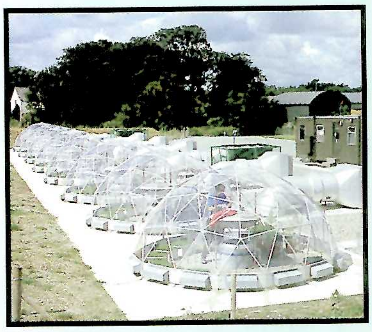
Contents

This has been a year of significant developments in international activities, in understanding global change processes and in global change itself.

Global change



We now know that, globally, 1995 was the warmest year on record, about 0.4°C warmer than the 1961–90 reference period. We also know that increases in atmospheric CO_2 and CH_4 concentrations have once again accelerated, with mean CO_2 levels now exceeding 360 ppm.

During the year, ITE staff contributed to the Second Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) and to the UK Climate Change Impacts Review Group. There is growing confidence that anthropogenic emissions of 'greenhouse gases' are causing global warming. Confidence in the integrity of general circulation models has been obtained by their ability to simulate large-scale spatial features of the current climate, seasonal changes, and the cooling caused by the eruption of Mount Pinatubo.

The IPCC concluded 'that global mean temperature changes over the last century are unlikely to be entirely due to natural causes, and that a pattern of climate response to human activities is identifiable in the observed climate record'. More succinctly, the IPCC statement for policy-makers was that 'the balance of evidence suggests that there is a discernible human influence on global climate'.

Against this background, there have been some significant scientific achievements in which ITE has played a part, within the NERC Terrestrial Initiative in Global Environmental Research (TIGER), the European Union, and UK Government department programmes. Three are covered in the reports that follow.

First, we know much more about the emission of methane from wetlands, owing to the development and deployment of micrometeorological and boundary layer techniques of measurement and the development of models. The amount of methane emitted over large areas can now be measured and estimated with reasonable precision. As reported by Arah, Ineson and Fowler, we have sufficient understanding to estimate the effects of increasing temperature, changes in water table, and pollutant deposition on methane production by wetlands. The challenge now is to apply this capability to the entire northern wetlands region of the world.

Second, we have established the magnitude and spatial distribution of the reservoirs of carbon in vegetation and soils in the UK, and have developed a national carbon flux budget for the land surface (see

Milne, Cannell and Harrison) The challenge now is to lessen uncertainties in this budget, particularly in the loss of carbon from drained peatlands and in the flux of carbon from agricultural soils It will be important for the UK to monitor changes in the national greenhouse gas budget and to take measures to preserve or enhance the sinks

Third, there is a growing consensus that the 'missing' carbon sink in the global budget is largely due to CO_2 and nitrogen fertilization of photosynthesis and vegetation productivity The essential assumption is that rising CO_2 levels are accelerating rates of photosynthesis As long as this occurs, the timelag between the increase in photosynthesis, litter input to the soil, the build-up in size of the soil carbon pool and total soil respiration ensures that ecosystems will sequester carbon The question, then, is how rapidly are rates of photosynthesis and plant growth being accelerated in response to rising CO_2 levels? The two large uncertainties are the degree of 'acclimation' of the photosynthetic mechanism and the way in which plants utilise or acquire nutrients – because no carbon can be stored in organic matter without nutrients Stirling, Harmens and Ashenden have shown that the degree of 'acclimation' and responses to elevated CO_2 vary among species and depend on levels of nutrition

There have been some significant scientific achievements in which ITE has played a part.

The essential assumption is that rising CO_2 levels are accelerating rates of photosynthesis.

