1991 — 1992
REPORT

Institute of Terrestrial Ecology

Natural Environment Research Council

The ITE mission

The mission of the Institute of Terrestrial Ecology is to understand the science of the natural environment with particular emphasis on terrestrial ecosystems Priority is placed on developing and applying knowledge in the following areas

- the factors which determine the composition, structure, and processes of terrestrial ecosystems, and the characteristics of individual plant and animal species
- the dynamics of interactions between atmospheric processes, terrestrial ecosystems, soil properties and surface water quality
- the development of a sound scientific basis for modelling and predicting environmental trends arising from natural and man-made change
- the dissemination of this research to decision-makers, particularly those responsible for environmental protection, conservation and the sustainable use of natural resources at national, regional and global levels

The Institute will continue to develop long-term, multidisciplinary research to maintain an international reputation, provide training of the highest quality, and attract commissioned projects By these means, ITE will seek to increase scientific knowledge and skills in terrestrial ecology, and contribute to national prosperity and prestige

Front cover illustration
Hedgerows in the landscape – photographer C J Barr

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Report of the Institute of Terrestrial Ecology 1991–92

Natural Environment Research Council

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Global environmental change

Last year's report on this programme area looked forward to the United Nations Conference on Environment and Development (UNCED), held in Brazil in June 1992 The details of the domestic and foreign policy by which the UK will fulfil its obligations undertaken at Rio are yet to be announced, but the Climate Convention agreed at the Conference addresses policy in terms of the capacity of natural systems to accommodate change The importance of current and future research into global change cannot, therefore, be overstated

This year saw a further commitment by NERC to research on global change with the start of the fourth part of its Terrestrial Initiative in Global Environmental Research (TIGER) TIGER IV covers ecosystem impacts of global change, and its launch coincides with the publication of the operational plan for the core project of the International Geosphere–Biosphere Programme on global change and terrestrial ecosystems, with which it shares many objectives Awards have been made to ITE staff to contribute to six of the seven multi-centre research projects funded so far in TIGER IV These will cover a range of topics, from the effects of increased carbon dioxide on plant physiology to shifts in the global distribution of biomes

The three reports which follow address issues of global change over a range of scales The value of mechanistic models is illustrated in the report on modelling the dynamics of bracken stands Information gained from studies of methods of controlling bracken has been used to aid the prediction of the impact of climate change on this species, because the model is mechanistic, it also allows prediction of the effects of novel combinations of climate and control practices The studies in the Arctic address global change at the ecosystem level field manipulations include increasing temperature and nutrient supply, the latter to mimic predicted increases in nitrogen deposition and release by accelerated decomposition At this scale, concern is not only with the impacts of the physical environment on biota, but also on the feedback effect of surface biota on the soil/vegetation/atmosphere transfers (SVATs) of energy, momentum, water, and CO_2 and other greenhouses gases The report on change in the global atmosphere represents a further stage in the process of scaling up to the level of the global system Recent technological developments allow key SVAT processes to be measured at various scales, on land, from the air and from space, thereby creating an unprecedented opportunity to build realistic biological feedbacks into climate models

As research increases our ability to understand, model and hence predict the behaviour of the global biosphere/atmosphere system, so policy-makers must rely more on that research to reduce uncertainties about future change and the effects of mitigative responses The challenge to ecologists and other scientists is exciting and far-reaching

Modelling the responses of bracken stands to cutting, herbicide spray and climate change

(This work was funded by the Department of the Environment)

Bracken (*Pteridium aquilinum*) is a major weed species in Britain, particularly in the hill land of the north and west It shades out pasture species, is toxic and carcinogenic to stock, and harbours sheep ticks, which can carry Lyme disease Because of these effects, farmers devote much time and money to controlling it, but often with poor long-term results A mathematical model of the growth of bracken stands and of their reaction to treatment has been developed to predict the outcome of different weed control strategies in a realistic manner

Climate is represented explicitly in the model, and so it can predict what may happen to bracken stands if the climate changes, it may spread faster or it may be more resilient when subjected to cutting or spraying

COBRA – a model of the growth and control of bracken

In this model we have synthesised what is known about the biology of bracken into a mechanistic model of its growth The model represents the transfer of carbon between three compartments of the bracken stand – rhizome tissue, rhizome carbohydrate stores and the fronds The direction of transfer is controlled by a number of environmental or physiological switches Carbon is gained through photosynthesis, and lost from the stand by senescence and death of both frond and rhizome, and through respiration

The model is driven by climate, which is of necessity site-specific Variables include light regime, soil temperature, actual and potential transpiration, and the dates of late-spring frosts and the first frost of autumn A number of management parameters can also be entered, such as the dates and intensity of cutting, or the effectiveness of herbicide spraying

There are, as yet, no suitable published data for comparison with the predictions of this model Results from a field experiment in the East Anglian Breckland will be used for testing its applicability

Simulating the effects of control

Cutting A proportion of the frond biomass is removed from the stand by cutting, and the stand responds by

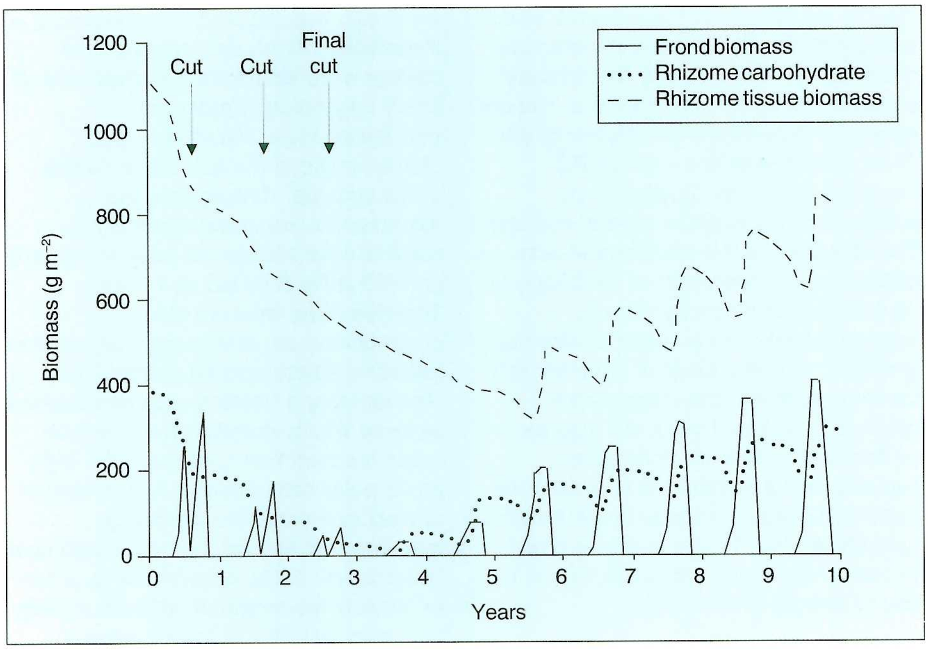

Figure 20. Predicted frond biomass, rhizome tissue biomass and rhizome carbohydrate ($g\ m^{-2}$) for a stand of bracken subject to a 100% effective cut on 1 August for the first three years, after which it is left to recover

producing more fronds (Figure 20). Removal of fronds reduces the carbon gain from photosynthesis, and hence reduces the carbohydrate reserves of the stand. Also, because the stand is losing carbon, biomass lost through senescence is not replaced. However, once treatment finishes, the stand recovers quickly.

Herbicide spraying The herbicide asulam works by killing buds on the rhizome, so in the first few years following spraying few fronds are produced (Figure 21). No carbon is actively removed by the treatment, but without fronds the stand uses up carbohydrate through respiration; senesced tissue is not replaced. However, bud numbers, and hence frond numbers and biomass, increase again and the stand quickly recovers. A recovering stand of bracken can be seen in Plate 6. Three years after spraying the fronds are appearing again. Below-ground biomass has been reduced by a third compared to pre-treatment levels.

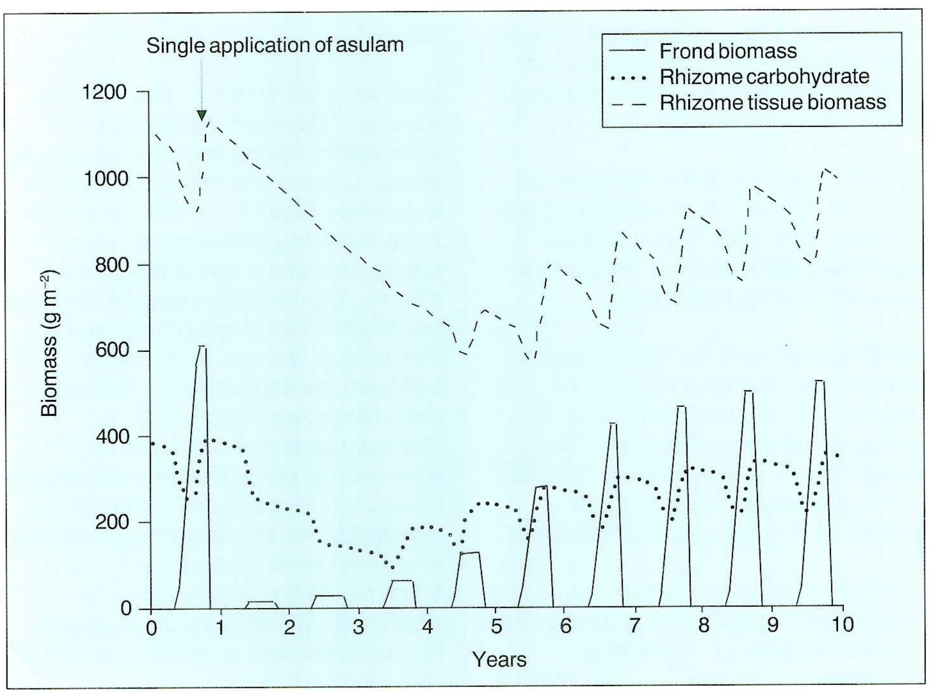

Figure 21. Predicted frond biomass, rhizome tissue biomass and rhizome carbohydrate ($g\ m^{-2}$) after spraying with asulam in year one. The initial kill of fronds is 98%

Developing COBRA

The basic site-specific model has been developed or is in the process of being developed in a number of ways.

If a number of simple assumptions are made, then the model can be used to calculate the rate of spread of bracken 'fronts' into unoccupied grassland or heathland under certain climatic conditions. The assumptions are that the resources used in spread come only from the edge of the stand where bracken is still increasing in biomass, and not from the centre of the stand where it is in equilibrium with its environment, and that the spread maintains the shape of the expanding front. In this form, the model has been used to represent the effects of a range of climatic scenarios on the rate of spread of bracken fronts (Pakeman & Marrs 1992).

Plate 6. A bracken stand regenerating three years after spraying at Sunley Slack, North York Moors National Park

COBRA has also been simplified to run using published climate data available at the national scale. The model can predict the biomass present and the rate of spread of bracken stands under optimum conditions for the whole of Great Britain. This approach will be used to model the effects of different climate scenarios on the performance of bracken and how this performance might differ in different areas of the country.

The basic model is also being used to drive another model which predicts changes in vegetation that will occur in a stand of bracken subject to control. The approach taken will be similar to that of the succession model SETSARIO (Hill

1993), where plants bid for space as it becomes available, eg through gaps open in the canopy and as the litter layer decomposes This part of the model will perhaps re-emphasise that long-term control of bracken is necessary both to maintain adequate control and to enable good colonisation by other species

R J Pakeman and R H Marrs*

(*University of Liverpool)

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A new NERC programme of research on ecology in the Arctic

(This work was funded by an NERC grant under the Special Topic programme on arctic ecology)

Scientific interest in polar regions has increased substantially over the past 40 years, and particularly recently since the important role of polar regions in global climate change scenarios has been realised In Britain, scientific activity has been concentrated through NERC's British Antarctic Survey In 1991, however, the NERC formalised its interests in the Arctic by leasing part of a building at Ny Ålesund, Svalbard (78°55'N 11°30'E), an archipelago in the High Arctic The building was converted into a temporary laboratory for visiting scientists During the winter of 1991–92 a new, larger facility was established It contains four laboratories, a small lecture room, workshop, office, storeroom, and seven bedrooms It is situated within the Norwegian settlement, and the Norwegian administration kindly provides 'mess' facilities A British base manager (N J Cox) was appointed in 1991 to spend each summer at Ny Ålesund, while organising the summer's logistics from ITE Merlewood during the winters

Priority for the use of the research station was given initially to a new programme of research Recognising the potential sensitivity of arctic ecosystems to climate change – expected to be greater in the Arctic than elsewhere – the NERC funded a three-year Special Topic programme on arctic terrestrial ecology The objective of this programme is to determine the sensitivity or resilience of contrasting Arctic ecosystems to environmental change along a latitudinal gradient A major focus of the work will be at Ny Ålesund, but comparative laboratory and field work will also be undertaken at Abisko, in Swedish Lapland, and it is intended to extend the latitudinal gradient of sites to the British uplands at Moor House in the northern Pennines where the climate is similar to that of Iceland at sea level

Five project groups have been funded

University of Aberdeen effects of elevated nitrogen availability on the growth and mycorrhizal infection of arctic dwarf shrubs
University of Bradford photosynthetic and respiratory responses to temperature in some arctic plants of varying ranges of latitude
Liverpool Polytechnic, British Antarctic Survey, University of Leeds and ITE temperature, climate change and environmental constraints on the life history strategies of arctic terrestrial invertebrates
University of Manchester and ITE arctic ecosystems and environmental change
University of St Andrews indicators of deleterious effects of climate change in arctic plant communities

In total, 22 people are involved in the projects The first field season began in late-May 1991, and 15 intensive and extensive field sites were established near Ny Ålesund and Abisko

As an illustration of the type of work, collaboration between ITE and the University of Manchester focused on manipulating the environment The manipulations aim to expose plants and soil to conditions similar to those predicted to occur as climate changes

At Ny Ålesund, microclimate was manipulated by establishing plastic tents in polar semi-desert vegetation dominated by *Dryas octopetala,* which is characteristic of the outer fjord zone (Plate 7) Precipitation and soil nutrients were also manipulated in experiments at these sites At Abisko, comparative studies were established in dwarf shrub heath vegetation (*Empetrum hermaphroditum, Vaccinium* spp), characteristic of the sub-arctic tundra/ forest ecotone These sites and experiments are complementary to collaborative studies established as early as 1989 at Ny Ålesund and Abisko Together, five different plant communities are now being subjected to intensive environmental manipulation, representing a gradient of environmental severity which stretches from the sub-arctic tundra/forest ecotone to the high arctic polar semi-desert A wide range of response variables are being measured on the soil, microbial and plant components of the ecosystems in order to quantify the sensitivity of each system to similar changes in environmental conditions At Abisko, the site established by the Manchester/ITE group was similar to that in which the effects of enhanced ultraviolet (UV-B) radiation on a natural plant community are being investigated by two research students co-supervised by T V Callaghan and Swedish professors

Early results demonstrate the effectiveness of plastic tents in raising air and soil temperatures (mean summer air temperature raised from 5 4°C to 8 9°C at Ny Ålesund and from 11 8°C to 14 6°C at Abisko), while the side-effects such as changes in humidity and photo-synthetically active radiation were minimal

Seed set in the Arctic is often rare and sporadic However, increases in temperature during the growing season, similar to those predicted, were shown to increase dramatically the number of *Dryas* flowering shoots which were setting seed at the end of the growing season This reaction was most likely the result of the earlier phenology we observed in warmed plots, which facilitated the completion of flowering shoot life cycles (Figure 22 i) In contrast, measures of changes in reproductive biology were most strongly influenced by nutrient additions, as opposed to warmer temperatures in sub-arctic vegetation (Figure 22 ii) *Empetrum* berry fresh weight was significantly greater in plots receiving NPK fertilizer, with no other treatments affecting berry mass

