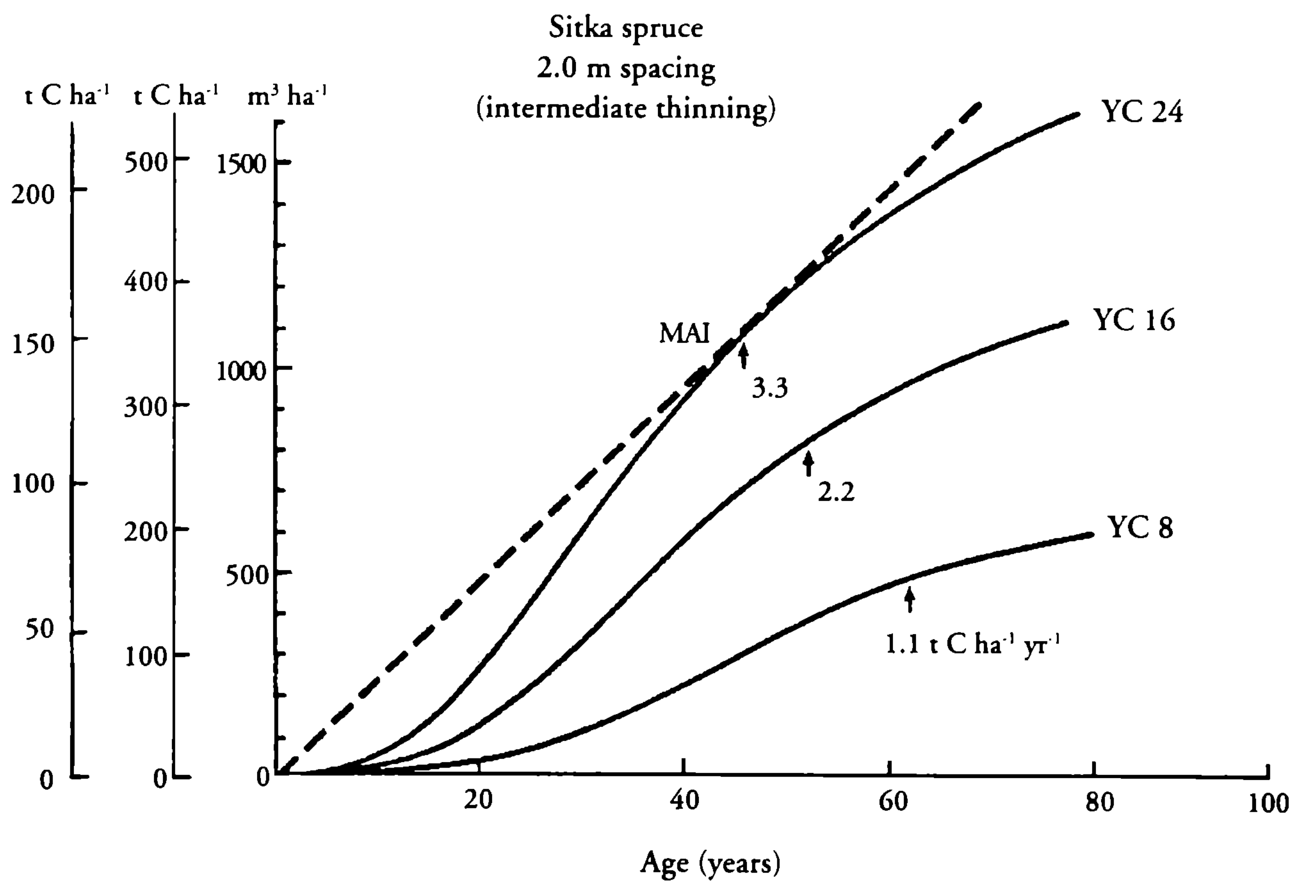


Figure 10 The increase with age in the total stemwood volume (including thinnings) in a Sitka spruce plantation with Yield Classes 8, 16 and 24 $m^3 ha^{-1} yr^{-1}$, showing the approximate corresponding values for carbon storage and the mean value at the point of Mean Annual Increment (MAI).

Figure 10 shows the increase in total stem volume for Sitka spruce plantation at 2 m spacing including intermediate thinnings, with equivalent values for dry biomass (t ha^{-1}) (0.33 x volume) and carbon (0.42 x biomass). For conifer stands in Yield Class 12 m^3 ha^{-1} yr^{-1}, the equivalent mean annual carbon storage in stem wood is about 1.7 x 10^6 g C yr^{-1}, much less than the UK emission per person per year. For Yield Class 18 the value is 2.5 x 10^6 g C ha^{-1} yr^{-1}, and a short-rotation poplar stand growing on agricultural land may take up to 5.0 x 10^6 g C ha^{-1} yr^{-1}. Table 5 shows that one million hectares of the latter type of plantation would take up only about 3% of the current UK carbon emission in stem wood.

Table 5 Amount of carbon stored by areas of new forest in the UK expressed as 10^{12} g C yr^{-1} (million tonnes) and as a percentage of the total UK carbon emissions *(given in brackets), assuming different mean rates of carbon storage and different areas of new planting