M G R Cannell

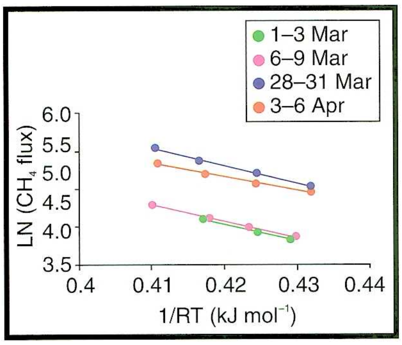


Figure 44. Arrhenius plots of methane emission from peat monoliths. Activation energies were similar before (Plots 1 and 2) and after (Plots 3 and 4) a period of 11 days with the monoliths maintained at 20°C

Factors controlling soil/ atmosphere methane exchange in peat and grassland

(This work was funded by the TIGER Programme and the European Union)

Methane (CH_4) is a 'greenhouse gas' produced in natural and artificial wetlands and consumed in most drained soils. It is essential to quantify the natural fluxes of CH_4 in order to assess the significance of anthropogenic emissions. Here, we report work which seeks to identify the major factors controlling large-scale fluxes from peat bogs and an investigation into the effects of enhanced carbon dioxide (CO_2) on CH_4 oxidation in grassland.

Effects of temperature on CH_4 emission

In spring 1995, a set of 25 peat monoliths were collected from Loch More, the site of micro-meteorological CH_4 flux measurements during 1993 and 1994 (Plate 16). Seventeen were placed in a controlled environment chamber and subjected to temperatures in the range 5–20°C. The thermal equilibration time was approximately 18 h. Measurements were made during the hours of darkness to avoid changes to the surface temperature of the peat during measurement; the monoliths were subjected to 12 h dark and 12 h light each day.

Results (Figure 44) showed, as expected, a precisely log-linear emission/temperature relationship, with Q_{10} for the 17 monoliths averaging 1.97 and activation energy averaging 44.3 kJ mole^{-1} (Plots 1 and 2, Figure 44).

Responses to longer timescale temperature variation, such as occurs in the field due to seasonal changes in the radiation budget, were investigated by maintaining the temperature of the monoliths at 20°C for 11 days. The mean CH_4 emission from the 17 monoliths increased roughly linearly during the period at 20°C from 85.5 µmol m^{-2} h^{-1} to 157 µmol m^{-2} h^{-1} after eight days. Following the 11-day period at 20°C, the temperature responses of the monoliths were examined again (Plots 3 and 4, Figure 44) and showed Q_{10} values and activation energies almost identical to those obtained from the initial measurements. The mean CH_4 emission at 10°C of 46 µmol m^{-2} h^{-1} is close to the mean CH_4 flux measured at Loch More by micrometeorological methods during the 1994 campaign.

These results suggest that the widely observed temperature responses of about 40 kJ mole^{-1} are appropriate for application over seasonal timescales, and it is then only the mean seasonal fluxes which need to be known to simulate the short timescale structure in the CH_4 fluxes due to temperature. The effects of water table are also, of course, important (Fowler *et al.* 1995).

Plate 16. The flow country at Loch More, Caithness: 25 peat monoliths were extracted from this site in spring 1995 and used to examine the effect of temperature, sulphate and nitrate on CH_4 emission

Effects of sulphate and nitrogen on CH_4 emission

The same, well-characterised, monoliths were used to examine the effects of chemical treatment on methane emission. Treatments to four replicate monoliths provided the equivalent of 40 kg S or N ha^{-1} as Na_2SO_4, $NaNO_3$, NH_4Cl, and a NaCl treatment was included to examine the 'salt' effect of the treatment. The control was deionised water. All treatments were maintained at 10°C throughout the experiment.

The results of the SO_4^{2-} and NO_3^- treatments (Figure 45) show a 15% and 20% reduction in CH_4 emission respectively over the 50–70 days following application. The reduction in CH_4 emission was approximately 0.1 mole mole^{-1} S or N. The results for the SO_4^{2-} treatment are consistent with the earlier field studies (Fowler *et al.* 1995). In both SO_4^{2-} and NO_3^- treatments, the CH_4 response returned to the pre-treatment conditions after approximately two months. In the case of SO_4^{2-}, there was evidence that the SO_4^{2-} was reduced to a gaseous reduced form and emitted from the monolith, while in the cases of NO_3^- a significant emission of N_2O was stimulated by the treatment.