The response of a dominant high arctic

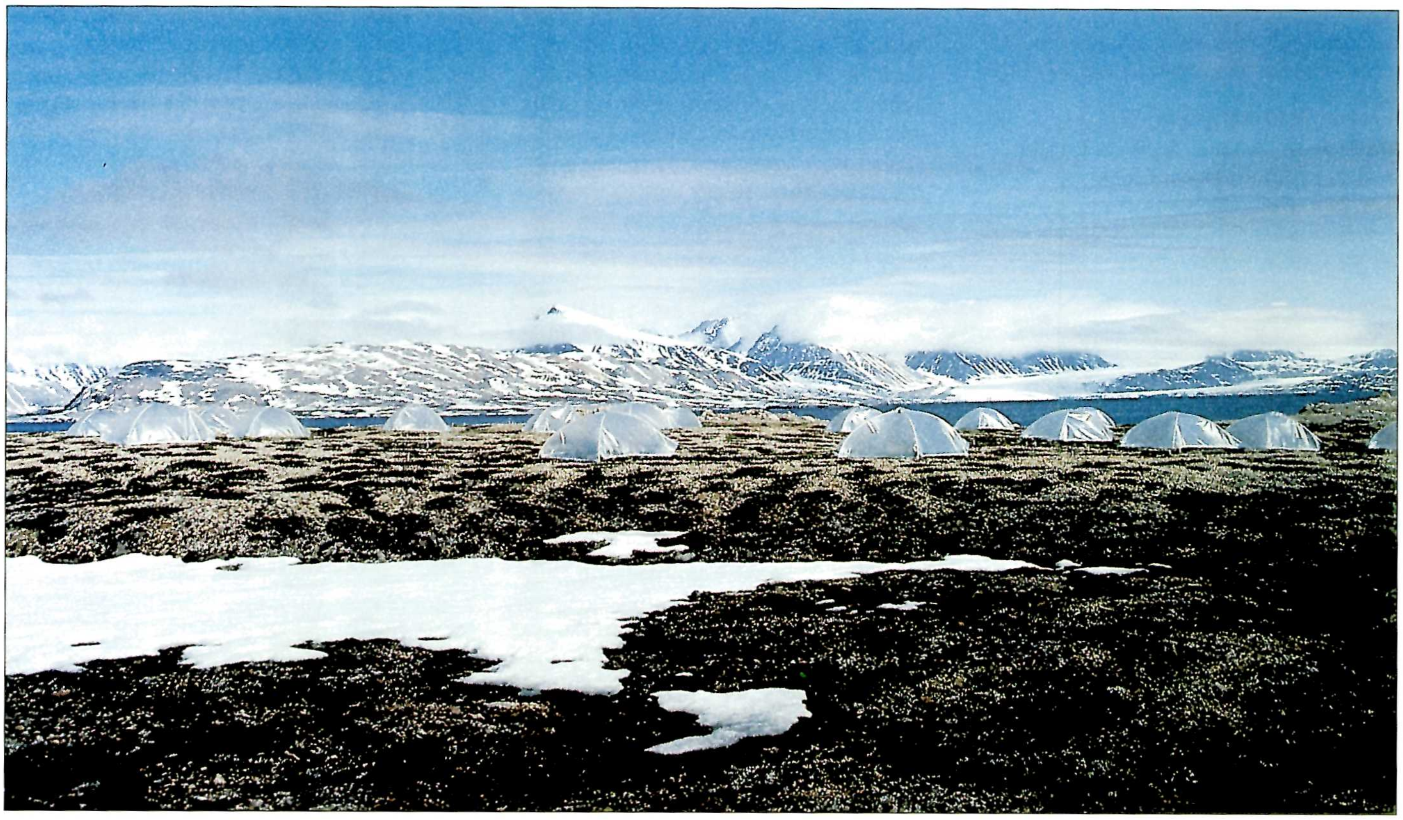

Plate 7. Environmental manipulations on high arctic semi-desert vegetation near Ny Ålesund, Svalbard. The plastic tents for increasing temperatures can be seen clearly

dwarf shrub to increased temperature suggests that climate warming may stimulate flowering and seed development. This effect could be particularly important in the High Arctic where colonisation can proceed in areas dominated by bare ground (Plate 7), and where genetic recombination must be required to generate tolerance to changing conditions. In the Sub-Arctic, however, the closed vegetation is dominated by clonally proliferating species (Callaghan *et al.* 1992a, b), and recruitment from seedlings is rare. Instead, competitive processes predominate, and responses to any increased nutrient availability from temperature-enhanced decomposition rates will increase plant fitness. Thus, the first indications are of a differential response by dominant species in arctic vegetation to changes in climate, depending on location.

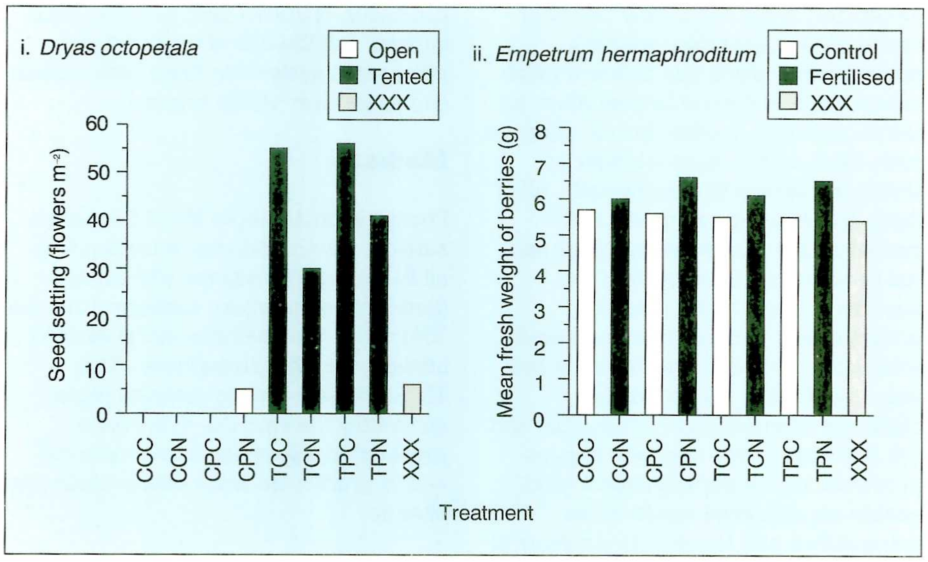

Figure 22 i. Response of seed set in the arctic dwarf shrub Dryas octopetala *to a range of environmental manipulations, showing the significance of increased temperatures for increasing seed set. ii. Response of fruit (berry) fresh weight in the subarctic dwarf shrub* Empetrum hermaphroditum *to similar manipulations, showing the insignificance of enhanced temperature but importance of nutrient addition*

(T=tented/temperature increase; N=nutrient addition; P=enhanced precipitation/irrigation; C=control; XXX=totally unmodified control)

T V Callaghan, N J Cox, P A Wookey and J M Welker in collaboration with J A Lee, M C Press, J Potter and N Parsons (University of Manchester)

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Wookey, P., Parson, A., Welker, J.M., Potter, J., Press, M.C., Callaghan, T.V. & Lee, J.A. 1992 Comparative responses of sub-arctic and high arctic plants to simulated environmental change *Oikos* In press

Change in the global atmosphere

During the year, a number of projects began within NERC's programme on global environmental change the Terrestrial Initiative in Global Environmental Research (TIGER) These projects, mainly involving staff based at the Edinburgh and Merlewood stations of ITE, all concern changes that are occurring in the composition of the global atmosphere The changes causing greatest concern are the current increases in atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), all of which are greenhouse gases The terrestrial biosphere acts as both a 'source' and 'sink' of these gases, and changes in land use and in the climate itself could readily affect the size of the terrestrial sources and sinks Some changes may increase the 'sink strength', thereby removing greenhouse gases from the atmosphere and mitigating the effect of fossil fuel emissions of carbon dioxide These changes need to be encouraged On the other hand, changes could occur that increase the 'source strength', accelerating the release of the greenhouse gases into the atmosphere, and increasing the risk and rate of future climate change

The results of the ITE projects will be reported in future years At this stage, it is appropriate to outline the nature of the problems and the scope of the work being undertaken

Carbon dioxide

The global carbon budget is being perturbed by the release of CO_2 into the atmosphere by burning fossil fuels, by the cement industry, and by the destruction of tropical forests Less than half of the CO_2 released remains in the atmosphere, the remainder is either taken up entirely by the oceans or by a combination of the oceans and land surface The problem for terrestrial scientists is to determine the magnitude of the **net** source or sink for CO_2 of the global land surface This problem is daunting, because the size of the net source or sink is likely to be less than 2% of the total amount of CO_2 exchanged each year between the terrestrial biosphere and the atmosphere through the processes of photosynthesis (CO_2 fixation) and plant, animal and microbial respiration (CO_2 release)

Three aspects of this problem are being studied by ITE within the TIGER programme

First, the increased atmospheric CO_2 resulting from fossil fuel emissions may itself be increasing the growth rates of plants and the production of above-ground and below-ground litter, causing more carbon to be stored in vegetation and in soil organic matter The extent of this 'CO_2 fertilization' effect on carbon sequestration is being investigated by growing plants in elevated CO_2 and tracking the production and fate of any extra carbon that is fixed It seems clear that most plants are capable of fixing more carbon at elevated CO_2 levels, but it is not clear if they 'acclimate' to elevated CO_2 over a period of years, or how shortages of nutrients and water that occur in nature limit their responses If extra carbon is fixed, is the extra litter transferred to the soil mainly below or above ground, and does it have a nutrient composition that makes it more or less easy for it to be broken down by soil organisms? In other words, does the extra fixed carbon have a longer or shorter residence time in the soil? All of these questions are complex, and involve numerous interacting plant and soil processes Consequently, an important aspect of the research programme is to build process-based ecosystem models for herbaceous and forest vegetation These models challenge what we know about plant and soil processes, they also help to pose problems for the experimenters, and enable experimental results to be extrapolated and tentative predictions to be made about the magnitude of the CO_2 fertilization effect (Thornley, Fowler & Cannell 1991)

Second, any increase in global temperature will affect plant growth, and more particularly will cause carbon to be released from soil organic matter The magnitude of this release is being investigated at the TIGER 'flagship' site at Moor House and Upper Teesdale, using an altitudinal gradient as a surrogate for temperature change and artificially heating the soil surface The upland vegetation being studied is the same as that being exposed to elevated CO_2 in chambers at the University of Lancaster

Third, at a global scale, changes in atmospheric CO_2 levels, temperature and rainfall patterns will be confounded with changes in land use In order to integrate all these effects, a global model is being built in which the exchange of CO_2 between the vegetation and atmosphere occurs dynamically This 'interactive vegetation' model will be coupled to the output from the general circulation model (GCM) of the atmosphere being developed by the Hadley Centre (UK Meteorological Office) It may then be possible to determine the extent to which future changes in climate and scenarios of land use will affect carbon fluxes globally The scenarios of land use change that are used depend crucially on knowing the amount of carbon contained in the tropical forests, how much is released when the forests are removed, and how much is refixed by the vegetation that replaces the forest These questions are being studied in field programmes in the Cameroon and Brazil, involving the direct measurement of CO_2 fluxes, the estimation of above- and below-ground carbon, and the use of geographical information systems to determine carbon exchange over whole regions

Methane

Peatlands cover about 3% of the earth's surface, they contain more carbon than all the tropical forests (*ca* 450 Gt) and contribute somewhere between 10% and 30% of the total methane that is emitted annually into the atmosphere This TIGER project aims to estimate more accurately the amounts of methane presently being emitted by peatlands, and to predict the likely effects of climate change

First, measurements will be made to determine the average methane fluxes (net emission or absorption) over peat wetlands in the UK for areas of 10^3–10^{10} m^2 Until recently, all measurements of methane emissions from wetlands were made by covering small patches with cuvettes (boxes) and measuring the rate of build up of methane inside the cuvettes. The fluxes measured differ by a factor of four and ten between 'pools' and 'hummocks', and so it is almost impossible to determine the net flux at the landscape scale. The project will use new techniques to measure methane fluxes over wetlands. These techniques depend upon measuring very small differences in methane concentrations in the atmosphere with distance from the surface and over time. A chromatograph with flame ionization can detect concentration differences of 5 ppbv CH_4, but will be at its limit of detection for measuring vertical gradients in many conditions. Both long-path infrared methods and fast-response tunable diode laser systems will, therefore, be used for methane field campaigns in 1992 and 1993. After modification (with new diodes), these systems will measure N_2O fluxes in 1993–94. An important part of the flux measurement work is to identify the most significant variables which control fluxes of methane from wetlands, and to provide field data for validating mechanistic models that describe the processes involved.

The second part of the project is to develop an understanding (and models) of the processes that influence methane emissions from wetlands, so that effects of climate and land use change can be predicted. These processes are being examined by subjecting monoliths (large intact cores) of peat to a range of temperature and hydrological conditions in controlled conditions (open-top chambers), and by erecting controlled-environment chambers over areas of peatland in the field. The flux of methane will be measured using a gas chromatograph with flame ionization detection, which monitors the difference in methane concentration between the air entering and leaving the chamber. In this way, an understanding of the physical factors regulating methanogenesis will be obtained, modelled and used to provide better estimates of current and future global emissions from natural wetlands.

Nitrous oxide

The concentrations of N_2O in the atmosphere have risen sharply during the last 50 years. Power generation and biomass burning used to be regarded as major sources of N_2O, along with soils, but it has recently been realised that soils are the major source. N_2O is produced in soils by denitrification in anaerobic microsites, and by nitrification in aerobic conditions. Nitrification may be the dominant source, it also produces nitric oxide, which affects tropospheric concentrations of ozone – another greenhouse gas.

The objective of this project is to develop a 'mass balance' method to measure N_2O emissions over fertilized grasslands, and to compare that method with long-path infrared analysis and conventional chambers. The aim is then to determine the effect of different soil and physical properties on N_2O emission by soils and, as with methane, to build a model for predicting emissions, given different scenarios of climate change.

A further strand to the greenhouse gas work within the TIGER programme concerns the photochemistry of gases in the atmosphere, which in part determines the residence time of some of the gases like methane, N_2O and ozone. Diurnal and seasonal variations in the concentrations of both relatively stable trace gases and short-lived radicals will be measured at lowland and upland sites, in order to improve our understanding of the chemistry of the atmosphere.

M G R Cannell and B G Bell

Reference

Thornley, J H.M., Fowler, D. & Cannell, M.G R 1991 Terrestrial carbon storage resulting from CO_2 and nitrogen fertilization in temperate grasslands. *Plant, Cell and Environment*, **14**, 1007–1011

Environmental pollution

The Institute's research on environmental pollution continues to address aspects of all the major current pollution problems. The following papers demonstrate this fact, and describe research on acidic deposition, enhanced nitrogen inputs, pesticides and radionuclides. The papers also show how ITE's research covers pollutant emission, transport and deposition, as well as impacts on plants, invertebrates and animals; they also demonstrate the strong links between our research and policy development.

Over the past few years, there has been a marked change in emphasis of research on acidic pollutants, with a move from work on sulphur compounds towards nitrogen and its impacts. The first three papers reflect this change and consider research on nitrogen which has direct relevance to policy development while addressing fundamental science questions. The setting of controls on nitrogen emissions will require information on current UK emissions and deposition; the work on fluxes presented here is enabling those budgets to be calculated. Setting emission targets for nitrogen will probably be based on the critical load approach, in which the concept of nitrogen saturation is a key concept. The research in Welsh forests and a transect of European sites discussed here provides important information for the further development and application of these concepts.

The fourth paper shows, however, that there are still many questions to be answered about the impacts of sulphur compounds and acidity. It demonstrates a significant growth reduction in mature Sitka spruce in response to exposure to acidic mists containing acidity and sulphur and nitrogen compounds, at concentrations known to occur in the British uplands.

Controls on the emission of acidifying pollutants are still being negotiated, but restrictions on the use of pesticides have been in place for a number of years. The banning of the use of pesticides such as DDT has led to significant improvements in the populations of a number of predatory birds. Work reported here clearly demonstrates the importance of long-term research; it presents results showing changes in the levels of pollutant residues in predatory birds over a 28-year period. Such long-term data sets are vital if we are to assess the success or otherwise of control policies. Many potentially toxic pesticides are, however, still in use, and research is required to enable conditions to be developed for their use in order to minimise their impact on non-target species. Thus, work reported here is defining the size of buffer zones necessary to protect non-target species of invertebrates from the effect of insecticide spray drift.

It is now six years since the Chernobyl incident and the subsequent deposition of radioactive fallout over the UK, but a large number of farms in the uplands of Wales, northern England and Scotland still have restrictions on the sale and slaughter of their sheep. Research is reported here from a study involving several European groups which is examining the factors influencing the transfer of radionuclides to grazing animals. Such research is essential for the development of improved models so that better predictions can be made of impacts following any future nuclear accident.