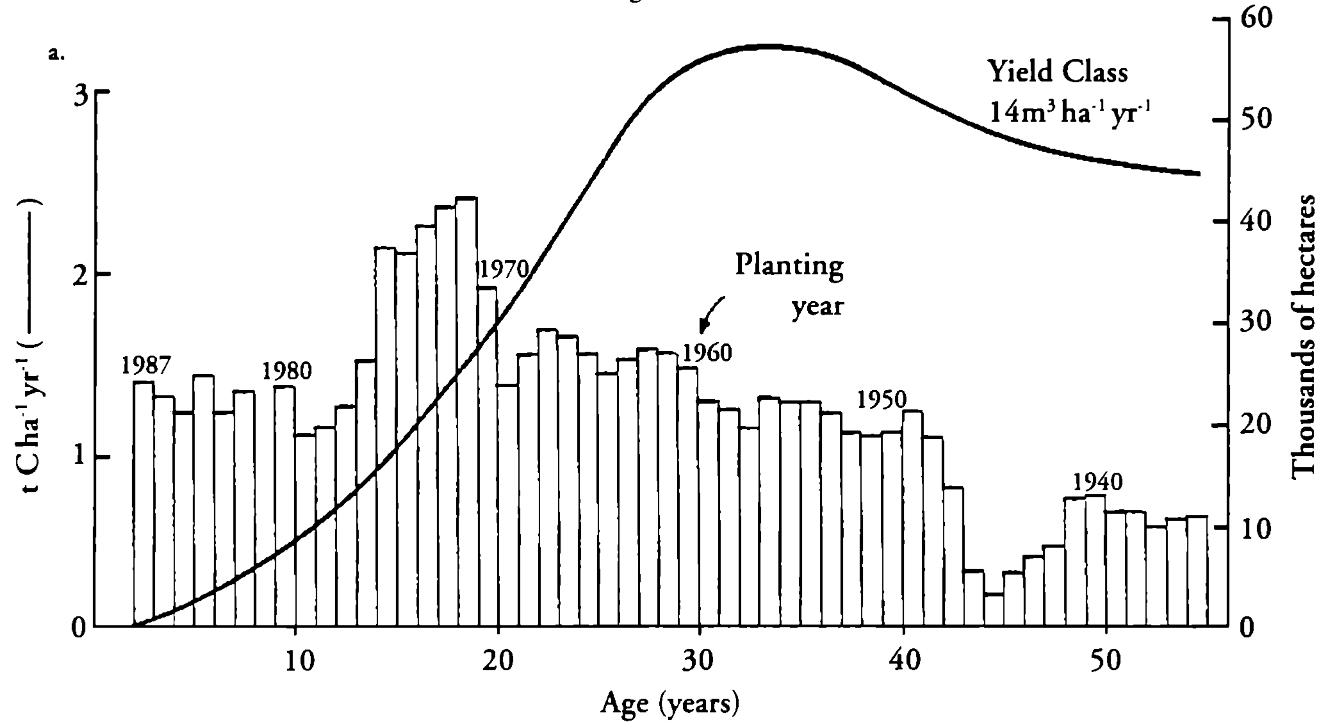
Rate of carbon storage by the forest (10^6 g C yr^{-1}) (tonnes year)	*Area of new planting* (ha)			
	100 000	500 000	1 million	10 million
1.7 (UK average)	0.2 (0.1%)	0.9 (0.3%)	1.7 (0.6%)	17 (5.7%)
2.5 (High yielding conifer)	0.3 (0.2%)	1.3 (0.7%)	2.5 (1.4%)	25 (14.3%)
5.0 (Poplar on good land)	0.5 (0.3%)	2.5 (1.4%)	5.0 (2.9%)	50 (28.6%)

* (175 x 10^{12} g C yr^{-1})

Some additional carbon storage occurs in branches, thick roots and in soil organic matter, perhaps increasing the total by 20-40%. The increase in organic carbon resulting from afforestation will be greatest on mineral soils (Jenkinson, 1971). Ovington (1959) measured an increase in dry weight of soil organic matter under Scots pine plantations in the Breckland over 30-50 years equal to the increase in dry weight of the trees. However, when organic upland soils are ploughed and planted there can be a net loss of soil organic carbon in the years before canopy closure and by the end of the rotation the total carbon in the litter and soil may not be very much greater than existed before planting (Harrison, personal communication).

The current weighted average Yield Class of UK forests is about 11 m^3 ha^{-1} yr^{-1}. Let us assume that the total carbon storage in stemwood branches, roots and soils in these forests is equivalent to carbon storage in stemwood of a Sitka spruce plantation with Yield Class 14. Figure lla shows the current annual stemwood carbon storage in such a plantation, together with the total area of forest planted in the UK (Forestry Commission plus the private sector) each year since 1935. It is clear that the large areas planted in the period 1970-1975 have still to grow through their peak period of carbon storage.

(That is, they will move to the right in Figure 11a.) Consequently, the total carbon taken up by forests will increase until about 2000 AD. In order to maintain carbon uptake during the early part of the twenty-first century at the rate achieved in AD 2000, planting after 1988 would need to be sustained at the level achieved in the early 1970s (about 40 000 $ha^{-1}\ yr^{-1}$). If, say, 25 000 $ha^{-1}\ yr^{-1}$ is planted after 1988, then total carbon uptake after AD 2000 will fall as shown in Figure 11b.