Modelling the processes leading to CH_4 emission from peatland

Methane is produced in peatlands under strictly anoxic conditions. It must pass through more oxic regions on its way to the atmosphere. This passage occurs by slow diffusion through the water-saturated peat matrix (permitting oxidation by microbial methanotrophs), through air passages called aerenchyma in the roots of vascular plants (faster, permitting less oxidation *en route*), or by ebullition (bubbles, effectively instantaneous, permitting no oxidation in transit).

We set up a process-based model of such a system (Figure 46). Measured reaction potential profiles (eg Nedwell & Watson 1995) are simplified for inclusion in the model, as are bulk diffusion constant profiles and effective root-ending area densities (for transport *via* aerenchymous roots) deduced from measurements of the movement of argon into cores (*cf* Stephen *et al.* 1996). Ebullition is not yet included in the model because, where vascular plants are present, root transport generally seems to

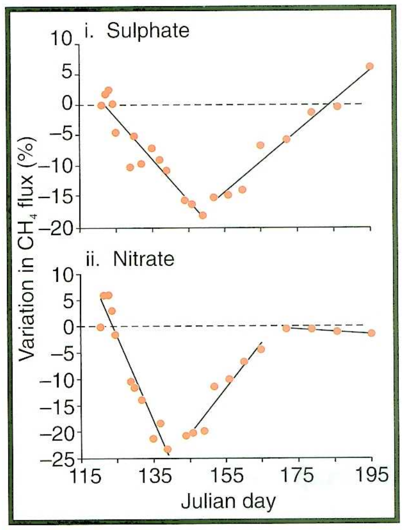


Figure 45. Effect of added oxidants on CH_4 flux: (i) 40 kg SO_4–S ha^{-1}; (ii) 40 kg NO_3–N ha^{-1}. Chemicals added on Julian day 121