Atmospheric budget for fixed nitrogen species in the UK

The atmospheric deposition of fixed nitrogen species is important because this contributes, alongside the deposition of sulphur pollutants, to the acidification of sensitive ecosystems. The compounds of interest include the products of both nitrogen oxides (NO_x) and ammonia (NH_3) emissions (Table 10). These compounds are also of particular concern because their deposition represents an extra input of available nitrogen which may disrupt the balance of normally nutrient-poor semi-natural ecosystems. While nitrogen oxides may be considered as 'conventional' acidifying pollutants, because they derive mainly from emissions from fuel combustion by industry and by transport, ammonia is neither acidic nor is its primary source fossil fuel combustion. It is often described as a natural trace gas, because it originates mainly from the volatilisation of animal urine, from manure and senescent vegetation. However, the presence of significant quantities of ammonia in the atmosphere is a result of intensive agriculture with large applications of nitrogen fertilizer, so that it may also be considered a pollutant, but from the agricultural industry.

It is, therefore, important to consider the atmospheric budget of these fixed nitrogen species, both to assess deposition to sensitive ecosystems, and, on a country basis, to estimate the contributions and transport of the different compounds. In this report, we briefly describe the present state of knowledge for nitrogen deposition processes and how these are being quantified on a UK scale. This

Table 10 Sources of oxidised (NO and NO_2) and reduced (NH_3) nitrogen emissions in the UK for 1990

	Source	Emission
NO, NO_2	Transport 55%	800 kt
	Industry 45%	
NH_3	Agriculture 95%	350 kt
	Industry 5% (?)	

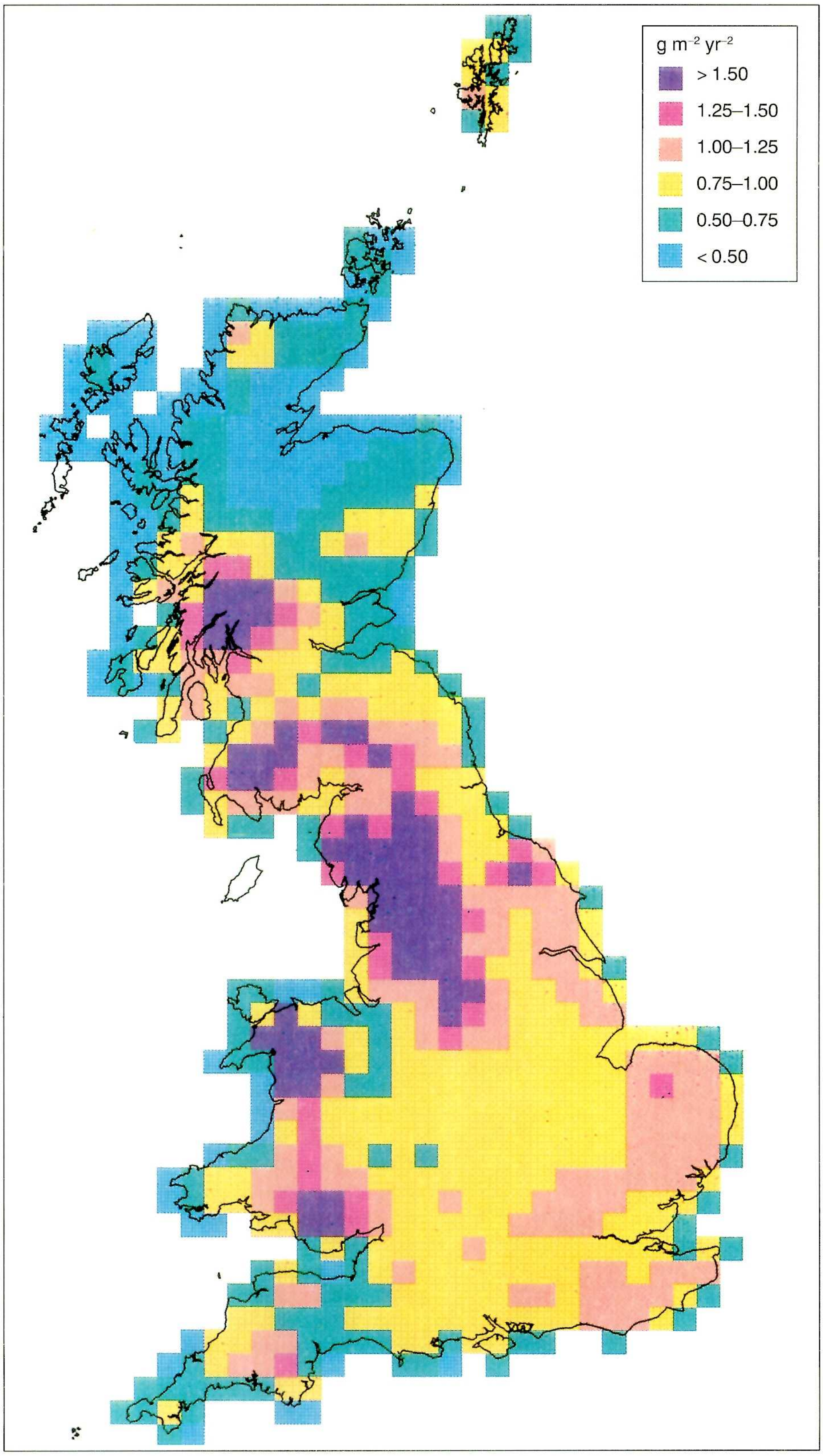

Figure 23. Annual wet deposition of nitrogen as nitrate and ammonium in the UK, 1990

information is then collated in the form of an atmosphere/land mass budget for fixed nitrogen species in the UK, which is used to identify the relative importance of the different compounds, as well as current uncertainties.

Deposition pathways

Nitrogen oxides and ammonia are emitted as gases (NO_x, NH_3), though they react rapidly in the atmosphere to form a range of products of which the main ones are gaseous nitric acid (HNO_3), and nitrate (NO_3^-) and ammonium (NH_4^+) ions present in precipitation and fine particles. As a consequence, these pollutants may be removed both by deposition in rain, snow and hail, collectively known as wet deposition, and by the direct absorption of the gases and fine particles at the ground, a process referred to as dry deposition. At high-altitude sites, where the ground is frequently enshrouded in cloud or hill fog, the direct impaction of cloud droplets to vegetation also becomes important, and is frequently referred to as occult deposition. The nitrogen inputs to the UK for each of these processes are considered below.

Wet deposition

Rainfall composition is monitored throughout the United Kingdom as part of the Department of the Environment's air quality monitoring programme. The data provide the regional average rainfall NO_3^- and NH_4^+ concentrations, which are combined with the areal precipitation field and enhanced for the effects of seeder–feeder scavenging of pollutants on hills. The resulting maps show the regional deposition fields for the country (Figure 23), the total wet deposition for the UK providing 108 kt of nitrogen as NO_3^- and 131 kt of nitrogen as NH_4^+. The total reduced nitrogen deposited wet, therefore, exceeds that of oxidised nitrogen and is proportionally greater than UK emissions, which are 800 kt N emitted as NO_x and 350 kt N emitted as NH_3.

Dry deposition

The other major removal pathway for both oxidised and reduced nitrogen is the direct absorption by the countryside of the gases and particles containing fixed N, or dry deposition. The process is controlled by the transport of gases and particles to absorbing surfaces and by reaction with or impaction on terrestrial surfaces.

Oxides of nitrogen NO, NO_2, HNO_3, HONO and PAN

The oxides of nitrogen are all transported at similar rates through the turbulent boundary layer close to the ground, where rates of transport are influenced by windspeed, atmospheric stability, and the aerodynamic roughness of the surface. The rates of uptake of these gases at the surface are controlled by the affinity of absorbing surfaces for uptake of NO, NO_2, etc. For nitric oxide, rates of uptake are very small, and it may be ignored as a component of deposition in the net exchange of nitrogen with the ground. For NO_2, recent work has shown that it is absorbed through stomata at rates which are very similar to those of water loss when expressed as a conductance (Hargreaves *et al.* 1992). The mass flux of water out of stomata is, of course, much larger than that of NO_2 uptake, because of the very different surface and atmospheric concentrations of the respective gases.

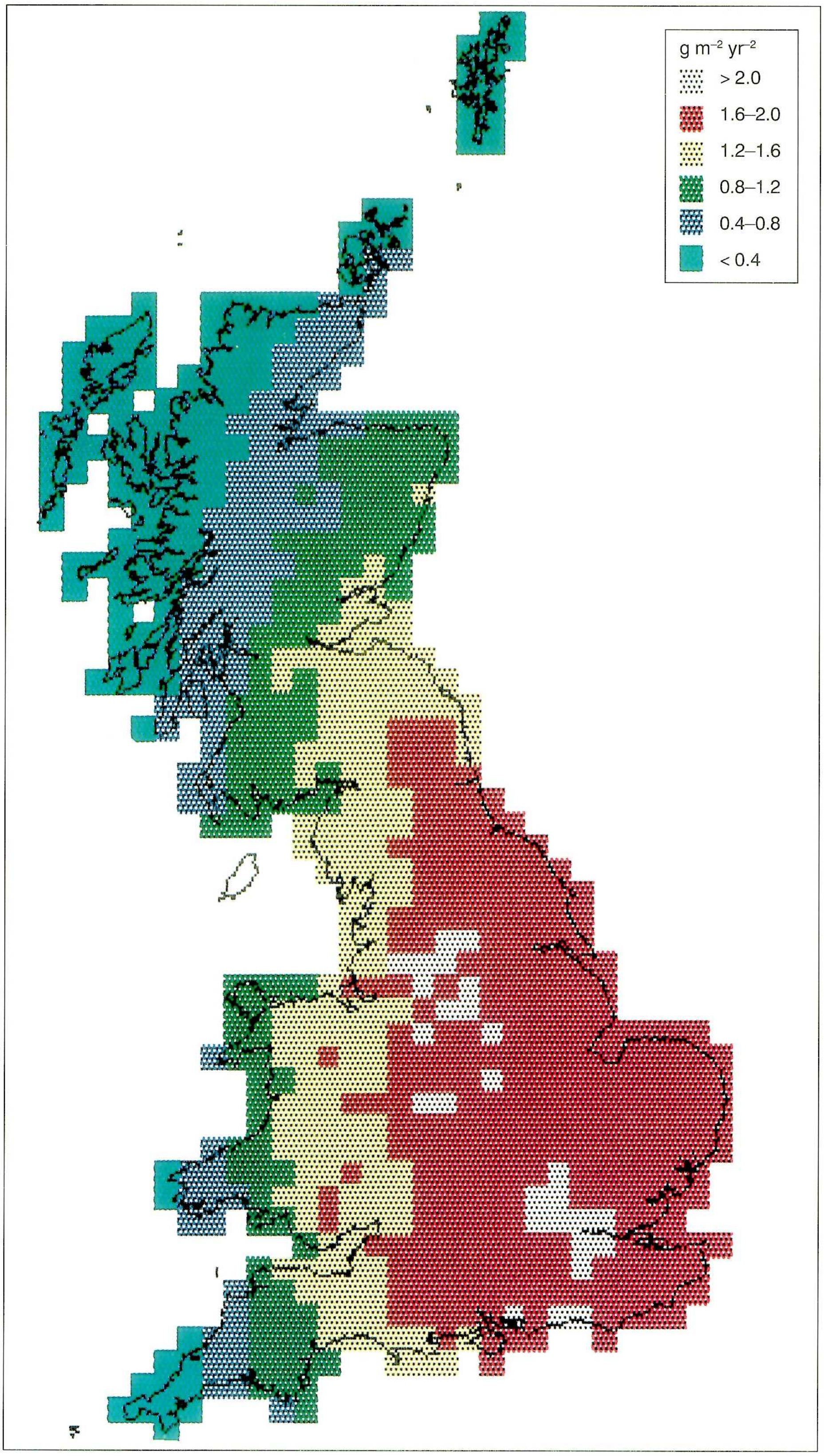

Figure 24. Annual dry deposition of nitrogen as NO_2 in the UK, 1990

The rate of deposition of NO_2 (expressed as deposition velocity (v_g)) shows strong diurnal and seasonal cycles as a consequence of the stomatal uptake. The current NO_2 concentration field can be coupled with land use and meteorological data, and a stomatal conductance model built to calculate hourly fluxes of NO_2 to the ground for each of five land use categories for the entire UK surface. These surfaces include lowland grass, arable cropland, moorland and upland grass, urban and forest areas. The model results show a pattern of NO_2 deposition across the country which closely corresponds with the areas of large concentrations, but the total dry deposition at 100 kt N yr^{-1} as NO_2 is of a similar magnitude to wet deposition of NO_3^- (Figure 24).

The deposition of HNO_3 is an efficient removal process, in that the rate of uptake by all terrestrial surfaces proceeds at the rate of transport to the absorbing surface. The absence of a surface resistance provides a convenient simplification in the deposition process which may then be scaled by land use (for aerodynamic roughness of the surface) and windspeed to provide the aerodynamic resistance (r_a) and additional boundary layer resistance (r_{bg}) according to Fowler *et al.* (1991). These atmospheric resistances provide the total resistance to deposition which is the reciprocal of deposition velocity (v_g) and may be used to calculate HNO_3 deposition to the surface. The total HNO_3 deposition for the UK amounts to only 15 kt N yr^{-1}, largely because atmospheric HNO_3 concentrations are small, generally 0.1–0.5 ppbv (10^{-9} atm.). Deposition of other oxidised forms of nitrogen (eg HONO, nitrous acid and PAN (peroxy-acetyl nitrate)) are also likely to be relatively small, as concentrations are small.

The dry deposition of ammonia is complicated by the fact that it is both emitted from and deposited on the ground in different situations. For unfertilized semi-natural ecosystems and forests, ammonia is generally captured very efficiently, with large rates of uptake. The values of the deposition velocity (v_g) approach the maximum possible, so that the resistance to deposition at the surface (r_c) is very small, and transfer is controlled by the rates of turbulent transfer.

By contrast, over agricultural crops and grazed pastures, both emission and deposition of ammonia occur, generally giving a net emission over annual scales. Emission is favoured by warm dry conditions, whereas deposition predominates when the surface is cold and wet. Ammonia is also important because it may affect the deposition of other gases, in particular sulphur dioxide (SO_2). It has been suggested that a large quantity of ammonia at the surface can promote SO_2 dry deposition by neutralising it on leaf surfaces, a process often referred to as co-deposition. From measurements over grassland in eastern England, ammonia upward fluxes (emission) have been observed concurrently with SO_2 deposition. An example of the results is given in Figure 25, and shows a link between SO_2 deposition and ammonia emission. This finding is consistent with NH_3 being a

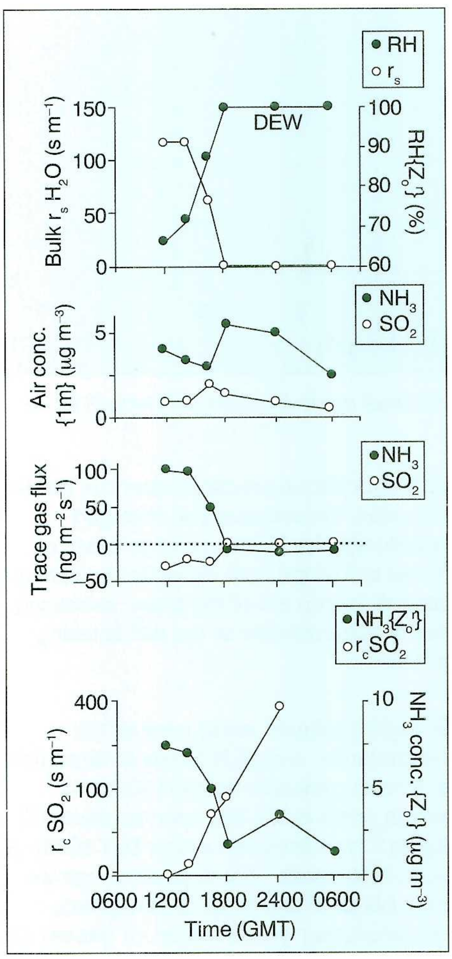

Figure 25. Surface exchange of NH_3 and SO_2, measured on 19 September 1989 over pasture vegetation

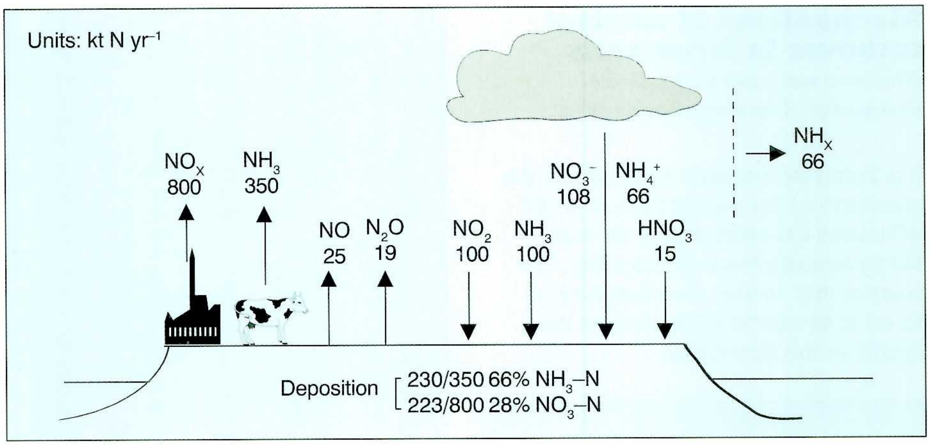

Figure 26. Atmospheric budget of reduced and oxidised nitrogen over the UK

requirement for rapid rates of SO_2 deposition on dry vegetation.