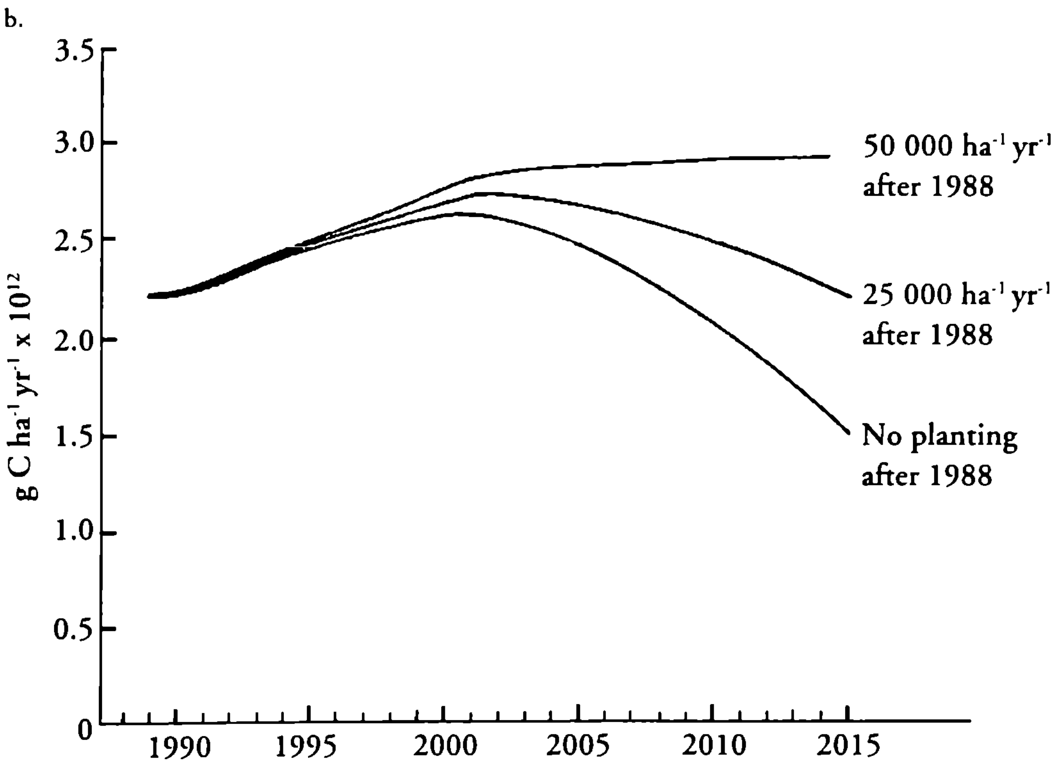


Figure 11 a. The approximate current annual storage of carbon in a Sitka spruce plantation with Yield Class 14 $m^3 ha^{-1} yr^{-1}$, also showing the hectarage of forest planted in the UK each year since 1985.

b. The total current annual storage of carbon in UK forests, derived from Figure 5a assuming different levels of planting after 1988.

So far, we have considered the uptake and storage of carbon in trees as if the carbon was fixed there permanently. In fact, after the trees are felled, or die naturally, the carbon will start to be reconverted back to CO_2 by the process of decay by bacteria, fungi or insects. Thompson and Matthews (1989 a and b) estimated the rates of release of $C0_2$ from different timbers when put to different uses (Table 6).

Table 6 Years taken to return 95% of the carbon stored in different timbers back to CO_2 as a result of decay (taken from Thompson and Matthews, 1989b).

Wood density (t m^{-3}) (wet)	*Spruce*	*Pine*	*Birch*	*Oak*
	0.33	0.40	0.53	0.56
Pulpwood	5	5	5	5
Particle-board	40	40	40	40
Medium density fibreboard	80	-	-	-
Pallet and packaging	4	5	5	5
Fencing	30	40	80	80
Construction	150	200	40	300

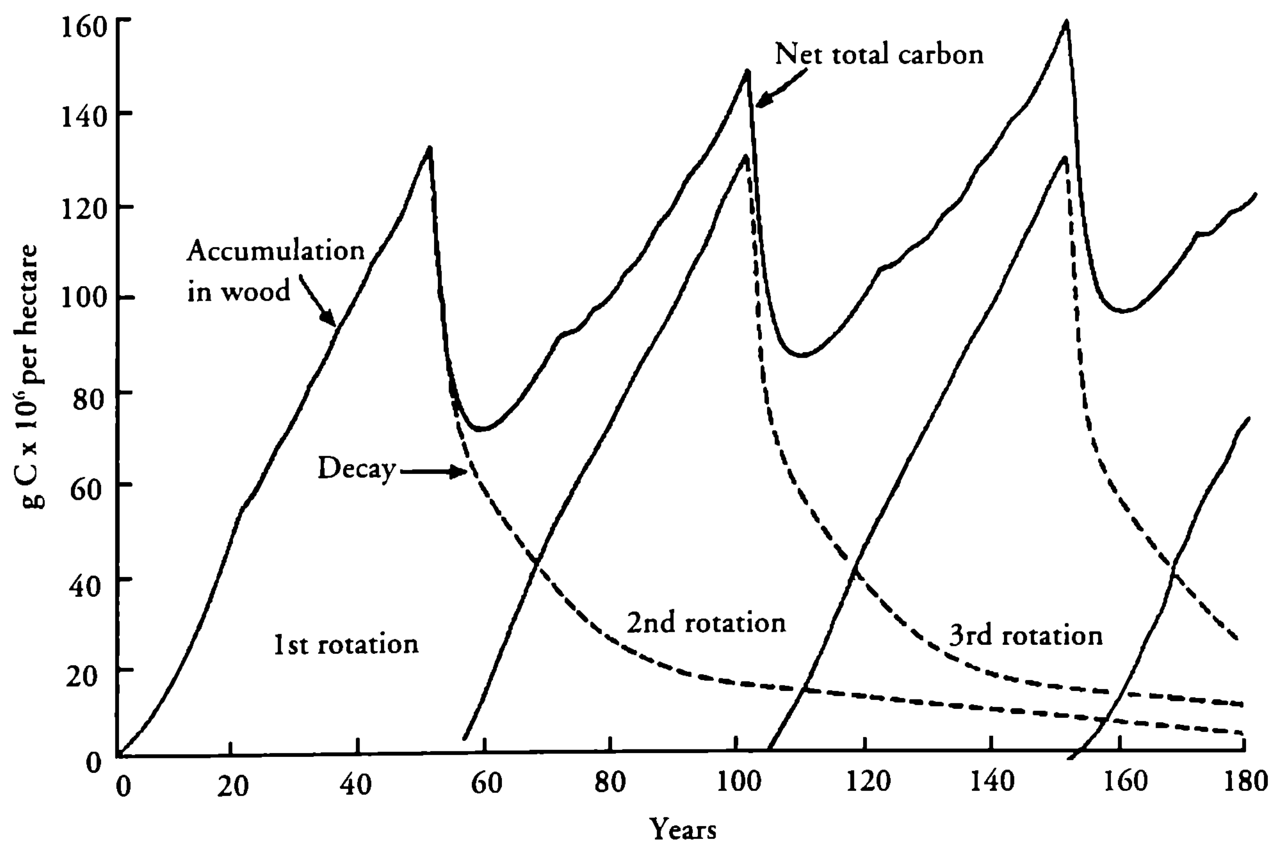


Figure 12 Amounts of carbon stored in Corsican pine timber over three rotations (Yield Class 16) with typical timber end uses giving the decay curves (broken lines). The upper line marks the net total carbon retained in timber in living trees plus the harvested products. Taken from Thompson and Matthews (1989a and b).