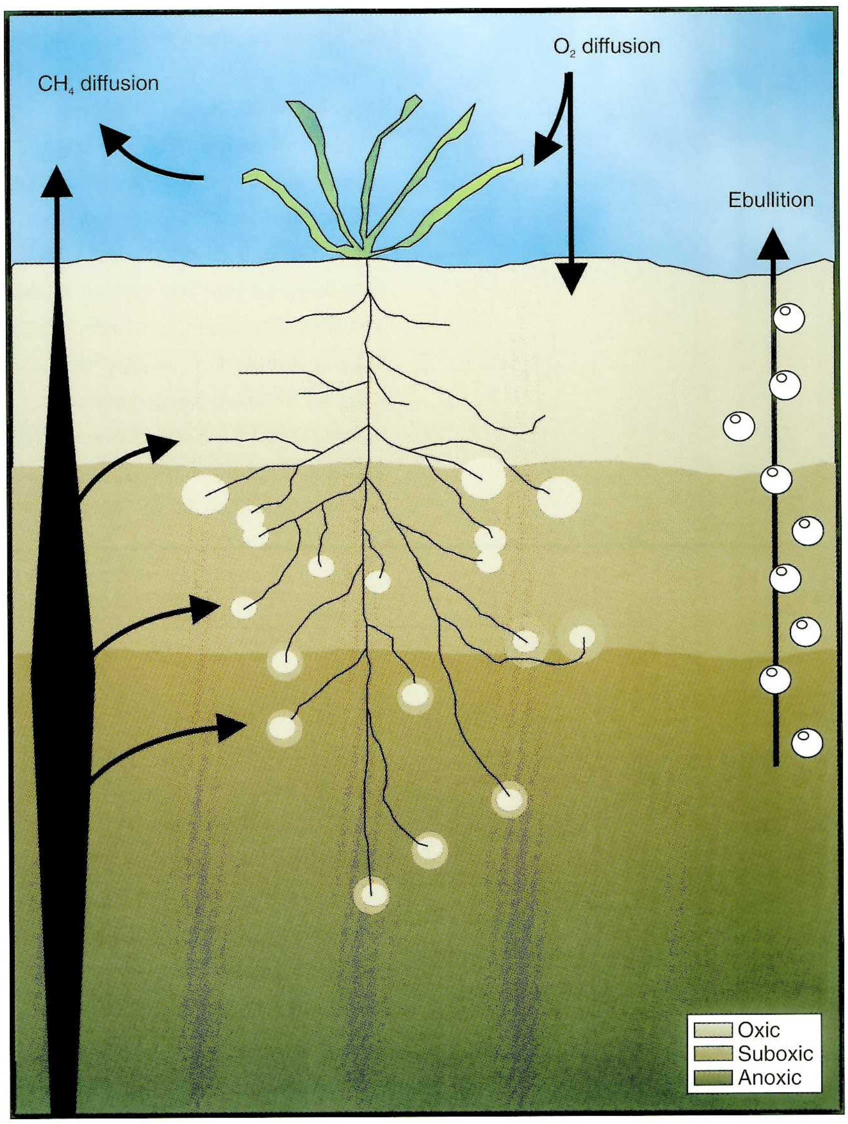


Figure 46. A schematic diagram of the model system

A major concern is that the production of other greenhouse gases is affected by rising CO_2 levels.

dominate. The model is used to simulate short-term responses to changes in temperature and water level, and the impacts of nitrate and sulphate deposition (acid rain). Simulations agree quite well with data measured in laboratory incubations, in mesocosms, and in the field.

Transient modelling of system response to short-term temperature variation shows a sensitivity similar to that observed experimentally; the system is heavily damped, however and longer-term simulations suggest much larger sensitivities. These are not in fact observed, pointing to the role of microbial population adjustment (not yet featured in the model) in buffering seasonal change.

Draining water from the system reduces predicted CH_4 emission rates, leading first to systems where CH_4 is simultaneously vented from depth through vascular plants and consumed in the oxic surface layers, and finally to those in which there is net consumption of atmospheric CH_4. All of these phenomena are observed in incubated cores and in the field. Reaction rate depth profiles predicted by the model parallel measured potentials, as would be expected if microbial populations thrive where the reactions on which they depend are favoured. A sensitivity analysis of the model is now underway.

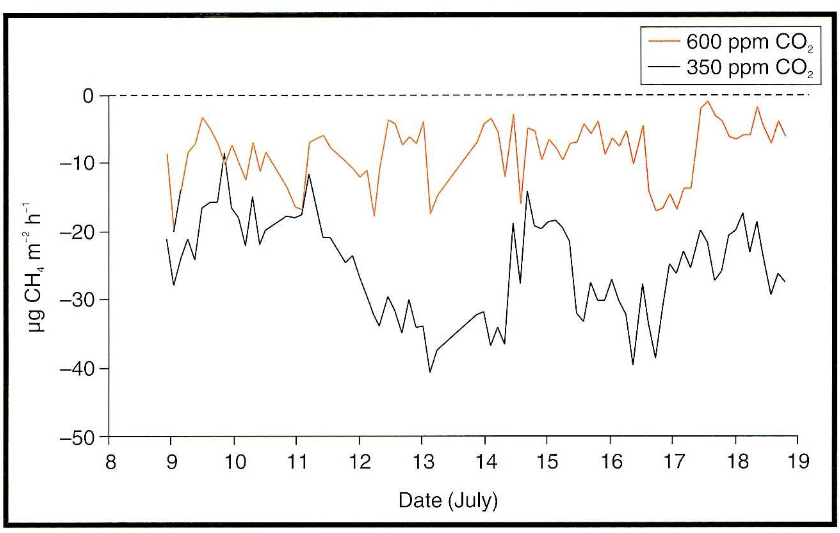


Figure 47. Methane oxidation rates in the control (350 ppm) and elevated CO_2 (600 ppm) plots at the ETH FACE experiment in Zurich. Negative CH_4 fluxes indicate oxidation by the soil

Methane oxidation under elevated CO_2: the Swiss FACE experiment

There is considerable debate about the effects of rising CO_2 levels on ecosystems and soil processes, one major concern being that the production of other greenhouse gases will be affected. If production is enhanced or consumption reduced, this would exacerbate the effects of CO_2 alone.