Total atmospheric impacts of fixed nitrogen to the UK

The sum of wet and dry deposition for oxidised compounds, collectively referred to as NO_y, and reduced nitrogen compounds, similarly known as NH_x, may now be compared with known emissions.

Figure 26 summarises these data and shows that the total deposition of fixed nitrogen from the atmosphere (ignoring microbial fixation of N_2) is 423 kt N per year, or 37% of the total emission of NO_y and NH_x compounds. However, the relative importance of agricultural and industrial sources of the deposited nitrogen is much more revealing. The deposition of reduced nitrogen in the UK accounts for two-thirds of all NH_x emissions, so that the UK exports relatively little to the rest of Europe in comparison with that deposited in the UK. Further, deposition of reduced nitrogen dominates the deposition budget, with agricultural sources contributing 55% of the deposited nitrogen, even though emissions from agriculture only contribute 30% of the total emission of fixed nitrogen. By contrast, the deposition of the oxides of nitrogen are rather a small fraction of UK NO_y emission (24%), and contribute only 45% of the UK total, even though NO_y emissions represent 70% of the UK total emissions of N-containing gases.

There are several important consequences of this budget. First, the average distance of travel of NO_y in the atmosphere is more than a factor of two larger than that of NH_x and the mean residence time for NO_y is much longer. Equally important for the policy-makers who have responsibility for regulating emissions of pollutants to the atmosphere, the emissions of fixed nitrogen from agriculture are too important to ignore. The control of agricultural emissions of ammonia would also be the most effective method of reducing total UK nitrogen deposition.

These simplified arguments serve merely to identify the relative source and sink strengths for oxidised and reduced nitrogen. They are not intended as a policy tool. However, prior to the recent research on deposition processes on which this budget has been based, it has not been possible to construct a nitrogen budget for the UK, except by pure speculation. The applications of the research and modelling to larger scales (Europe), and to address practical questions, present important opportunities for the next few years.

D Fowler and M Sutton

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Mechanisms of nutrient turnover in forest soils

(This work was partly funded by the Commission of European Communities)

It is being increasingly realised that the chemistry of the atmosphere strongly influences the chemistry of the rain falling beneath trees (throughfall). We suspect that, in turn, the chemistry of forest soils can be influenced by the quality of the throughfall.

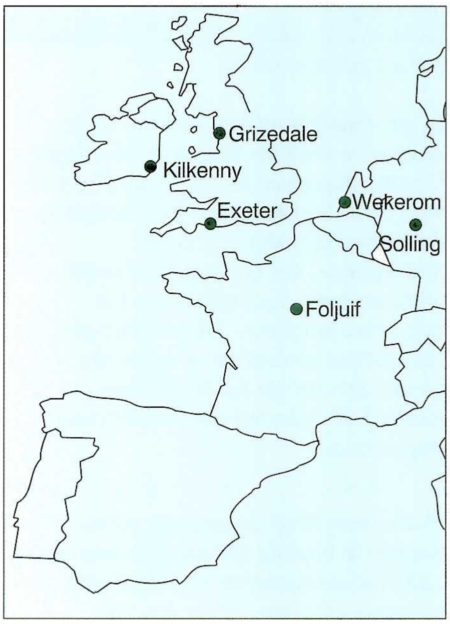

Figure 27. Location of the CORE sites used in the reciprocal soil transplant experiment

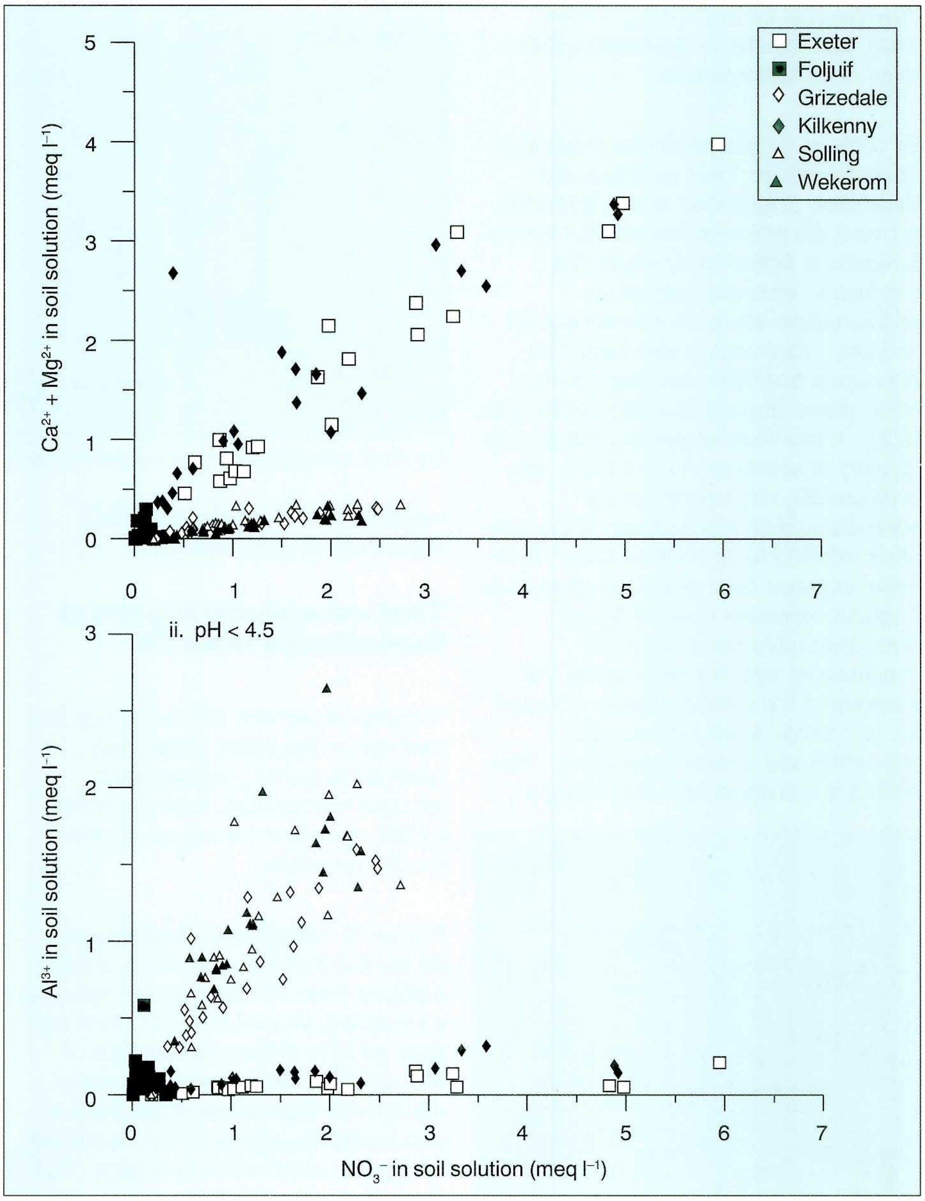

Figure 28. The relationship between cation release and nitrate production in the soils with pH values (i) above and (ii) below 4.5

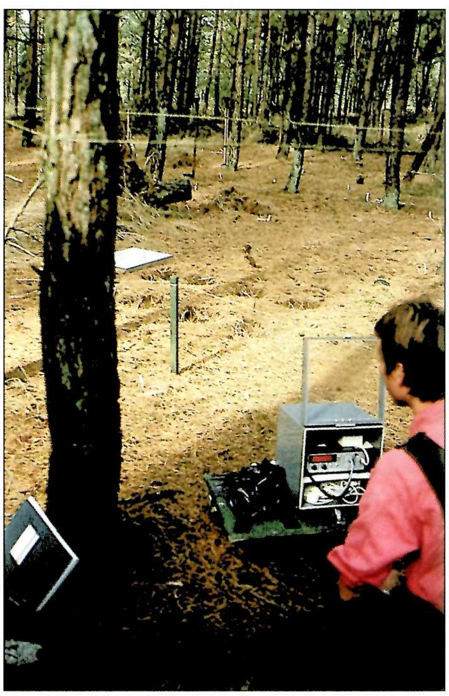

Plate 8. Soil temperature measurements being collected at the Wekerom site in the Netherlands

The hypothesis that the chemistry of European forest soils is markedly affected by the deposition of air pollutants in throughfall has been tested in the current work using a series of reciprocal soil transplants. A transect of forest sites was chosen across Europe, with differing nitrogen (N) and sulphur (S) inputs, the tree species being Norway spruce *(Picea abies)* and Scots pine *(Pinus sylvestris)*. The project, referred to as the CORE project, initially involved six different European research groups, and the location of the forests is shown in Figure 27.

With a few exceptions, N has been the main factor limiting the productivity of forest ecosystems in central Europe in the past. Because of increased industrial and agricultural practices over the last few decades, the situation has changed drastically; the N load to large areas of forest in Europe now exceeds the annual growth increment of the trees, indicating that N accumulation in the soil is taking place.

In highly polluted areas such as the Netherlands, annual N fluxes in throughfall in forests generally exceed 50 kg ha^{-1}, and in some areas can even exceed 100 kg ha^{-1} (van Breemen & van Dijk 1988). At such high levels of N deposition, nitrate may begin to leach out of the system, contaminating groundwater, or excess N may be released to the atmosphere as the greenhouse gas N_2O. Imbalance in nutrient supply to the trees may also have detrimental effects on tree growth.

The transect

The CORE sites were initially chosen to represent different pollution environments across Europe In general, our preconceptions about polluted and non-polluted sites have been confirmed, for example, the Irish site is the 'clean' site, with annual depositions of less than 10 kg of both S and N ha^{-1} beneath the canopy In marked contrast, the Solling site in Germany receives just under 50 kg S ha^{-1}, whilst highest depositions of N are found at the Wekerom site in the Netherlands, with around 65 kg N ha^{-1} Therefore, the sites do have very different pollution climates

The deposition data show certain other trends, which have implications for the setting and control of 'critical loads' For example, there is clear evidence of co-deposition of ammonium and sulphate beneath the canopies across all sites, with the exception of those sites dominated by marine inputs Similarly, marine-dominated sites provide an extremely difficult case for setting critical loads for S deposition because of their high levels of non-anthropogenic deposition

Reciprocal transplant

Each site has acted as a 'host', receiving standard soil cores (seven replicates per soil) from each of the six other sites, so that forest soils have moved from polluted to unpolluted sites, and *vice versa* Soil solution concentrations of major cations and anions have been monitored, and certain ions have been dramatically affected by the transfer (eg NO_3^-), whereas others have remained unaffected (eg K^+) In particular, soils moved to the Wekerom site have shown very large increases in nitrification Similarly, when the Wekerom soil has been moved to other sites, nitrification has declined We initially believed that this effect was caused by enhanced ammonium deposition at the Wekerom site, but a complementary experiment has demonstrated that this is not the case

In this experiment an extra set of soils from Exeter were placed at each site, where they received distilled water in place of incident precipitation These 'control' soils also exhibited high nitrification at Wekerom, even though they were not receiving incident N inputs We now believe that the increase

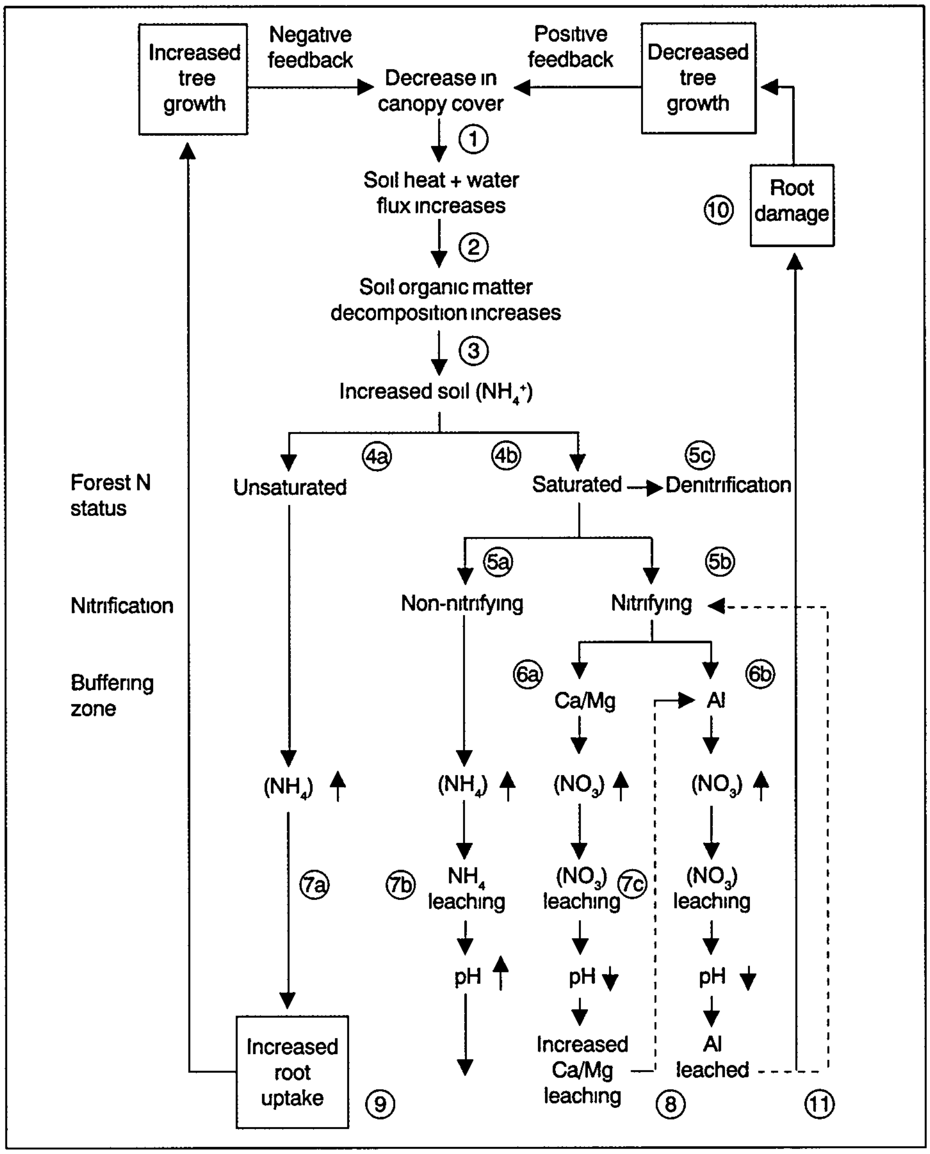

Figure 29 Framework showing the suggested links between soil N processes and tree dieback

in nitrification is caused by the higher temperatures at this site (Plate 8), which in turn are the result of pollution damage to the forest canopy

Several ions in soil solution were completely unaffected by the exclusion of incoming throughfall (eg K), and were totally dominated by internal soil sources In contrast, sulphate concentrations were significantly greater in uncovered lysimeters, and the conservative ion, Cl^-, was also affected significantly

Nitrification and soil acidification

Perhaps the most dramatic observation from the transplant experiment was the extreme importance of nitrification in determining acidification and cation leaching in the soils The soils can be readily separated into three groups according to the way in which the nitrogen cycle responded to perturbation

In the more acid soils, with a pH less than 4 5, nitrification resulted in the production of aluminium (Al) on a stoichiometric basis In contrast, those soils having a pH more than 4 5 lost Mg^{2+} and Ca^{2+} as a consequence of proton production during nitrification (see Figure 28) One of the soils, from Fontainebleu in France, failed to nitrify under any conditions, and soil acidification did not occur in this soil Thus, we are able to assign forest soils to one of three functional classes, according to their ability to nitrify and their pH