Thompson and Matthews (1989a and b) combined the growth curves giving the carbon stored in trees with decay curves for carbon release to give the net total carbon retained over successive rotations. Figure 12 shows data for Corsican pine in Yield Class 16 with different proportions of the timber used for different products (23% particle-board, 14% pallets, 19% fencing, 13% construction and so on). Clearly, the net total carbon retained in timber in the living trees plus the products, depends greatly on the end uses as well as the growth rate of the trees, and the maximum carbon retained in the system will only be achieved after several rotations (depending on the durability of the end products).

Table 7 Carbon stored by British trees and in their timber products. From Thompson Matthews (1989b)

Tree species	*Yield Class* ($m^3 ha^{-1} yr^{-1}$)	*Equivalent carbon stored* ($10^6 g C ha^{-1} yr^{-1}$)	*Rotations* (yrs)	*Period to maximum carbon storage* (yrs)	*Average amount of carbon stored at time of maximum storage* ($10^6 g C ha^{-1}$)
Upland					
Sitka spruce	12	1.7	55	110	78
Scots pine	8	1.4	70	140	74
Birch	4	1.0	45	90	61
Lowland					
Scots pine	10	1.7	65	130	91
Corsican pine	16	2.7	50	100	135
Oak	6	1.5	150	300	118
Poplar coppice*	-	4.0	7	70	121

*Used for fibreboard

Table 7 shows the maximum amount of carbon retained by different types of forest with typical growth rates, rotation ages and end products (Thompson and Matthews 1989a and b). Successive rotations of fast-growing poplar yielding fibreboard will fix equally as much carbon (121×10^6 g C ha^{-1}) as an oak forest (118×10^6 g C ha^{-1}) but in a much shorter time, and the lowland forests generally give a greater carbon storage than upland forests.

Direct effect of increasing CO_2 levels on tree growth

The atmospheric CO_2 concentration has increased from about 275 p.p.m. in pre-industrial times to its current value of 350 p.p.m., and it is increasing by about 1.5 p.p.m. per year.

Eamus and Jarvis (1989) reviewed the literature on the effects of CO_2 concentration on tree physiology. All of the experiments conducted so far have been less than 12 months duration, on small trees, growing in containers, and often with suboptimal growing conditions. The conclusion from such work is that CO_2 concentrations of about

650 p.p.m. increase tree photosynthetic rates by 10-150%, increase seedling growth by 20-120%, and decrease stomatal conductance by 10-60% with a consequent increase in the amount of dry matter produced per unit of water transpired (the water use efficiency). In general, elevated CO_2 levels mitigate the effects of environmental stress, including water stress, poor nutrition and low light levels. There is also evidence that high CO_2 levels increase leaf production and increase assimilate allocation to roots.

The effects on trees that are exposed to high CO_2 levels over long periods may be less than those observed in short-term experiments, because the trees may 'adapt' to high CO_2 levels by producing fewer stomata per unit leaf area and by producing less photosynthetic enzyme (rubisco).

No stand growth models are available that permit estimates to be made of the likely effect on UK forest growth or water use of future increases in CO_2 levels. Any effect of the past increase in CO_2 is likely to have been masked by improvements in silviculture. At a larger scale, D'Arrigo *et al.*, (1987) found a close relationship between annual tree-ring widths in boreal trees in northern Canada and the seasonal amplitude in atmospheric CO_2 levels (which are higher in winter than in summer, especially in the northern boreal zone), suggesting that increasing CO_2 levels are increasing the total photosynthesis of boreal forests.

Effects of climatic change on tree growth

If we accept that effective CO_2 doubling will occur by AD 2050 (i.e. accounting for other greenhouse gases), then, as mentioned, the equilibrium warming in the UK may be 2.9-6.0°C, equivalent to transient (i.e. actual) warming of about 1.5-3.0°C. That is, the mean temperature rise will be 0.25-0.50°C per decade over the next 60 years. Note that warming by 0.5°C/decade is 10 times faster than occurred globally over the past 100 years. Note also that 3°C is the difference in mean July temperatures between southern England (17°C) and the Grampian region (14°C); in January, a 3°C rise would increase mean UK temperatures from 3-6°C to 6-9°C. The 'lapse rate' of temperature with increase in altitude in the UK is about 0.7°C/100 m, so 3°C is equivalent to 428 m (1404 feet) in altitude. A 3°C rise will greatly extend the length of the growing season, especially in our maritime climate.

The main effects of 0.25-0.50°C/decade warming on existing forests and new plantings are likely to be beneficial, provided there are not more, or more severe, droughts, gales, unseasonal extreme temperatures, and increased vapour pressure deficits (i.e. drier air). The evidence for improved growth lies in the better performance of existing forests in mild southerly and westerly locations and at low altitudes. The magnitude of the improvement can be judged by examining the change in General Yield Class of Sitka spruce with elevation in Scotland. The average regression for 20-30-year-old trees given an increase of 4.3 m^3 ha^{-1} yr^{-1} for every 100 m in altitude, with 31 m^3 ha^{-1} yr^{-1} at sea level and zero at about 700 m (the tree line). Figure 13 shows the effect of a 1°C rise in temperature, assuming 0.7°C per 100 m. An average site now producing 14 m^3 ha^{-1} yr^{-1} growing at 400 m would produce 20 m^3 ha^{-1} yr^{-1} following a 1°C rise. Obviously, this simplistic calculation assumes that the decrease in yield with altitude is due entirely to temperature, ignoring effects of soil depth, nutrition, windspeed and possibly pollutant deposition. However, even if only half of the effect is due to temperature, Figure 13 shows that 0.25-0.50°C/decade warming is likely to produce an appreciable improvement in performance. Greatest confidence may be put in the prediction that trees growing in the coolest part of the UK will benefit; less confidence may be put in the prediction that trees already growing in mild southerly and westerly locations will benefit from further warming.