Elevated atmospheric CO_2 can have significant effects on soil processes, increasing plant productivity, enhancing allocation of C to below-ground components and leading to a general increase in C input to soils. Root exudation has been shown to increase under elevated CO_2, with the extra C entering the soil being generally energy-rich but nutrient-poor (Van de Geijn & van Veen 1993). This can have major effects on the consumption and production of trace gases within the soil. Current work is designed to assess these changes.

Fluxes of CH_4, nitrous oxide (N_2O) and CO_2 were measured from soils under ambient and enhanced CO_2 concentrations in the Free Air Carbon Dioxide Enrichment (FACE) experiment run by the Eidgenössische Technische Hochschule (ETH) in Switzerland (Plate 17). The ETH FACE consists of six experimental plots, each 18 m in diameter, with treatments randomly allocated to one of each of three pairs. Fumigated plots are enriched to 600 ppm CO_2 during the daytime, and allowed to revert to ambient CO_2 concentrations at night; control plots receive ambient air (*c* 350 ppm CO_2). This is currently the only large-scale free-air CO_2 enrichment facility in Europe.

Measurements were made on rye-grass (*Lolium perenne*) plots receiving high N inputs (560 kg N ha^{-1} yr^{-1}). We used a mobile laboratory containing a gas chromatograph to monitor trace gas fluxes in experimental plots at the site. Trace gas sampling was carried out immediately after a harvest in July 1995 and continued through one subsequent N fertilizer addition. The control plot consistently oxidised significantly more CH_4 than the enhanced plot. The amount of CH_4 oxidised was 25.5±0.8 mg CH_4 m^{-2} h^{-1} for the control, with an average of 8.5±0.4 mg CH_4 m^{-2} h^{-1} for the enhanced plot (Figure 47). This result suggests that elevated CO_2 may cause less CH_4 to be removed from the atmosphere.

Despite the limited nature of the current study, our data suggest that interactions between elevated CO_2 and soil trace gas release may be significant.

Conclusions

These measurements show the strong links between soil CH_4 emissions, climate, atmospheric CO_2 concentrations, and deposition of S and N from the atmosphere. Responses of CH_4 emissions to short-term temperature variations are characterised by Q_{10} values around 2, whatever the baseline emission rate. Additions of annual loads of NO_3 and SO_4 in single rainfall events led to reductions in CH_4 emission of 15–20%, these reductions lasting 50–70 days. Enhanced root exudation under elevated CO_2 apparently leads to reduced oxidation of CH_4 in grassland soil. It is clear that the interactions between global change and this important greenhouse gas are many and complex, and need to be quantified if management of these emissions is to be achieved.

Plate 17. FACE experimental plot at ETH, Zurich, showing the ring of CO_2 release pipes

J Arah, P Ineson and D Fowler

It is clear that the interactions between global change and CH_4 are many and complex, and need to be quantified if management of these emissions is to be achieved.

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UK forests are storing carbon at a net rate of 2.2 million tonnes each year.

Plate 18. Measuring carbon dioxide fluxes over undisturbed Scottish peatland

Carbon pools and net fluxes in UK vegetation and soils

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

In support of commitments under the European Framework Convention on Climate Change, an inventory of carbon pools and fluxes associated with the vegetation and soils of the UK has been developed under contract from the Department of the Environment. UK Government policy is to conserve the present size of the pools and fluxes and, if possible, secure an annual increase in the net amount of carbon stored.

Carbon pools

Vegetation

Cannell *et al.* (1994) produced a map of the amount of carbon in Great Britain (mass of carbon per unit area). This map was based on the ITE land classification and Countryside Survey, and provided a good estimate of the total pool size. Milne and Brown (1996) presented an improved map of the distribution of carbon in vegetation using the 25 cover classes of the remotely sensed ITE Land Cover Map. The total mass of carbon in the vegetation of Great Britain was estimated to be 114 million tonnes (Mt). Woodland holds 80% of this mass, although occupying only 11.1% of the rural land area: broadleaf woodland accounts for 47.3% and conifer woodlands 24.8% of the total amount of carbon in British vegetation. In Northern Ireland, calculations of the amount and distribution of vegetation carbon are based on the CORINE (Co-ordinated Environmental Information in the European Community) cover map. Carbon in the vegetation of Northern Ireland totals 4.4 Mt (55% in forests). The variation in vegetation carbon density in the UK is mapped in Figure 48.