In order to predict the acidification response of a forest soil to climate change or increased N deposition, there is one further important factor which needs to be considered – the N saturation status of the trees Taking this factor into consideration, we have been able to construct a framework which may describe one of the major underlying mechanisms in the causation of forest dieback The framework is described below and outlines the feedback mechanisms which may lead to forest decline on certain soil types and under conditions of N saturation

Figure 29 summarises the importance of the soil N cycle in determining forest health If the canopy cover decreases, through whatever cause (in Wekerom, this is believed to be direct NH_3 toxicity to the canopy), there is a greater soil heat flux This has important consequences for soil organic matter turnover, resulting in an increase in organic matter decomposition and consequent enhanced mineralisation of N in response to canopy thinning

If the soil is not N saturated, then soil warming leads to increased soil concentrations of NH_4 and greater uptake of NH_4 by the trees We suspect that, in this situation, the trees will compete effectively with the bacterial population in the soil responsible for nitrification, resulting in increased root uptake and tree growth, and low soil nitrate concentrations This process will feed back on itself, resulting in the recovery of the canopy structure

If the soil is N saturated, which is equivalent to the condition in our unrooted lysimeters, then the implications for acidification depend upon whether the soil is nitrifying or non-nitrifying If the soil does not nitrify, there are few implications for soil acidification or nitrate leaching, and the soil pH will probably rise If the soil does nitrify, then the result will be either Ca^{2+}/Mg^{2+} leaching in soils with a pH above 4 5, or the enhanced release of Al in soils with a pH below 4 5 A key question is the amount of acidity that a soil can buffer, which will dictate the time that a soil will take to 'tip over the ridge' into the Al buffering zone Our data, and those of other workers, suggest that the transitory zone between calcium/magnesium and aluminium buffering is very unstable, and soils will either belong to one class or the other

If the soil has a pH below 4 5, is capable of nitrifying, and is N saturated, then we expect root damage to occur Because damaged roots lead to a reduction in canopy cover, this positive feedback is accelerated, and the forest has little chance of recovery We strongly suspect that this is the case at the Wekerom site, and the diagram suggests that recovery can only be achieved by adding Ca/Mg, inhibiting nitrification, cooling the soil, or removing N saturation

The approach adopted by CORE for investigating the influence of chemical and physical environments on the processes occurring in forest soils is unique The concept of reciprocally transplanting soil columns across a wide pollutant gradient, using different soil and forest types, is new, and has produced a data set that reveals interactions not previously quantified and which have wide applicability Not only has the project, to date, demonstrated the over-riding importance of changes in physical climate on forest soil acidification, but it has clearly highlighted the inadequacy of existing soil ionic balance models which ignore the biotic components of the soil

P Ineson

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Effects of Sitka spruce stand age on critical loads for nitrogen deposition

The concept of critical loads of sulphur (S), nitrogen (N) and acidity for soils is widely applied as a means of determining the ability of soils to neutralise acid deposition (Hornung 1991) In many upland areas of Britain, acid deposition inputs exceed the critical loads for acidity of soils However, there is an additional source of soil acidification which has so far been excluded from the critical loads assessments in Britain This is the acidifying effect of nitrification and nitrate leaching in acid soils

Nitrification is the conversion in the soil of ammonium-N (from atmospheric inputs or mineralisation of soil organic matter) to nitrate Acidification of the soil occurs if this nitrate is lost by leaching Rates of nitrate leaching from upland soils are generally low, perhaps because nitrogen limits vegetation growth in most British upland ecosystems However, in a 55-year-old Sitka spruce (*Picea sitchensis*) plantation at Beddgelert forest in north Wales, streamwater nitrate-N losses were relatively high at 14 6 kg N ha^{-1} yr^{-1} (Stevens *et al* 1992) At this site, wet deposition inputs averaged 10 3 kg N ha^{-1} yr^{-1} – substantially more than the 2–3 kg N ha^{-1} yr^{-1} deposited to pristine sites Because there are high rates of nitrification in the soil and nitrate losses are significant, acidification will occur Losses of nitrate and other mobile anions will be accompanied by balancing amounts of cations, including base cations, hydrogen ions and particularly aluminium Depletion of the base cation store will exacerbate soil acidification, while increased aluminium concentrations in streams may result in toxicity to fish and, in extreme circumstances, render the water unsuitable for human consumption

Other forest catchment studies by ITE Bangor in Wales at Plynlimon and Llyn Brianne show small nitrate losses compared with Beddgelert The forest nitrogen survey described here aims to discover whether Beddgelert is unusual If not, is there any relationship between plantation age and nitrate leaching rate, and, if so, what are the processes responsible?

The study involved 25 catchments (Figure 30) Five were unimproved moorland, and, to ensure a spread of forest ages, there were five catchments in each of four age bands 0–15, 16–30, 31–45 and over 46 years All forests except one were of first-rotation Sitka spruce growing on stagnopodzol soils A one-year programme of monthly sampling of streams, soil water from the B horizon (below the main rooting zone) and O horizon (surface peat), throughfall and rainwater (Plate 9) was completed in November 1991 This sampling confirmed a trend of increasing nitrate concentration with plantation age in streams and B horizon soil water (Figures 31 & 32), although the increase occurred only in plantations older than 30 years Sources of this nitrate in the older crops might be

- increased inputs of N in throughfall (increased dry and cloudwater deposition)
- reduced demand by the trees, allowing available ammonium-N to be nitrified and the nitrate to be leached

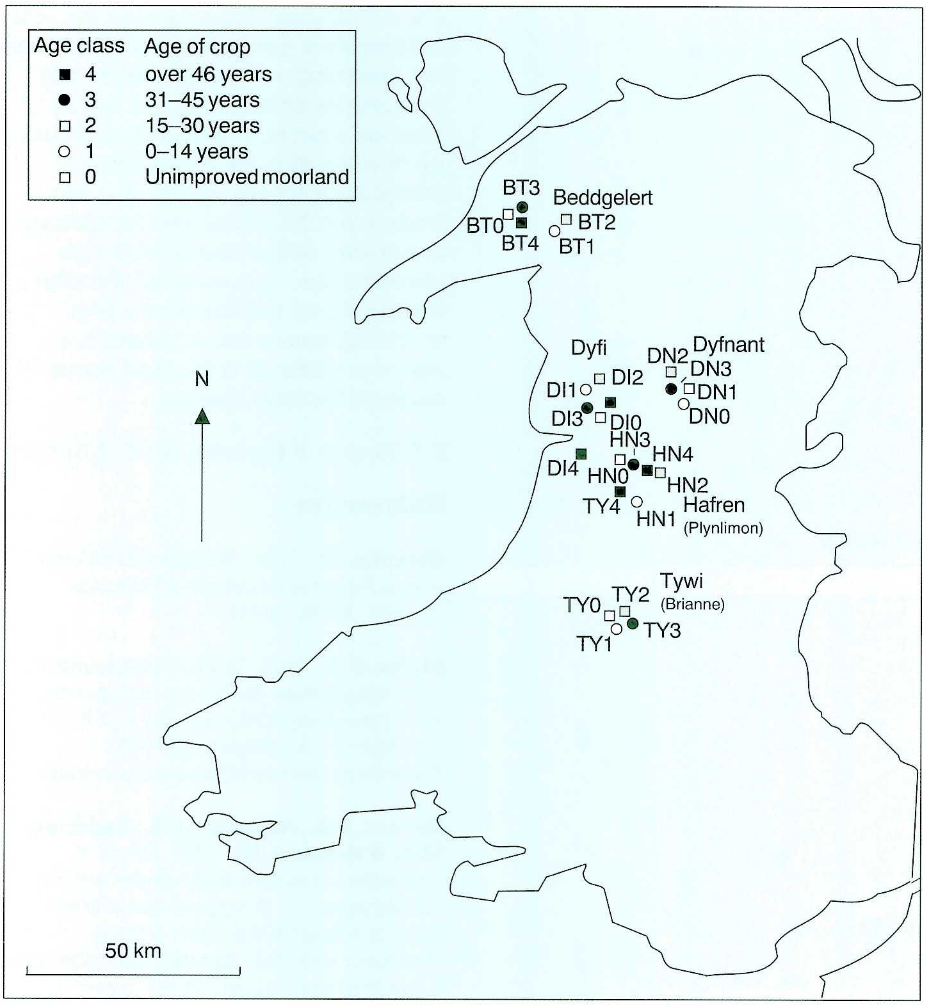


Figure 30. Locations of the 25 sites used in the forest nitrogen survey

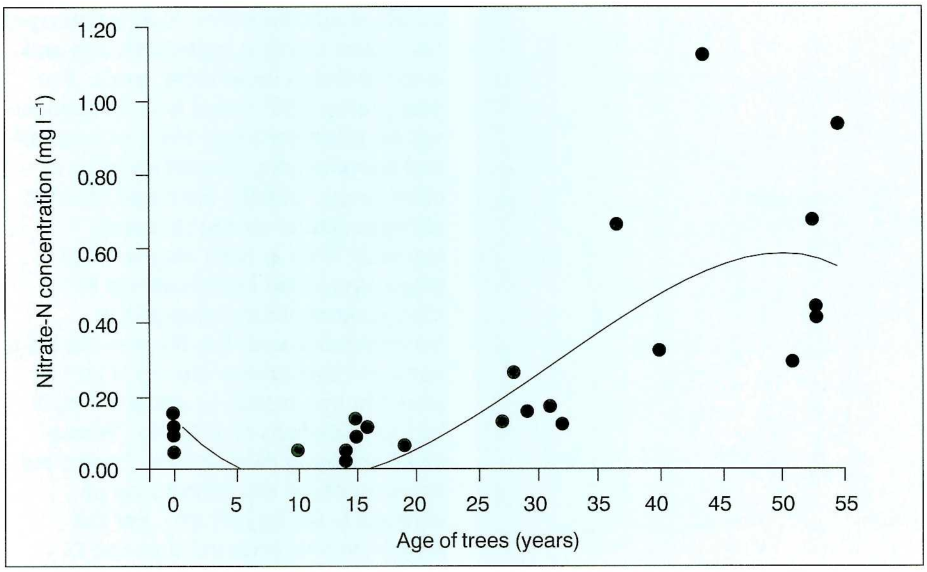
- increased rates of mineralisation and nitrification in the soils of the older stands

Throughfall data show that inputs of inorganic-N (nitrate-N plus ammonium-N) to the soil increased with crop age (Figure 33), but the increase was insufficient to explain the observed nitrate losses, and the trend was different. Also, we have been unable to detect any relationship between crop age and rates of mineralisation and nitrification in forest floor organic matter. By default, nitrogen uptake and immobilisation in the crop may, therefore, be the main process which controls nitrate leaching rates. Only in crops 30 years old or more do inputs from the atmosphere, plus mineralisation, supply more N than can be immobilised by the crop, which by this stage has a much reduced demand for nitrogen from the soil (Miller 1978). In older crops we have also obtained evidence that deficiencies of phosphorus and potassium (K) limit the ability of trees to utilise available soil N, which will exacerbate the situation.

The inability of crops older than 30 years to immobilise available nitrogen indicates that the critical load for nitrogen (as a plant nutrient) varies with age and is exceeded in these older crops. For young crops the critical load for nitrogen will be relatively large, but it will decline and become zero or even negative in older crops. Ideally, the target load for nitrogen should ensure no nitrate leaching, even in older stands. This target load could be the amount of nitrogen immobilised annually in harvested material. For 50-year-old Sitka spruce at Beddgelert, 128 kg N ha^{-1} is stored in tree trunks, or about 2.5 kg N ha^{-1} yr^{-1} (Stevens *et al.* 1988). Whole tree harvesting (428 kg N ha^{-1} removed) would increase the critical load of nitrogen to 8.5 kg ha^{-1} yr^{-1}, but soil acidification through calcium and K removal in biomass could become unacceptable.

These estimates of the N critical load may be compared with the wet deposition inputs at Beddgelert, which average 10.3 kg N ha^{-1} yr^{-1}. More realistically, a throughfall N flux of 20 kg N ha^{-1} yr^{-1} (Stevens *et al.* 1990) may be used as a surrogate for total inputs, although this figure assumes that no canopy leaching occurs. A substantial reduction in nitrogen inputs is, therefore, needed to ensure that the critical load for nitrogen is not exceeded in older plantations where conventional, bole-only, harvesting is practised. We estimate that nitrification and nitrate leaching acidify the soils at Beddgelert forest at the rate of 1.0 kmol ha^{-1} yr^{-1}, significantly more than acidification due to sulphate deposition (0.4 kmol ha^{-1}

Plate 9. An automatic weather station outside a forest plantation in north Wales



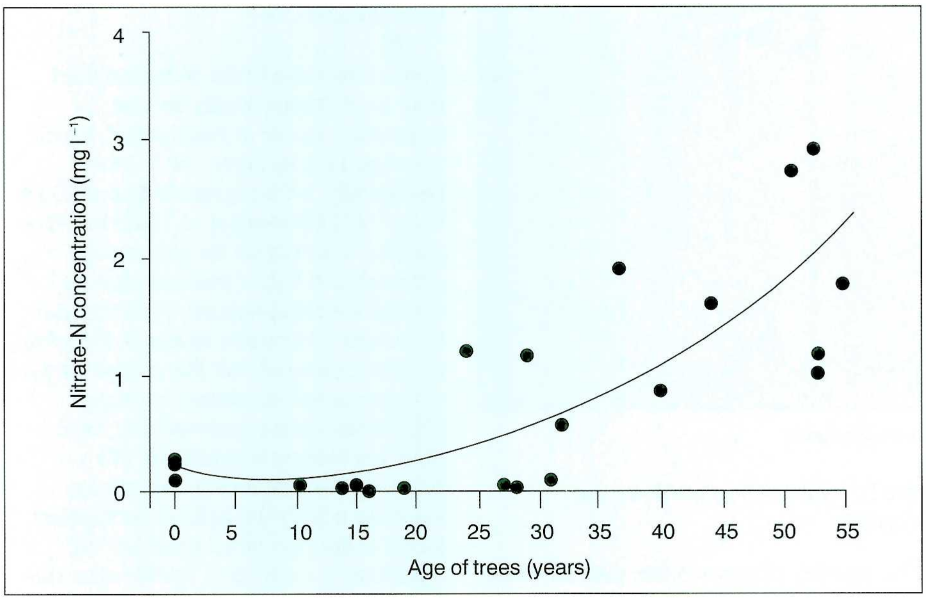


Figure 31. (Top) Mean nitrate-N concentration in the streams. Moorland sites are plotted as age zero. Regression equation is nitrate-N concentration = 0.1301 – 0.0299 Age + 0.001685 (Age)^2 – 0.0000183 (Age)^3 (R^2=0.823, $F_{7,17}$=11.29, P<0.001)

Figure 32. (Middle) Mean nitrate-N concentration in the B horizon soil water. Moorland sites are plotted as age zero. Regression equation is nitrate-N concentration = 0.14 – 0.015 Age + 0.000952 (Age)^2 (R^2=0.641, $F_{2,22}$=19.65, P<0.001)

yr^{-1}) or base cation removal in bole-only harvest (0.3 kmol ha^{-1} yr^{-1}). At Beddgelert, and all the forest nitrogen survey sites, approximately 50% of incoming inorganic-N is ammonium-N, whether determined in throughfall or in rain. Soil acidification occurs through nitrification of ammonium-N to nitrate-N, but only if the latter is leached from the system, as occurred in the older forests. Deposition of both ammonium-N and nitrate-N is therefore implicated in soil acidification.

It is evident from these data that the soils of older Sitka spruce plantations in Wales are becoming acidified at a faster rate than previously believed, and that all potential sources of acidification should be considered in the assessments of critical loads for soil acidity. It is also evident that the critical load for nitrogen and acidity varies considerably with plantation age. It is essential, therefore, that the critical load be set at a level which will ensure that acidification is kept to a minimum at the most sensitive stages of the crop rotation.