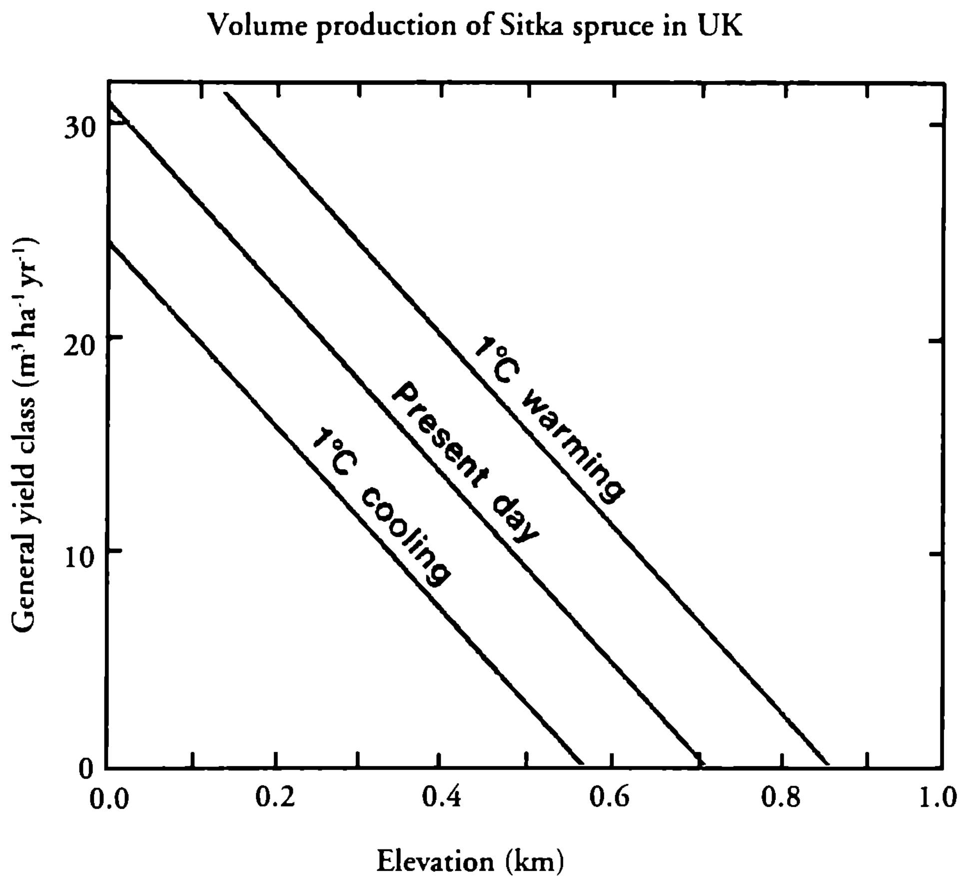


Figure 13 Present day relationship between General Yield Class of Sitka spruce plantations and elevation in northern Britain, and possible future relationships given a 1°C warming or cooling. Taken from Cannell *et al.*, (1989).

The growth response of particular forests will depend upon the soils: those growing in fertile soils may benefit most. Forest responses to climate in the uplands are sensitive to the effects of climate on soil properties and nutrient release as well as to the direct effects of temperature on tree growth (Pastor and Post, 1988).

Opportunities to grow different species and provenances

The fossil pollen record shows an effect on the distribution of tree species of the warmest part of the present interglacial, 4000-8000 years ago. At that time, Europe may have been about 1°C warmer than at present. Deciduous forest was predominant in England, consisting of alder, elm, hazel and lime, with birch occurring more in the north and west. Pine had become scarce in England and was common only in the northern half of Scotland (Lamb, 1977). Scots pine stumps, dated 4000 BP, occur in peat deposits in the Cairngorm Mountains at about 790 m above sea level, well above the present tree line of 620 m (Pears, 1975). At that time, Norway spruce grew in the high Alps in areas now occupied by the more hardy *Pinus cembra* (Zukrigl, 1975). In recent time, also, changes have been observed at the tree lines. In Canada, white spruce has expanded northwards in the Hudson Bay area in response to warming in the period 1920 to 1965 (Payette and Filion, 1985), while Scots pine populations in the mountains of Sweden may have declined in response to cooling in northwest Europe in the period 1965-1980 as well as in response to atmospheric pollution (Kullman, 1988).

The natural distributions of some native tree species in Britain seem to be determined by temperature. The small-leaved lime does not regenerate naturally north of the Lake District, apparently because the temperatures are too cool in spring for pollen tube growth (Piggot and Huntley, 1978, 1981) while bird cherry is found almost exclusively in northern and upland Britain.

These relationships between climate and tree distribution suggest that considerable opportunities will exist to extend the ranges of some species in Britain, and also to introduce more exotics. Cannell *et al.*, (1979) listed many broadleaved species that might be planted more widely, including species currently growing in southern Europe and elsewhere. It will become possible, for example to grow some *Eucalyptus* and *Nothofagus* species quite widely in southern England, and there will be greater scope for growing Douglas fir throughout Britain instead of Sitka spruce.

Most of the exotic conifers planted in the uplands, like Sitka spruce and lodgepole pine, have large natural ranges. In general, the areas that provide the best seed possess climates that match those in Britain (with some exceptions). Following climatic warming, the best seed origins might be places which are warmer than Britain now, although the climate in those places will change too. Thus, it might be wise to anticipate warming in the 1990s by planting more Oregon/Washington provenances of Sitka spruce, and perhaps more Washington origin Douglas fir.

An important consideration is that the seed produced from breeders' seed orchards of Sitka spruce, lodgepole pine and larch may not fully exploit the warmer climate in the twenty-first century. Many of the genotypes in UK seed orchards were progeny-tested in the 1970s, while the trees grown from seedorchard seed will grow in the period 1990-2050 AD. If the climate warms at 0.25-0.50°C/decade, tree breeding generations must be kept very short to provide improved material that is adapted to the current and future climate. Genotypes will be needed with small winter chilling requirements, which can take full advantage of longer growing seasons.

Possible harmful effects on tree performance

Although there is no reliable scenario for precipitation and evaporation, there remains a possibility that summers could become drier. This would adversely affect the growth of most forests, as evidenced by the summers of 1976 and 1979 in England. More particularly, the growth of Sitka spruce would be adversely affected by high vapour pressure deficits and dry soils in summer. This species is particularly adapted to humid, foggy conditions, as occur at present along the western seaboard of North America and in western Scotland.