Soil

Several estimates of the amount of carbon in the soils of Great Britain have been made (eg Department of the Environment 1994; Cannell *et al.* 1994). However, problems have been identified with those estimates:

- the mass of carbon stored in Scottish peat was poorly estimated because of inappropriate bulk density data, and
- it was assumed that the vegetation cover for a location (which affects soil carbon) was the dominant vegetation given by its ITE land class, which does not reflect very well the true geographical variation of vegetation at this scale.

Subsequently, bulk densities of peat (~0.1 g cm^{-3}) from a forest survey conducted by the Forestry Authority Research Division were used to calculate better estimates of carbon in Scottish peat soils (Milne & Brown 1996). Also, an improved description of vegetation cover was made using the ITE Land Cover Map (Milne & Brown 1996). The total size of the soil carbon pool was then estimated to be 6948 Mt for Scotland and 2890 Mt for England and Wales, giving a total for Great Britain of 9838 Mt. Peat soils hold 4997 Mt of this carbon (91% in Scotland). The distribution of soil carbon in Northern Ireland was prepared from surveys carried out by the NI Soil Survey, and the CORINE cover map was used for vegetation. Soil carbon was found to total 386 Mt, of which 164 Mt is in peat soils. The variation of soil carbon density in the United Kingdom is mapped in Figure 49.

Carbon fluxes

Carbon accumulated in growing forests

Cannell *et al.* (1994) estimated that in 1993 the net flux of carbon to forests planted in Great Britain since 1925 was about 2.25 Mt yr^{-1}, excluding wood products. They assumed that all planting was of Sitka spruce (*Picea sitchensis*) of yield class 14, and did not consider geographical variation in planting rates. Here, we present estimates of carbon uptake of conifer and broadleaf forests in Forestry Commission Conservancies and for Northern Ireland. The uptake of carbon was calculated using the same carbon accounting model as previously but with species, yield class and planting rates individual to each Conservancy. The contribution of private planting to each Conservancy was estimated by allocating the Scotland/England/Wales private totals to Conservancies in the same ratio as Forestry Commission planting. Using this approach, the total uptake of carbon by the conifer and broadleaf trees and broadleaf forest soils of Great Britain was calculated to be 2.04 Mt yr^{-1}. The flux to the forests of Northern Ireland was similarly calculated to be 0.2 Mt yr^{-1}. The uptake of carbon by the forests of each Conservancy is mapped as a flux density (ie uptake per unit area of Conservancy) in Figure 50.

Accretion in undisturbed peatlands

The annual magnitude of CO_2 exchange over a blanket bog has been measured at Auchencorth Moss in SE Scotland (Plate 18). Measurements of CO_2 exchange were made using the eddy covariance technique and showed strong diurnal and seasonal patterns, driven by solar radiation, air temperature and vegetation cover (leaf area index). Maximum rates of CO_2 uptake occurred in July, corresponding to the period of fastest vegetation growth, and maximum rates of CO_2 loss occurred in October, corresponding to the period when vegetation was senescing. The site fixed 248 kg C ha^{-1} during the 12 months studied. It was estimated that an increase in air temperature of 2°C would result in a net loss of carbon from this site.

Effects of afforestation on carbon balance in peatland

The next phase of eddy covariance measurements of CO_2 will be to compare undisturbed peatland with drained and/or recently afforested blanket bog. Carbon flux to the atmosphere is also being examined by comparing carbon store changes in open bog and in adjacent lodgepole pine (*Pinus contorta*) forest at Lochar Moss, SW Scotland. Afforestation causes peat drying, aeration and compaction. Possible losses of carbon from peat are being estimated by two approaches:

- based on the difference in C/Pb ratio in the bog peat and peat under the forest, the Pb having originated from 'local' past lead smelting activities, and
- calculating the difference in the mass of carbon stored above a common peat layer defined by its radiocarbon age.