P A Stevens, B Reynolds and D A Norris

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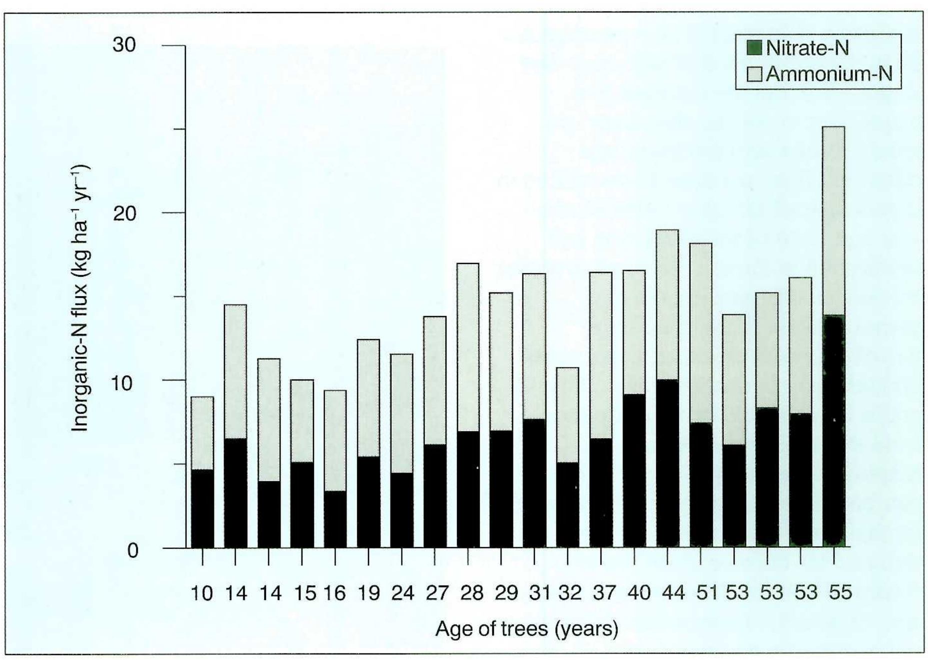

Figure 33. Inorganic-N flux in throughfall of the forest stands

Stevens, P.A., Williams, T.G., Norris, D.A. & Rowland, A.P. 1992. Dissolved inorganic nitrogen budget for a forested catchment at Beddgelert, North Wales. *Environmental Pollution*. In press.

Acid mist impairs the volume growth of mature spruce

(This work was partly funded by the Department of the Environment)

Upland forests in Europe and eastern North America are frequently enveloped in cloud. Concentrations of acidic pollutants in cloud are usually much greater than in rain, with concentrations of sulphate and hydrogen ions occasionally over 3 mM (equivalent to pH<2.5). The potential effects of such high concentrations on trees exposed to polluted cloud have been studied for the past five years at ITE Edinburgh, in experiments which have exposed young trees to artificial acid cloud under controlled conditions. A series of studies has shown that red spruce (*Picea rubens*), Norway spruce (*Picea abies*) and Sitka spruce (*Picea sitchensis*) can be affected by acid mist. Symptoms of injury include visible discoloration of foliage (Leith *et al.* 1989), changes in cell structure (Eamus, Leith & Fowler 1989), and significant reductions in frost hardiness in autumn (Fowler *et al.* 1989; Cape *et al.* 1991). The growth of these young potted trees has not been affected.

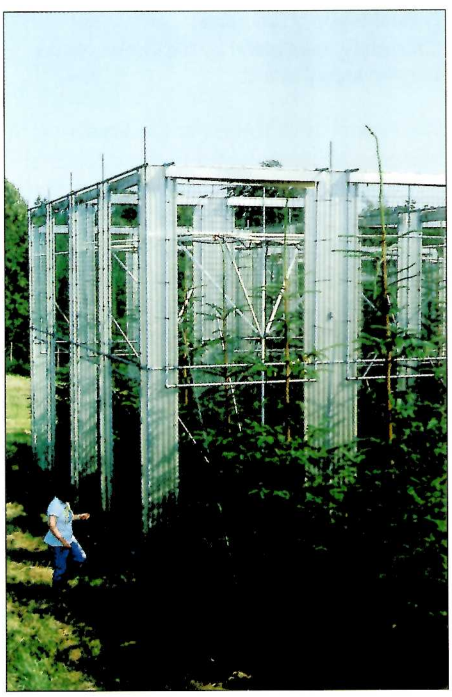

Plate 10. Experimental site, showing scaffolding framework and roller blind units surrounding mature Sitka spruce trees

Although there are clear effects of acid mist on seedlings, at pollutant concentrations in the mist typical of many upland areas, it is difficult to extrapolate these results to predict the effect of real polluted cloud on mature trees growing in these upland areas. We do not know whether mature trees will respond quantitatively, or even qualitatively, in the same way as seedlings. To address this problem, an experiment has been designed to expose whole mature trees of Sitka spruce to artificial acid mist, and to compare the results obtained with those found for seedlings. Close to the Edinburgh Research Station is a field site where 144 Sitka spruce trees, grown from cuttings taken from a single tree in 1972, were planted out in 1984. At the start of the experiment in 1990, these clonal trees were between 2.5 m and 5 m in height, and the smaller trees had produced cones. The site slopes to the south-east, with the smallest trees at the top of the slope, and the largest at the bottom. These genetically identical trees were ideal experimental material for testing the effects of acid mist on whole large trees.

In designing the experiment, it was important that the growing conditions of the trees should not be greatly affected. Blocks of four trees were, therefore, enclosed in an open scaffolding framework. This framework supported roller blinds, which could be pulled down only during the misting treatment, to prevent the acid mist from drifting on to adjacent trees (Plate 10). The mist treatment was based on the treatments which had been used in the seedling experiments, with twice-weekly exposure to a mixture of sulphuric acid and ammonium nitrate (typical of polluted cloud) at pH 2.5. The treatment was not regular, as application during rain or strong winds was avoided. An additional treatment was included, based on observations that real clouds often contain very large concentrations of insoluble particles, by adding small glass spheres to the acid mist solution before it was sprayed on the trees. The trees were assigned to five height classes, with two treatment blocks for each height class – one with and one without added particles. One block of four trees, in the centre of the

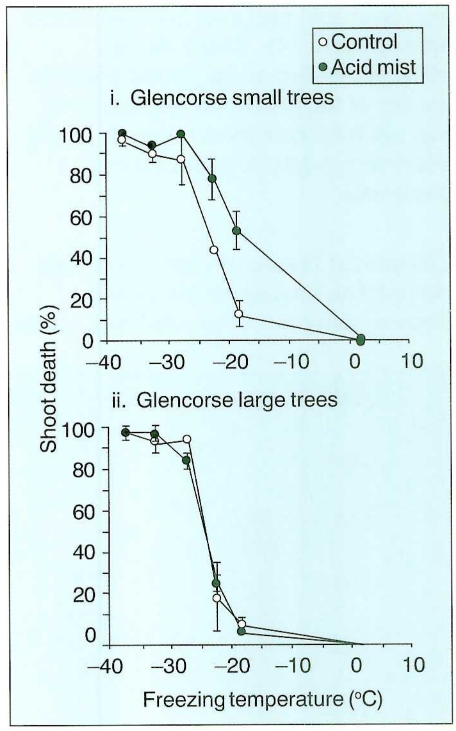

Figure 34. Percentage of spruce shoots killed, by freezing to different temperatures, for acid mist treatments and untreated 'control' trees. The acid mist treatment caused shoots from the smallest trees (height class 1) to be more sensitive to frost than the smallest control trees. Shoots from the largest trees (height class 5) were not affected

experimental area, received a double dose of mist. Unsprayed trees from the same height class were used as 'controls'.

After the first season's experiment in 1990, the most obvious difference from the seedling experiments was the total lack of any discoloration of the spruce needles. The trees appeared to be healthy, and nutrient analysis confirmed that the acid mist treatment had not significantly affected the overall nutrient composition of the trees.

Frost hardiness was assessed by taking sections of shoot and freezing them in the laboratory at a range of temperatures. The proportion of shoots killed, determined by measuring the rate at which salts leaked from frozen needles (Murray, Cape & Fowler 1989), was recorded for each freezing temperature to establish whether there were differences between the treated trees and the control trees. Frost hardiness was adversely affected, as had been found for seedlings, but only in the smallest trees. A higher proportion of shoots was killed at warmer temperatures from trees which had received acid mist than from the control trees (Figure 34). There was no detectable effect of the added particles on any of the measured responses, so the two treatment blocks at each height class were taken as experimental replicates.

Continuous measurements of tree size were taken throughout the growing season, using stem diameter girth bands fixed round the tree at the tenth internode, close to the base of the tree. These measurements were then converted into cross-sectional areas of the stem, so that radial growth over the summer could be determined. Because the trees were different sizes, the absolute increase in cross-sectional area was divided by the cross-sectional area at the beginning of the experiment to give the relative area increment. When these data were analysed, a marked effect of the acid mist treatment was apparent (Figure 35 i). The trees which had received the mist treatment had relative area increments, on average, 25% smaller than the untreated trees. Tree heights were also estimated, and, although the results were more variable, the treated trees also had smaller relative height increments.

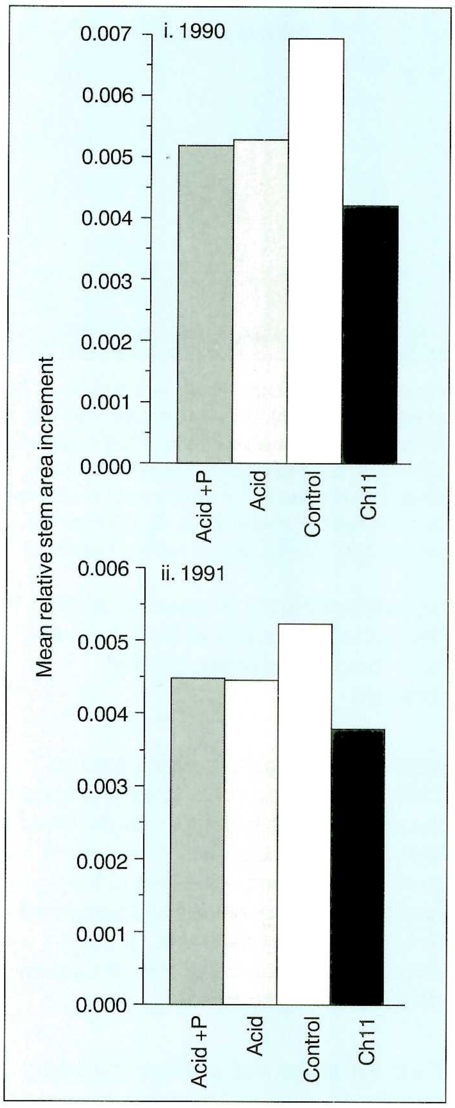

Figure 35. Average relative area increment of all trees in each of the mist treatments, and of untreated 'control' trees. Acid+P refers to the treatment including particles, and Ch11 refers to the block of four trees which received a double dose of mist.
i. 1990 experiment: the measurements refer to the increase in cross-sectional area of the stem between July and November 1990, relative to the cross-sectional area of each stem in July 1990
ii. 1991 experiment: the measurements refer to the increase in cross-sectional area of the stem between May and November 1991, relative to the cross-sectional area of each stem in May 1991

This unexpected result – given the lack of any detectable effects on seedling growth when exposed to acid mist – was repeated in 1991. Using the same trees and treatment regime, a continuation of the experiment showed that the effect on growth could be reproduced in a second year of treatment (Figure 35 ii). The effect was statistically significant only for the smaller height classes, with little or no effect on the bigger trees.

These large reductions in tree growth, in the absence of any visible symptoms of damage to foliage, suggest that timber production in some upland areas of Britain may be adversely affected by polluted cloud. The dose of acidity applied in the experiment was about three times that estimated to be received by a spruce forest in southern Scotland from cloud (Crossley, Wilson & Milne 1992). The trees in the experiment, however, were growing under ideal conditions in a former agricultural soil at a sheltered location. The additional stress of acid mist on trees growing in poor soils at high altitudes may have a much greater effect on forest trees than on our experimental trees. Even within the experiment, it was the smaller trees that were most severely affected by the acid mist treatments. The experiment will be repeated in 1992 for a third year, and continuous measurements of cloud composition are currently being made at two upland locations in Britain to assess the frequency and duration of exposure of upland forests to pollutants in cloud.

A Crossley and J N Cape

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Long-term trends in pollutant levels in predatory birds

(This study was funded by the former Nature Conservancy Council)

We report here trends in the levels of certain pollutants found in the bodies of some predatory birds examined during a 28-year period, 1963–90. The chemicals involved include pp'-DDE (the main metabolite of the insecticide DDT in avian tissues), HEOD (the active ingredient in the insecticide 'dieldrin' and a metabolite of the active ingredient in the insecticide 'aldrin' in avian tissues)

Plate 11. Sparrowhawk at nest

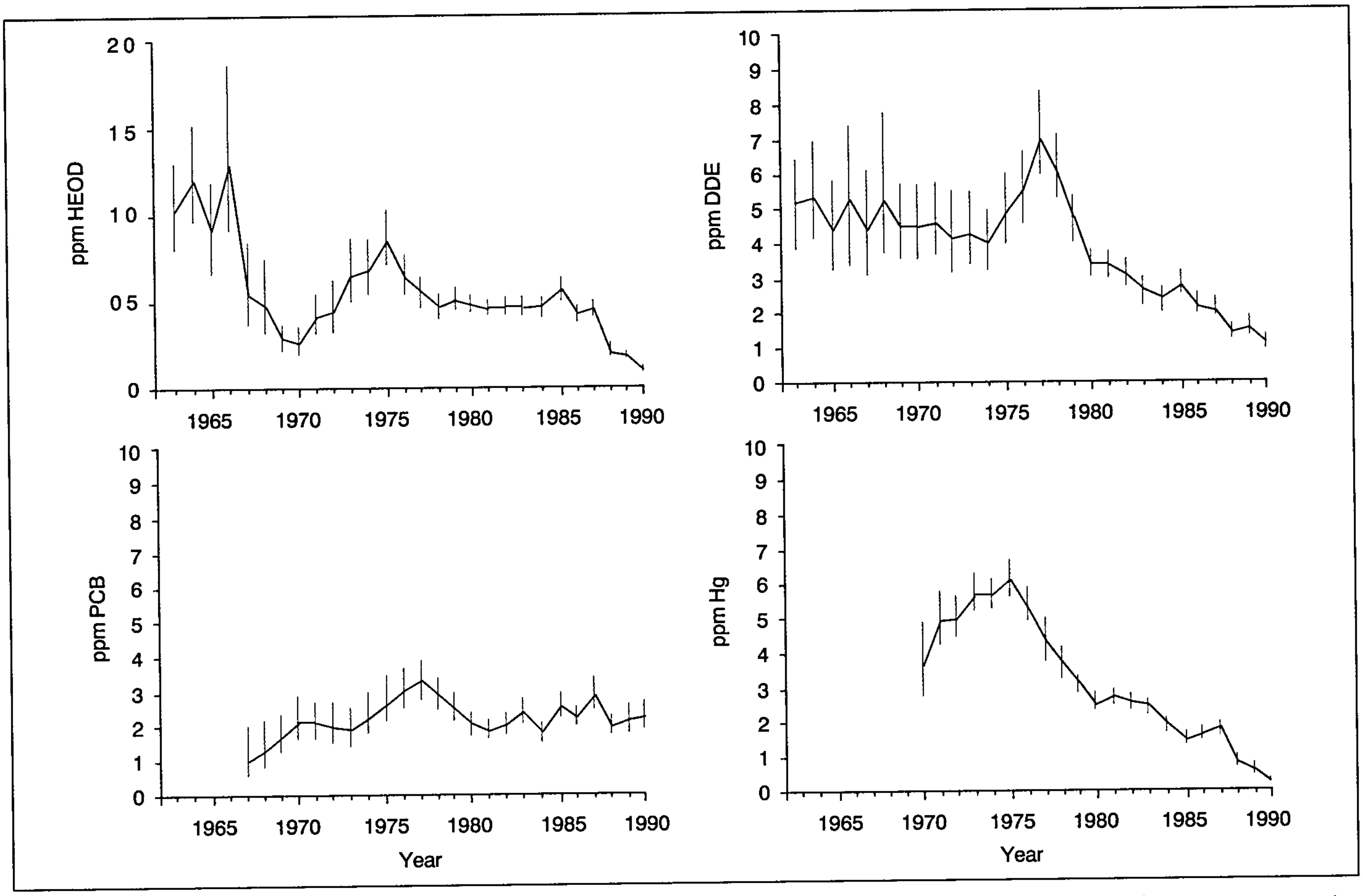

Figure 36 Levels of chemical contaminants in the livers of sparrowhawks, 1963–90, based on analyses of 1001 livers Lines show 3-year moving geometric means of residue levels, and bars show geometric standard errors Figures show ppm in fresh weight

PCBs (industrial polychlorinated biphenyls) and Hg (mercury, from industrial and agricultural sources) The bird species involved include the sparrowhawk (*Accipiter nisus*) (Plate 11) which eats small birds, the kestrel (*Falco tinnunculus*) which eats mainly small rodents, and the heron (*Ardea cinerea*) which eats mainly fish All these species obtain pollutant residues in their food