Other possible undesirable effects of climatic change could include more profuse flowering following hot summers, delayed budburst in the absence of winter chilling and dormancy release, dieback resulting from soil drying and fine root death, an increased risk of fire in the south and east, and an increased incidence of pest outbreaks, especially of aphid and other insects that overwinter as adults or larvae rather than as eggs or pupae.

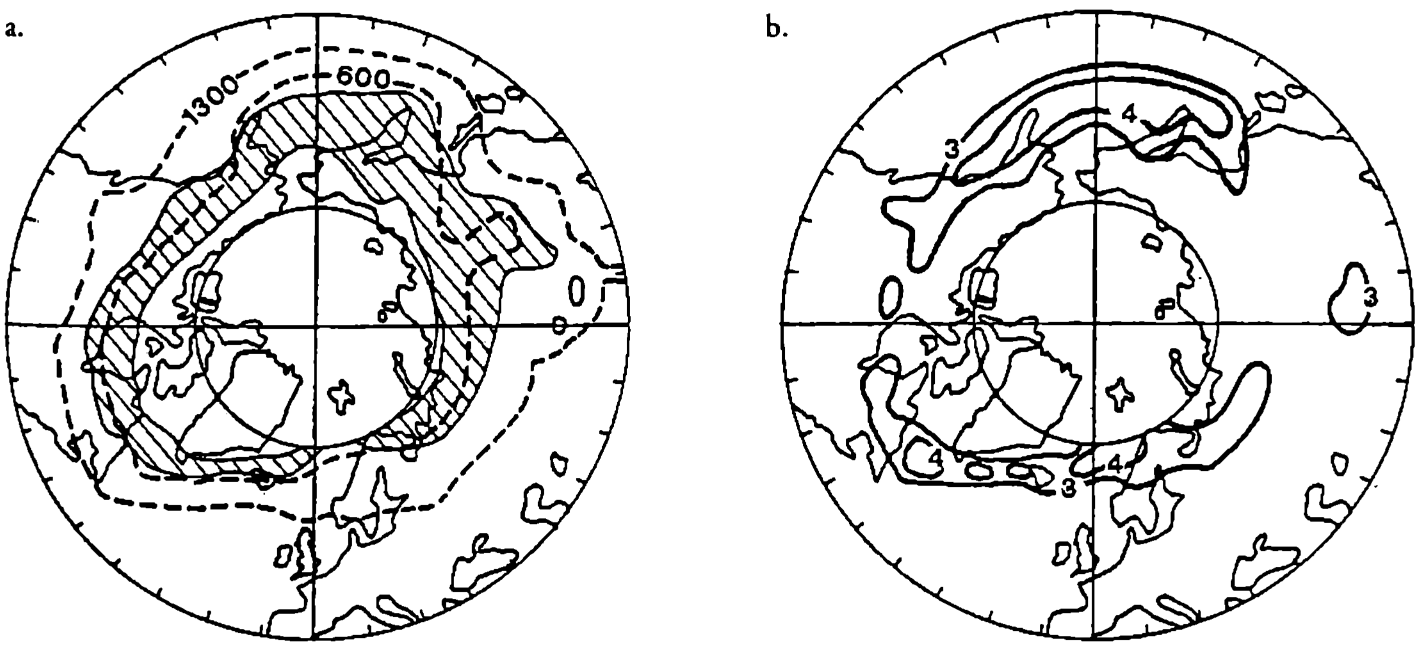
Possible effects of climatic change on world timber resources

At present, the GCMs are unable reliably to predict the climatic change that may occur in particular regions of the world. In particular, it is impossible to say how shifts in rainfall patterns could alter the land areas currently and potentially devoted to timber production.

However, there is a concensus that the greenhouse effect will have a major impact on the northern boreal zone. Greenhouse warming will be most pronounced at high latitudes, and most authors agree that the temperature shift resulting from doubled greenhouse gas warming (2 x $C0_2$ scenarios) could eventually shift or extend the boreal forest northwards by 500-1000 km into areas now occupied by tundra (Kauppi and Posch, 1985); (Emanuel *et al.,* 1985). Emanuel *et al.,* (1985) assumed no change in precipitation due to climatic warming and no increase in water use efficiency by the trees due to higher $C0_2$ levels, so they predicted that much of the present boreal forest area will be replaced by cool temperate steppe, or by cool moist forest. The eventual result would be little change in the extent of the boreal forest. By contrast, Kauppi and Posch (1988) assumed that the northern boreal forest is bounded by annual isopleths of 500 and 1300 accumulated day-degrees above 5°C, and that the move northwards of the boreal forest would greatly extend the exploitable forest area (Figure 14a). Furthermore, Kauppi and Posch (1988) estimated from a simple regression of forest productivity on temperature in Finland that the potential productivity of the existing boreal forest area would increase by 3-4 m^3 ha^{-1} yr^{-1} in the maritime regions, but not in the continental regions of the USSR and Canada (Figure 14b).

a.

b.



2 x CO_2 climate
Observed climate

Figure 14 a. Calculated boreal zone for the GISS 2 x CO_2 climate scenario relative to the calculated present-day zone.

b. Estimated change in potential productivity from baseline level to double CO_2 conditions (in m^3 ha^{-1} yr^{-1}).

SUMMARY AND CONCLUSIONS

The composition of the earth's atmosphere is changing as a result of man's activities. Some constituents are regarded as pollutants that can damage forests, others are radiatively active, and could enhance the atmosphere's greenhouse effect.

Forests in different parts of the UK are exposed to different amounts and mixes of atmospheric pollutants, depending on the climate and the proximity of pollutant sources. There has been a reduction in recent years in levels of sulphur dioxide and of sulphate and acidity, which is likely to continue following the EC directive to reduce emissions from large combustion sources. However, acid mist and ozone could, potentially, have deleterious effects on forests at high altitudes, possibly enhancing the harmful effects of other stresses. In theory, acidifying pollution may need to be reduced by 80-90% to avoid all possibility of damage to forest-growing on sensitive soils in the UK. However, in practice, it has been impossible to detect widespread damage or benefit to UK forests that could unequivocally be attributed to atmospheric pollutants. This situation is likely to continue for the next decade or so.