From its inception in 1963, the aim of this pollutant monitoring scheme was to assess temporal trends in chemical residues against the background of successive restrictions on organochlorine and mercurial pesticide use As the scheme was countrywide, it was also intended to assess regional variations in levels A secondary aim was to provide long-term residue data, against which to assess the changing population status of affected species The chemicals involved were known to be highly persistent, and some of the pesticides caused mass mortalities and reproductive failures in birds As predators, all the species chosen for study accumulated residues of these chemicals to a high level They had all shown some degree of eggshell thinning attributed to DDE, and the sparrowhawk and kestrel had shown obvious population declines attributed to poor breeding (from DDE) and enhanced mortality (mainly from HEOD) (Newton 1979, 1986) The sparrowhawk was the most seriously affected, as it almost disappeared from eastern districts of Britain and became much reduced elsewhere during the peak years (around 1960) of aldrin and dieldrin use The kestrel showed some decline in eastern arable districts but maintained its numbers elsewhere The heron showed some reduction in breeding success, but not in numbers, except that it took more years than usual to recover from hard winters

Specimens for analysis were obtained each year by making requests in bird journals for bodies of birds found dead All carcases were requested, irrespective of mode of death Most specimens had died from accidents, or from shooting or starvation, and probably no more than a small proportion had died from chemical poisoning These birds may not have been representative of the living population of each species with respect to contaminant levels, but they formed a consistent sample throughout Analyses were conducted on samples of liver, and chemical residue levels were expressed as parts per million (ppm) in fresh weight The long-term trends in contaminant levels for three species are shown in Figures 36–38, for Britain as a whole The data were also examined on a regional basis, dividing the country into four zones according to the proportion of the land area devoted to arable crops (where pesticide use was heaviest) (Table 10)

The general decline in DDE and HEOD levels in all three species was associated with progressive reductions over the years from 1963 in the agricultural uses of DDT, aldrin and dieldrin, ending with their total withdrawal in 1986 In the sparrowhawk and kestrel, levels of HEOD in the 1960s were highest in the eastern (most arable) parts of the country, and in the ensuing years declined more steeply there, as restrictions on use came into effect By the 1980s, regional differences had

Table 10 Time trends in DDE, HEOD and Hg levels in the livers of three predatory bird species in different zones of Britain, classed according to agricultural land use Trends were examined by regression analyses of individual residue levels (log transformed) against years The figures show regression coefficients (and sample sizes), negative values indicate declines (*P<0.05, **P<0.01, ***P<0.001)

Percentage of arable land	Zone 1 <10	Zone 2 11–30	Zone 3 31–60	Zone 4 >60
HEOD				
Sparrowhawk	–0.013 (251)	–0.018 (409)***	–0.034 (185)***	–0.061 (107)***
Kestrel	–0.031 (90)*	–0.021 (261)***	–0.027 (247)***	–0.045 (427)***
Heron	–0.053 (131)***	–0.028 (136)*	–0.037 (113)***	–0.051 (298)***
DDE				
Sparrowhawk	–0.022 (257)***	–0.024 (413)***	–0.036 (187)***	–0.030 (109)*
Kestrel	–0.059 (92)***	–0.035 (267)***	–0.023 (252)**	–0.035 (437)***
Heron	–0.075 (135)***	–0.038 (140)***	–0.021 (114)*	–0.024 (299)***
Hg				
Sparrowhawk	–0.034 (172)***	–0.056 (317)***	–0.064 (169)***	–0.077 (94)***
Kestrel	–0.082 (62)***	–0.085 (181)***	–0.080 (158)***	–0.085 (326)***
Heron	–0.034 (107**	–0.020 (108)	–0.013 (64)	–0.034 (112)***

largely disappeared, and birds from eastern arable areas were no more contaminated than those from elsewhere

As the use of organochlorines fell over the years, populations of depleted species recovered, while shell thickness and breeding success improved (Newton 1979, 1986, Ratcliffe 1980) In the sparrowhawk, population recovery began in the west in the mid-1960s and spread eastward, occurring latest (in the mid-1980s) in the more arable eastern areas (Newton 1986) In the kestrel, decline was obvious only in the east, and recovery occurred in the late 1970s Interestingly, the recoveries of sparrowhawk numbers in different agricultural zones, and the recovery of kestrel numbers in the eastern zone, all began when the geometric mean HEOD residue in livers from those zones fell below about 1.0 ppm fresh weight (Newton 1988) As the population decline in these species was attributed mainly to increased mortality from aldrin and dieldrin, this HEOD level indicated a critical threshold above which population recovery occurred

In the heron, variations in residue levels between agricultural zones were less marked than in the raptors This was perhaps because residues in this fish-eater came partly from industrial, as well as agricultural, sources, and because many river systems were not restricted to any one agricultural zone Over the years, residues of DDE, HEOD and Hg declined similarly in herons from all agricultural zones

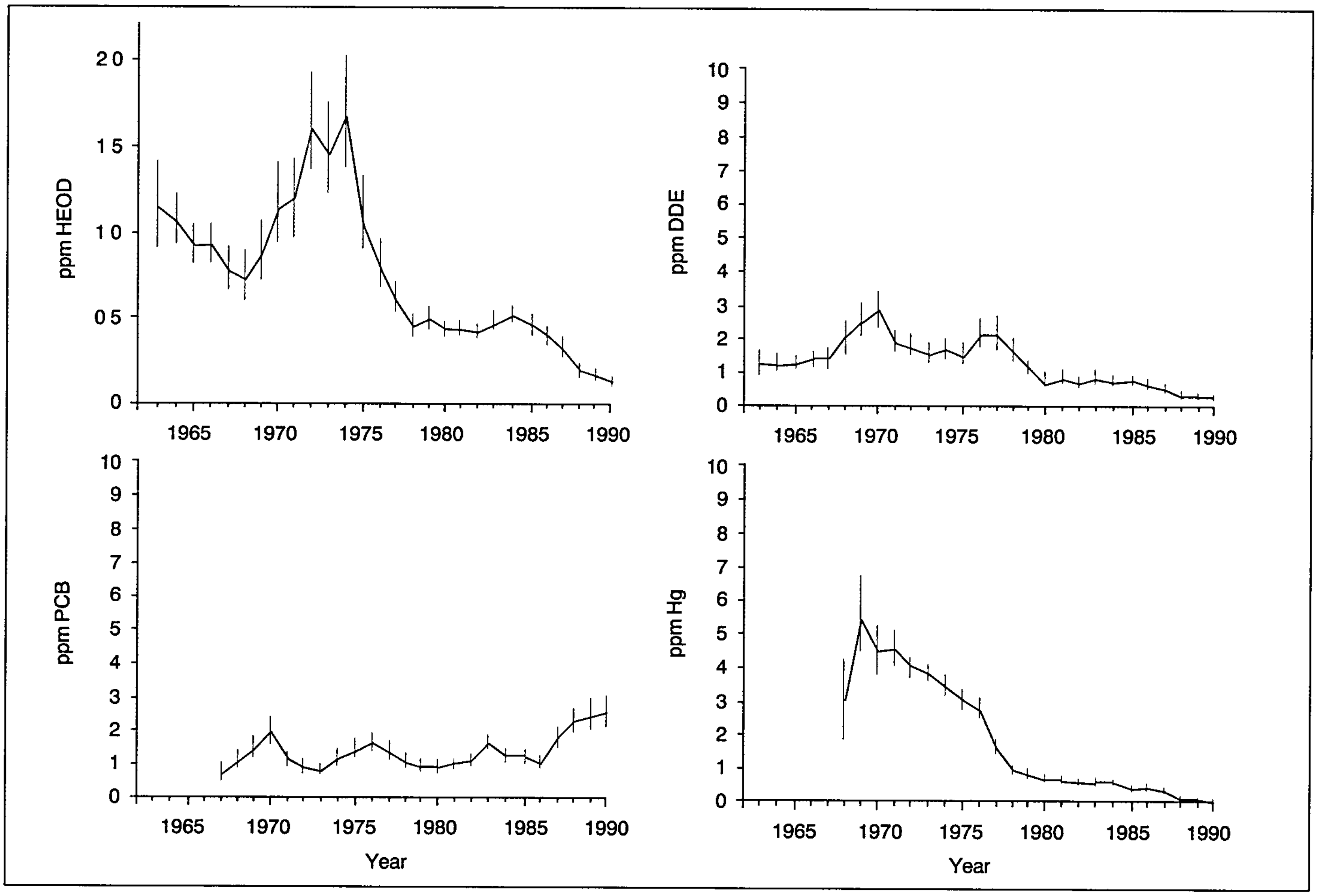

Figure 37 Levels of chemical contaminants in the livers of kestrels, 1963–90, based on analyses of 1075 livers Lines show 3-year moving geometric means of residue levels, and bars show geometric standard errors Figures show ppm in fresh weight

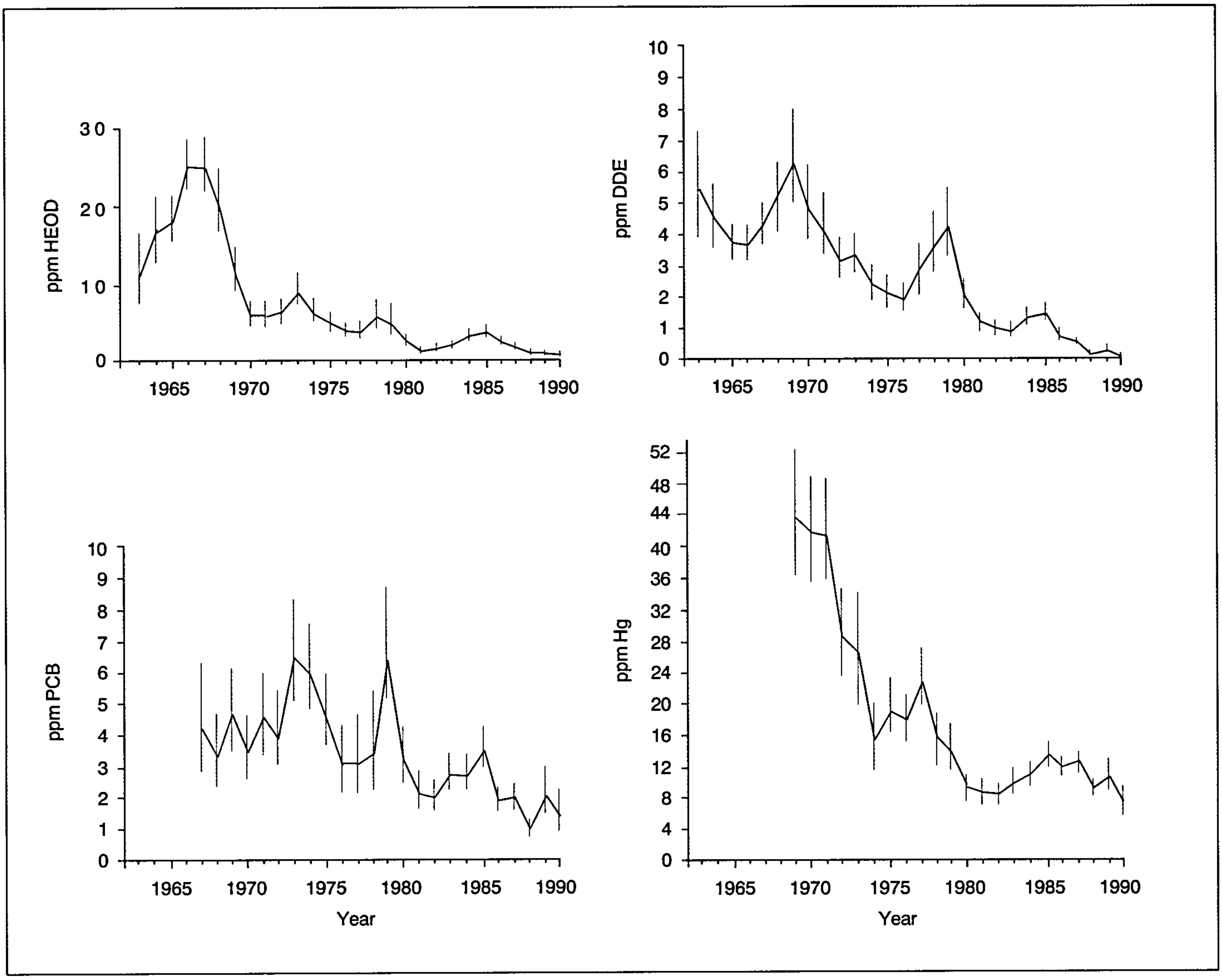

Figure 38 Levels of chemical contaminants in the livers of herons, 1963–90, based on analyses of 689 livers Lines show 3-year moving geometric means of residue levels, and bars show geometric standard errors Figures show ppm in fresh weight

In contrast to the other chemicals, the levels of PCBs declined only in the heron, and not in the kestrel and sparrowhawk, despite the withdrawal in 1970 by Monsanto (the sole manufacturer in Britain) of PCBs from all uses except in 'closed systems' However, no system is completely closed, and continual escape of PCBs to the environment would be expected from products made in earlier years Moreover, the great chemical stability of PCBs could ensure their persistence in the environment for long periods

Because much more mercury has been used in Britain in industrial processes than in agriculture, and major emissions are associated with industrial processes and fossil fuel combustion, such emissions are likely to have provided the main source of residues for at least the heron, which showed much the highest levels Contamination of herons may have been enhanced by the fact that, in aquatic systems, inorganic mercury can be converted by microbial action to methyl-mercury, the first crucial step in the bio-accumulation process However, the industrial uses and disposal of mercury have been more rigorously controlled in recent years, and agricultural uses of pesticides have also been reduced Thus, it was not unexpected that residues declined in all three species over the period concerned

In conclusion, successive restrictions in the use and emissions of these various chemicals over the past 28 years have resulted in reductions in the residues found in predatory birds, and in improvements in the population status of the most affected species The survey continues because high pesticide residues still appear in birds from certain regions, and because PCB levels in some species show no sign of falling

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Buffer zones from insecticide spray drift, and the effect of hedges

(This work was funded by the Department of the Environment and the former Nature Conservancy Council)

Herbicides and insecticides are usually applied to crops as sprays to ensure thorough wetting of foliage. Their selective action ensures that weeds and pests are controlled with little or no damage to the crop itself. The coarser spray droplets sediment out quite quickly on vegetation or on to the ground, while the finer droplets, 0.1 mm in diameter or less, are more liable to be carried by wind away from the target, where they may cause undesirable effects.

Many factors can affect the extent of spray drift, including windspeed, height of spray boom, type of spray nozzle, and the cumulative increments from several swaths of sprayed crop. Spray deposition depends on the ability of structures to intercept spray droplets. As air currents are deflected by an obstruction, the heavier droplets may impact on it, while lighter ones are carried around it. Narrow structures such as stems, hairs and insect legs trap very small droplets more 'efficiently' than smooth broad ones. The use of plate-like artificial targets, therefore, generally underestimates drift deposition, though they may be suitable for very coarse sprays, eg from raindrop nozzles used for the aerial spraying of asulam on bracken (*Pteridium aquilinum*).

Many studies have been made of spray drift, mainly in the development of more efficient sprayers and to avoid economic damage to neighbouring crops from herbicides. The effects on plants and invertebrates in field margins and adjacent non-crop habitats are less readily noticed, but should also be avoided as far as possible. In the case of particularly sensitive areas, such as Sites of Special Scientific Interest, it is important to determine suitable buffer zones where spraying should not take place, at least of the more toxic compounds. This restriction would apply, for example, to broad-spectrum and widely used herbicides and insecticides, such as glyphosate (eg Roundup) and cypermethrin (eg Ambush).

Measurements of drift have often been made with marker dyes or by direct analysis of residues collected on a variety of receptors. These measurements, however, do not directly indicate potential hazards to wildlife. Such effects are best measured by using sensitive target plants or insects as bioassays. Previous work has described the development of a suitable bioassay technique for insecticides using young larvae of cabbage white butterfly (*Pieris brassicae*) (Davis, Lakhani & Yates 1991). The larvae were exposed on horse-radish (*Armoracia rusticana*) leaves to drift at various distances downwind of a sprayed area. The results were used to estimate the distances at which 50%, 20% or 10% mortality would occur under standardised conditions, and the estimates were then used to compare variables such as different windspeeds and a range of different compounds used at commercial rates of application (Davis *et al* 1991).