The concentration of greenhouse gases in the atmosphere is increasing, and there is a strong possibility that the earth will become warmer during the twenty-first century. The magnitude and speed of that warming cannot yet be predicted, and most meteorologists consider that no enhanced greenhouse effect has yet been detected. However, it seems likely that the rate of warming that has occurred over the last 100 years (by less than 0.1°C/decade) will increase by a factor of 2 to 10 during the next 100 years. The UK will become warmer, especially in the autumn and winter, and possibly wetter in the autumn.

New forests remove carbon from the atmosphere and store it in wood. It would require a five to sixfold increase in the world plantation area to take up the CO_2 emitted by burning fossil fuels; in the UK, one million ha of new forest plantations would remove less than 3% of the total annual UK emission of CO_2. Carbon storage by existing UK forests will increase until 2000 AD, after which it will decline unless 40 000 ha is planted each year from now on.

An increase in atmospheric CO_2 and in temperature of up to, say, 0.2°C/decade is likely to increase forest growth in the UK and make it possible to plant more southerly provenances and species such as Douglas fir and *Eucalyptus* more widely. Only the more extreme scenarios of rapid warming might be harmful. Elsewhere in the world, the boreal forest is likely to be more productive, but it is impossible to say how world timber resources will be affected.

REFERENCES

ANON (1988). *Digest of environmental protection and water statistics* No 11 HMSO, London.

BARNOLA, J.M., RAYNAUD, D., KOROTKEVISH, Y.S. AND LORIUS, C. (1987). Vostok ice core provides 160,000-year record of atmospheric carbon dioxide. *Nature* **329**, pp.408-414.

BARRETT, C.F., ATKINS, D.H.F., CAPE, J.N., CRABTREE, J., DAVIES, T.D., DERWENT, R.G.L., FISHER, B.E.A., FOWLER, D., KALLEND, A.S., MARTIN, A., SCRIVEN, R.A. and IRWIND, J.G. (1987). *Acid deposition in the United Kingdom 1981-85* Warren Spring Laboratory, Stevenage.

BINKLEY, C.S. (1988). A case study of the effects of $C0_2$ – induced climatic warming on forest growth and the forest sector. B. Economic effects on the world's forest sector. In *The impact of climatic variation on agriculture.* Vol. I, eds, M.C. Parry, T.R. Carter and N.T. Konijn, pp.107-218. Kluwer Academic Publishers.

BOLIN, B. (1986). How much $C0_2$ will remain in the atmosphere? In *The greenhouse effect, climatic change, and ecosystems,* eds. B. Bolin, B.R. Doos, J. Jager and R.A. Warrick, 93-155. John Wiley and Sons, Chichester, N York, Brisbane, Toronto.

CALVERT, J.G., LAZRUS, A., KOK, G.L., HEIKES, B.G., WALEGA, J.G., LIND, J. and CANTRELL, C.A. (1985). Chemical mechanisms of acid generation in the troposphere. *Nature* 317, pp.27-35.

CAMPBELL, G.W., DEVENISH, M., HEYES, C.J. and STONE, B.H. (1989). *Acid rain in the United Kingdom: spatial distributions in 1987.* Report LR735 (AP) M, Warren Spring Laboratory, Stevenage.

CAPE, J.N. (1988). Recent developments in the diagnosis and quantification of forest decline. In *Air pollution* and *ecosystems,* ed. P.Mathy, pp.292-305. Reidel, Dordrecht.

D'ARRIGO, R., JACOBY, G.C. and FUNG, I.Y. (1987). Boreal forests and atmosphere-biosphere exchange of carbon dioxide. *Nature* **329**, pp.321-323.

EAMUS, D. and JARVIS, P.G. (1989). Direct effects of CO_2 increases on trees and forests in the UK. *Advances in Ecological Research* (in press).

FARRAR, J.F., RELTON, J. and RUTTER, A.J. (1977). Sulphur dioxide and the scarcity of *Pinus sylvestris* in the industrial Pennines. *Environmental Pollution* 14, pp.63-68.

FOWLER, D. (1984). Transfer to terrestrial surfaces. *Philosophical Transactions of the Royal Society B* **305**, pp.281-297.

FOWLER, D. and CAPE, J.N. (1984). On the episodic nature of wet deposited sulphate and acidity. *Atmospheric Environment* **18**, pp.1859-1866.

FOWLER, D., MULLOCK, S., LEITH, I.D., CAPE, J.N. and UNSWORTH, M.H. (1985). Production of oxides of nitrogen during strawburning. *Annual Report Institute of Terrestrial Ecology* 1984, pp.61-62. ITE, Huntingdon.

FOWLER, D., CAPE, J.N., LEITH, I.D., CHOULARTON, T.W., GAY, M.J. and JONES, A. (1988). The influence of altitude on rainfall composition at Great Dun Fell. *Atmospheric Environment* **22**, pp.1355-1362.

FOWLER, D., CAPE, J.N. and UNSWORTH, M.H. (1989). Deposition of atmospheric pollutants on forests. *Philisophical Transactions of the Royal Socociety B.* **324**, pp.247-265.

FOWLER, D., CAPE, J.N., DEANS, J.D., LEITH, I.D., MURRAY, M.B., SMITH, R.I., SHEPPARD, L.J. and UNSWORTH, M.H. (1989). Effects of acid mist on the frost hardiness of red spruce seedlings. *New Phytologist* **113**, p.21335.

HARRINGTON, J.B. (1987). Climatic change: a review of causes. *Canadian Journal of Forest Research* 17, pp.1313-1339.

HULME, M. and JONES, P.D. (1988). *Climatic change scenarios for the UK.* Report for the Institute of Hydrology, NERC. Climatic Research Unit, University of East Anglia, UK.

INNES, J.L. and BOSWELL, R.C. (1989). *Monitoring of forest condition in the United Kingdom 1988. Forestry Commission Bulletin 88.* HMSO, London.

HORNUNG, M. and ADAMSON, J. (1991). The impacts on water quality and quantity. *Forestry Commission Occasional Paper 42.* Forestry Commission, Edinburgh.

JENKINSON, D.S. (1971). The accumulation of organic matter in soil left uncultivated. *Annual Report Rothamsted Research Station,* UK, pp.113-137.

JONES, P.D., WIGLEY, T.M.C., FOLLANT, C.K. and PARKER, D.E. (1987). Spatial patterns in recent worldwide temperate trends. *Climate Monitor* **16**, pp.175-185.

KAUPPI, P. and POSCH, M. (1985). Sensitivity of boreal forests to possible climatic warming. *Climate Change* 7, pp.45-54.

KAUPPI, P. and POSCH, M. (1985). Sensitivity of boreal forests to possible climatic warming on forest growth and the forest sector. A. Productivity reactions of northern boreal forests. In *The impact of climatic variations on agriculture.* Vol. I., ed M.L. Parry, T.R. Carter and N.T. Konijn, pp.183-195. Kluwer Academic Publishers.

KAUPPI, P. and POSCH, M. (1988). A case study of the effects of $C0_2$-induced climatic warming on forest growth and the forest sector. A. Productivity reactions of northern boreal forests. In *The impact of climatic variations on agriculture.* Vol. I., eds. M.L. Parry, T.R. Carter and N.T. Konijn, pp.183-195. Kluwer Academic Publishers.

KRAUSE, G.H.M. (1988). Impact of air pollutants on above-ground plant parts of forest trees. In *Air pollution and ecosystems,* ed P. Mathy, pp.126-168. Reidel, Dordrecht.

KULLMAN, L. (1988). Recent natural decline of Swedish montaine forests. In *Effects of air pollutants and acidification in combination with climatic factors: soils and waters in northern Fennoscandia.* Workshop, Rovaniemi, Finland, October 1988.

LAMB, H.H. (1977). *Climate: present, past and future. 2. Climatic history and the future.* Methuen, London.

LAST, F.T., CAPE, J.N. and FOWLER, D. (1986). Acid rain – or 'pollution climate'? *Span* **29**, pp.2-4.

LINES, R. (1981). Performance of different species and seed origins in the industrial Pennines of northern Britain. *Joint meeting of IUFRO working parties 1979,* p.204. Polish Academy of Sciences.

MARLAND, G. (1988). *The prospect of solving the CO_2 problem through global reforestation.* US Dept Energy. DoE/NBB-0082, p.66.

McELROY, M. (1988). The challenge of global change. *New Scientist* **119**, pp.34-36.

METCALFE, S.E., ATKINS, D.H.F. and DERWENT, R.G. (1988). *Acid deposition modelling and the interpretation of the UK secondary precipitation network data.* Report R013287, AERE, Harwell.

MÖLLER, D. (1984a). Estimation of the global man-made sulphur emission. *Atmospheric Environment* **18**, pp.19-28

MÖLLER, D. (1984b). On the global natural sulphur emissions. *Atmospheric Environment* **18**, pp.29-40.

NIHLGARD, B. (1985). The ammonium hypothesis – an additional explanation to the forest dieback in Europe. *Ambio* **14**, pp.2-8.

NILSSON, J. and GRENNFELT, P. (1988). *Critical loads for sulphur and nitrogen.* Miljorapport 1988: l5/Gotab, Stockholm.

OVINGTON, J.D. (1959). The circulation of minerals in plantations of *Pinus sylvestris* L. *Annals of Botany* **23**, pp.229-239.

PASTOR, J. and POST, U.M. (1988). Response of northern forests to CO_2-induced climate change. *Nature* **334**, pp.55-58.

PAYETTE, S. and FILION, L. (1985). White spruce expansion at the tree line and recent climatic change. *Canadian Journal of Forest Research* **15**, pp.241-251.

PEARS, N.V. (1975). Tree stumps in the Scottish hill peats. *Scottish Forestry* 7, pp.225-259.

'FORESTRY EXPANSION: A STUDY OF TECHNICAL, ECONOMIC AND ECOLOGICAL FACTORS'

This is one of a series of papers which form part of a study to consider the scale, location and nature of forestry expansion in Britain.

The Forestry Commission invited fourteen specialist authors, including economists, foresters, ecologists and biological scientists to write about current knowledge and to assess the main factors bearing on decisions about the future direction of forestry expansion. It is intended that the papers will form the basis for future discussions of the location and type of forestry that will best meet the demands of society for wood products, jobs, recreation, amenity, wildlife conservation, carbon storage and the other uses and public benefits supplied by the country's forests.

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The full list of papers is as follows:

Occasional Paper No	Title	Author
33	Introduction	Professor Ian Cunningham, Macaulay Land Use Research Institute
34	British Forestry in 1990	Hugh Miller, University of Aberdeen
35	International Environmental Impacts: Acid Rain and the Greenhouse Effect	Melvyn Cannell and John Cape, Institute of Terrestrial Ecology
36	The Long Term Global Demand for and Supply of Wood	Mike Arnold, Oxford Forestry Institute
37	UK Demand for and Supply of Wood and Wood Products	Adrian Whiteman, Forestry Commission
38	Development of the British Wood Processing Industries	Iain McNicoll and Peter McGregor, University of Strathclyde and Bill Mutch, Consultant
39	The Demand for Forests for Recreation	John Benson and Ken Willis, University of Newcastle
40	Forests as Wildlife Habitat	John Good, Ian Newton, John Miles, Rob Marrs and John Nicholas Greatorex-Davies, Institute of Terrestrial Ecology
41	Forestry and the Conservation and Enhancement of Landscape	Duncan Campbell and Roddie Fairley, Countryside Commission for Scotland
42	The Impacts on Water Quality and Quantity	Mike Hornung and John Adamson, Institute of Terrestrial Ecology
43	Sporting Recreational Use of Land	James McGilvray and Roger Perman, University of Strathclyde
44	The Agricultural Demand for Land: Its Availability and Cost for Forestry	David Harvey, University of Newcastle
45	Forestry in the Rural Economy	John Strak and Chris Mackel, Consultants
46	New Planting Methods, Costs and Returns	Jim Dewar, Forestry Commission
47	Assessing the Returns to the Economy and to Society from Investments in Forestry	David Pearce, University College London

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