This technique was used in 1989–90 to measure the effects of drift from agricultural crops during spraying by farmers. The crops were peas and brussels sprouts which were sprayed with cypermethrin or triazophos against caterpillar pests. Preliminary topical dosing tests showed that cypermethrin was about 6.6 times as toxic as triazophos, but it is used at a much lower application rate on crops so that the contact 'field hazard' should actually be lower. The aphicides demeton-S-methyl and dimethoate which were included at two sites had very low toxicity to cabbage white larvae.

Six field bioassays were done at four farms in Cambridgeshire and Bedfordshire. The targets were set out downwind of the sprayed field in two to four replicate lines about 10 m apart. The pots were usually placed on the ground but at one site, where there was a tall crop of field beans downwind, they were suspended from collapsible tripods just above crop height. Table 11 summarises the salient features for four sites, and Figure 39 illustrates the bioassay results for one of these in diagrammatic form to show the mean mortality curves superimposed on the ground features. If buffer zones are set by distances at which larval mortality was <10%, then trials 2–4 gave similar

Table 11 Four field bioassays of insecticide spray drift: spraying details and estimated distance for 10% mortality of larvae

	Swavesey	Haverhill 2	Chatteris	Upper Caldecote 2
Crop	Peas	Peas	Peas	Brussels sprouts
Date	11 June 1990	10 July 1990	16 July 1990	27 July 1990
Insecticide	Triazophos	Cypermethrin	Cypermethrin	Cypermethrin
Windspeed (m s^{-1})	2.5	3.5	5.0	2.5
LD_{10} distance	12.0	24.0	21.6	18.6

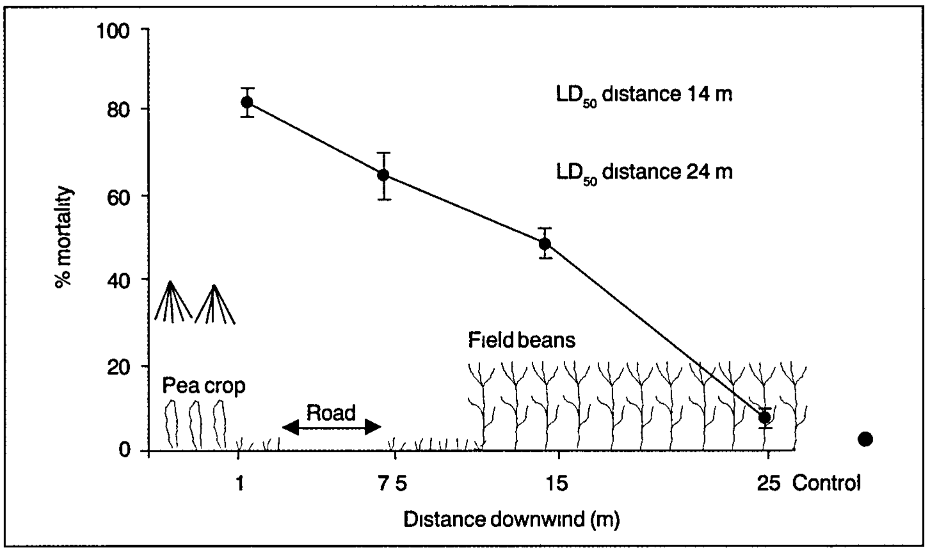

Figure 39 Mortality profile for cabbage white larvae exposed to cypermethrin spray drift from peas at Haverhill, Cambridgeshire, 10 June 1990

Plate 12. *Tractor spraying 6 m upwind of a hedge with an array of receptors to collect drift*

estimates of 16–24 m. These results are comparable with the higher estimates of LD_{10} distance obtained under controlled field conditions for diflubenzuron (Davis *et al.* 1991).

The mortality curve at Swavesey (site 1 in Table 11) was affected by the presence of a low hedge at 12 m downwind, so the LD_{10} value was probably less than it would have been in more open terrain. There was an even more marked shelter effect at another Upper Caldicote trial, where the mortality curve was abruptly truncated by a hedge at 16 m. Hedges are known to have an important influence on air flow (Rider 1951), and are therefore likely to have an effect on spray drift in many field situations. Experiments were, therefore, done in 1991 to examine the profile of drift deposition behind hedges under controlled conditions. For this purpose, sodium fluorescein was used as a tracer dye (Sharp 1974). Deposits were collected on 'efficient' receptors placed in front of and behind a hedge, washed off and measured by a spectro-fluorophotometer as parts per million in a standard solution, and the results were corrected for recovery and fade (Brown 1991).

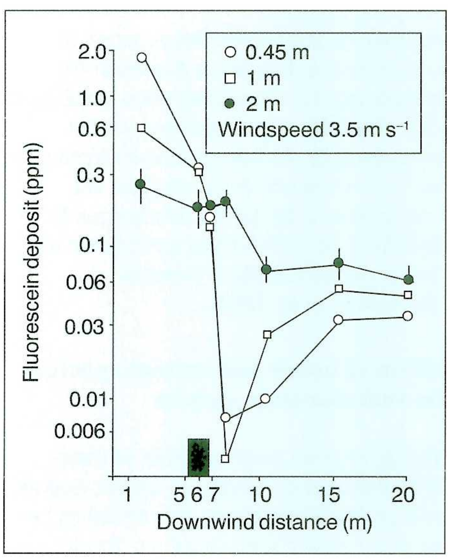

Figure 40. Spray drift deposition using sodium fluorescein, at 0.45 m, 1 m and 2 m height, showing the effect of a hedge 6 m downwind of a sprayed area

A first series of trials used a continuous length of laid hawthorn (*Crataegus monogyna*) hedge, 1.6 m high x 1.2 m wide, to examine both vertical and horizontal profiles of drift particles. A second series compared the difference between drift over a hedge and drift through a 16 m wide gap where the hedge had been cut down. Both series consisted of three trials done at different windspeeds, when the wind was roughly at right angles to the hedges. In each case, the sprayed swath was 24 m wide, starting 6 m from the hedge. Pairs of receptors were hung from support masts at 0.45 m, 1.0 m and 2.0 m height at various distances, from 5 m in front of the hedge to 14 m behind it (20 m downwind of the sprayer). Windspeeds were measured with anemometers placed in front of and behind the hedge (Plate 12).

A typical result from the first series is shown in Figure 40. At a moderate windspeed of 3.5 m s^{-1}, there was a clear difference between receptors 1 m from the sprayer, with most deposition on the lowest receptor and least at 2 m height. There was a sudden decrease in deposition at 0.45 m and 1.0 m heights immediately behind the hedge, and then a gradual increase again to 20 m downwind, where there was little difference from that received at 2 m height. For low receptors, the sudden decrease and subsequent increase in deposition behind the hedge were confirmed by the second series of trials, which contrasted the presence and absence of a hedge.

The shelter effect of hedges is well known in agronomy and is related to height and porosity (Pollard, Hooper & Moore 1974). However, the implications for pesticide drift have not previously been demonstrated. The biological significance was checked by several insecticide bioassays, but the generality is shown here by the result of a bioassay using the herbicide MCPA and young plants of ragged-robin (*Lychnis flos-cuculi*) (Figure 41).

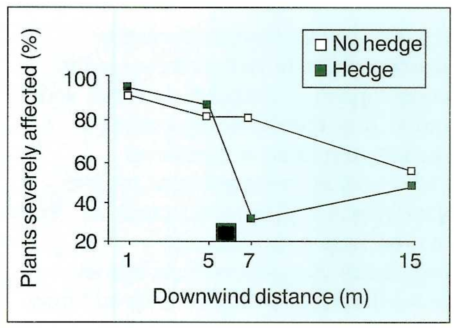

Figure 41. Bioassay results for ragged-robin receiving MCPA drift in the presence or absence of a hedge 6 m downwind from a sprayed area

With strong winds and sensitive target species, hedges may afford quite limited protection. In other cases, the sheltered zone may extend to the point where 'normal' drift deposition (in the absence of a hedge) is reduced to sublethal levels so that a hedge provides a high degree of protection.

B N K Davis, A J Frost and M J Brown

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Factors affecting radiocaesium transfer to ruminants

(This work was partly funded by the Commission of European Communities)

A major route of human radiation exposure due to radiocaesium is the consumption of contaminated milk and meat It is, therefore, important to quantify the rates of transfer of radiocaesium released from nuclear installations to these food products Such studies help to predict how radiocaesium, present from above-ground nuclear weapons tests and from nuclear accidents, will behave in agricultural, semi-natural and natural environments A multi-national two-year research programme, co-ordinated by ITE, has been identifying and quantifying some of the most important factors influencing the levels of radiocaesium in animal food products Participants in the programme are shown in Table 12

As a result of collaboration between participants, it has been possible to focus a wide variety of techniques on to different aspects of the behaviour of radiocaesium and its transfer to animal tissues These aspects have included (i) gut absorption, (ii) physiological factors affecting radiocaesium levels in meat and milk, (iii) assessment of the importance of soil as a source of radiocaesium to ruminants, and (iv) model development The main findings arising from those parts of the programme to which ITE contributed are summarised below

Table 12 Participants in the collaborative CEC research programme on factors affecting radiocaesium transfer to ruminants

Howard, B J, Beresford, N A & Barnett, C L	ITE, UK
Vandecasteele, C & Pollaris, K	CEN-SCK, Belgium
Mayes, R W, Lamb, C S & Eayres, H F	MLURI, Scotland
Belli, M & Sansone, U	ENEA, Italy
Stakelum, G & Dillon, P	TEAGASC, Ireland
Colgan, P A & Rafferty, B	RPII, Ireland
Assimakopoulos, P A, Pakou, A A & Ioannides, K G	Ioannina, Greece
Crout, N M J, Galer, A M & Buttery, P	University of Nottingham, UK
Jones, B-E V & Eriksson, O	SUAS, Sweden
Hove, K & Hansen, H S*	Agricultural University of Norway, Norway
Voigt, G*	GSF, Germany

*informal involvement

Gut absorption

The transfer of a radionuclide to animals has commonly been characterised using the transfer coefficient, defined as the ratio of the equilibrium tissue/milk activity concentration to the daily intake of the radionuclide However, the transfer coefficient has the disadvantage that it only applies under equilibrium conditions, which are rarely attained in practice Furthermore, it amalgamates a number of different processes, including absorption, translocation, deposition and mobilisation in tissues Therefore, it does not indicate, or quantify, the underlying mechanisms which determine the final observed radionuclide level in each tissue

In this programme, some of the participating laboratories have adopted a more mechanistic approach, by measuring the true absorption coefficient (A_t) of radiocaesium This is a measure of the proportion of a radionuclide which is transferred across the gut wall, taking account of endogeneous secretions from blood plasma into the gastro-intestinal tract (GIT) (Figure 42) Gut absorption can be estimated using this approach by measuring radiocaesium output in milk, urine and faeces

Measurement of A_t has the advantage that estimates can be made within a relatively short time period because equilibrium conditions between tissues and diet are not necessary The effects on A_t of a number of animal and dietary factors have been assessed, and are summarised below

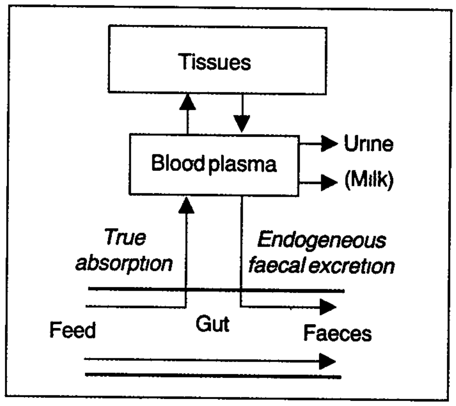

Figure 42 The main processes involved in measuring the true absorption of radiocaesium in the ruminant gut

Effect of age on radiocaesium uptake

ITE and the Macaulay Land Use Research Institute (MLURI) measured the absorption of radiocaesium in seven groups of lambs ranging from 11 to 59 weeks of age Radiocaesium absorption from milk was complete (ie A_t=1) True absorption of radiocaesium when administered within gelatin capsules (representing solid food) was between 0 80 and 0 85 for all age groups and did not change with age (Mayes *et al* 1992)

Effect of radiocaesium source

The bioavailability of an ionic and a number of environmental sources of radiocaesium has been assessed by measuring the true absorption coefficient (A_t) Transfer across the gut varied considerably, A_t values ranged from 0 12 for radiocaesium in Ravenglass silt, contaminated by liquid discharges from Sellafield, to 0 88 for the ionic form and that contained in plant material (Beresford *et al* 1992)

Effect of breed and animal species on radiocaesium uptake

The A_t of ionic radiocaesium in three different breeds of sheep, Texel, Suffolk and Scottish blackface, was found to be similar Sheep were used as 'model' ruminants within the programme To test the validity of extrapolating results from sheep to other ruminants, the true absorption coefficients of ionic radiocaesium were measured in Friesian dairy cows and Scottish blackface ewes Values of A_t measured in lactating cows (Irish collaborators) and sheep were 0 71±0 099 and 0 85±0 033 (mean±SD) respectively

Modelling studies

ITE and MLURI conducted an experiment to measure the behaviour of radiocaesium in lambs given a single oral radiocaesium dose The data were used by Crout and Galer to develop a mechanistic model of radiocaesium behaviour in ruminants The transfer coefficient for radiocaesium to cattle milk (f_m) and meat (f_f) is an order of magnitude higher than that to sheep It seems from these studies that absorption across the gut wall is not responsible for the observed variations in the radiocaesium f_m and f_f in ruminants of different species or ages Therefore, other processes must be responsible for these differences Models developed during the course of this work suggest that increases in tissue size with increasing age could be the principal cause (Figure 43) This will be one of the parameters studied in future work

Soil as a dietary source of radiocaesium

Soil adhesion on to vegetation surfaces is acknowledged as a potential source of radiocaesium intake by grazing animals (Beresford & Howard 1991) The importance of soil as a source of radiocaesium will depend upon (i) the amount of soil-associated radiocaesium ingested, and (ii) its availability for absorption in the gut ITE contributed to the studies outlined below

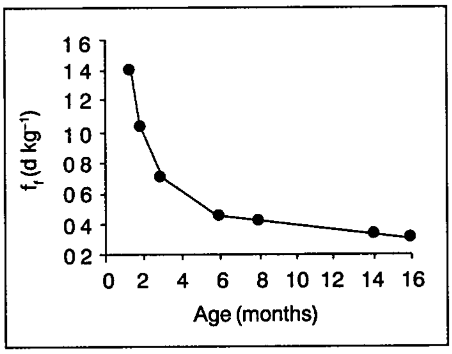

Figure 43 Changes in model-predicted transfer coefficients (f_f) with increasing age, estimated by allowing for increases in muscle mass

Soil adhesion

The extent of soil adhesion on to vegetation was measured throughout one year at 17 sites in five countries covering a range of different soil types At sites within the UK, Ireland and Belgium, soil adhesion on to vegetation was highest in the autumn/winter when it accounted for most of the radiocaesium activity in vegetation samples In both the UK and Ireland, there was a significant correlation between the ^{137}Cs activity and Ti (a commonly used soil marker) concentrations of vegetation from sites with mineral soils, and adhered soil was the most important factor in determining the ^{137}Cs activity concentration in vegetation samples However, in both countries, on pastures with organic soils where root uptake of radiocaesium was comparatively high, there were no relationships between ^{137}Cs activity and Ti concentrations in vegetation Correlations were found between the Ti concentrations in vegetation and those in faeces, showing that animals were ingesting more soil at the times of year when vegetation samples contained more adhered soil

The importance of adhered soil

Radiocaesium associated with soil adhered to vegetation surfaces can constitute a considerable proportion of the total radiocaesium activity of sampled vegetation Therefore, soil adhesion should not be ignored when attempting to estimate radiocaesium levels in the tissue or milk of grazing animals from levels in sampled vegetation, because the available radiocaesium intake is likely to be overestimated, particularly in autumn/winter However, in most circumstances, where the gut absorption of radiocaesium from soil is low, ingested soil is unlikely to be an important source of radiocaesium to the grazing ruminant

In many circumstances, it is difficult to obtain reliable site-specific estimates of the comparative importance of radiocaesium associated with adhered soil Therefore, because the ultimate aim is usually to estimate the overall available radiocaesium intake, it may be preferable to subject vegetation samples to *in vitro* availability tests, which could provide an availability value for use in models

Summary

The results from the whole research programme have been incorporated into research models, which can now be used to identify the most important processes determining the extent to which radiocaesium is transferred into ruminant tissues and milk Such studies will help us to develop new countermeasures to reduce the radioactive contamination of food products from animals

B J Howard

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