Other fluxes

Carbon is exchanged between soils/vegetation and the atmosphere by several other routes. Work is presently being carried out to quantify the most important of these. In particular, loss of carbon from soils through land use change is being estimated using data from the 1984 and 1990 Countryside Surveys. The effect of CO_2 fertilization is being investigated in chamber experiments on birch (*Betula* spp.). Fluxes due to peat extraction for fuel and horticulture, decomposition in lowland fens, and natural accretion in coastal marshes will also be investigated. The sizes of the pools and fluxes associated with natural sources, as presently understood, are summarised in Figure 51.

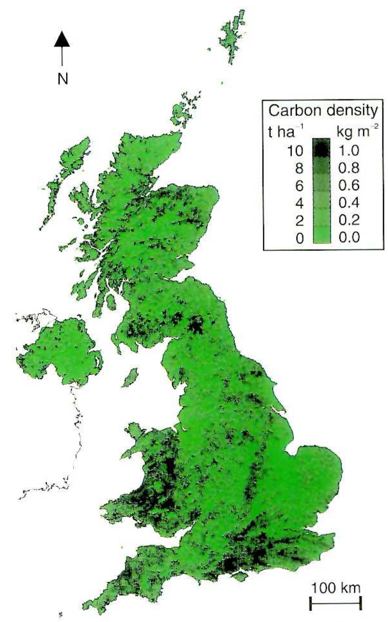

Figure 48. Distribution of carbon in UK vegetation

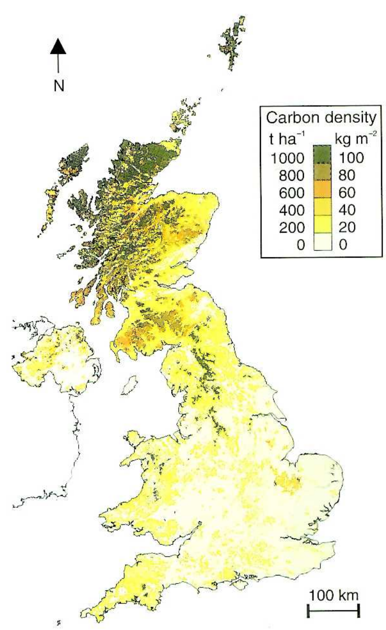

Figure 49. Distribution of carbon in UK soils

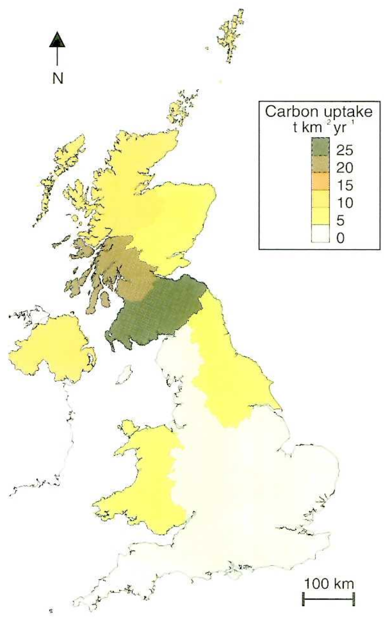

Figure 50. Rate at which carbon was removed in 1993–94 from the atmosphere and fixed in new forests in the UK

Anthropogenic sources in the United Kingdom emit about 150 Mt (ie 150 x 10^{12} g) of carbon, as carbon dioxide, into the atmosphere each year. About one third of the emission comes from power stations and the rest comes, about equally, from road transport, industry and commercial/domestic sources. The sizes of the natural pools and their uptake rates are small compared to the anthropogenic emissions, but they are an important component of the UK Government's policy for enhancing uptake and storage of carbon.

R Milne, M G R Cannell, A F Harrison and K J Hargreaves
(Northern Ireland data supplied by M Cruickshank, R Tomlinson & P Devine, Queen's University, Belfast)

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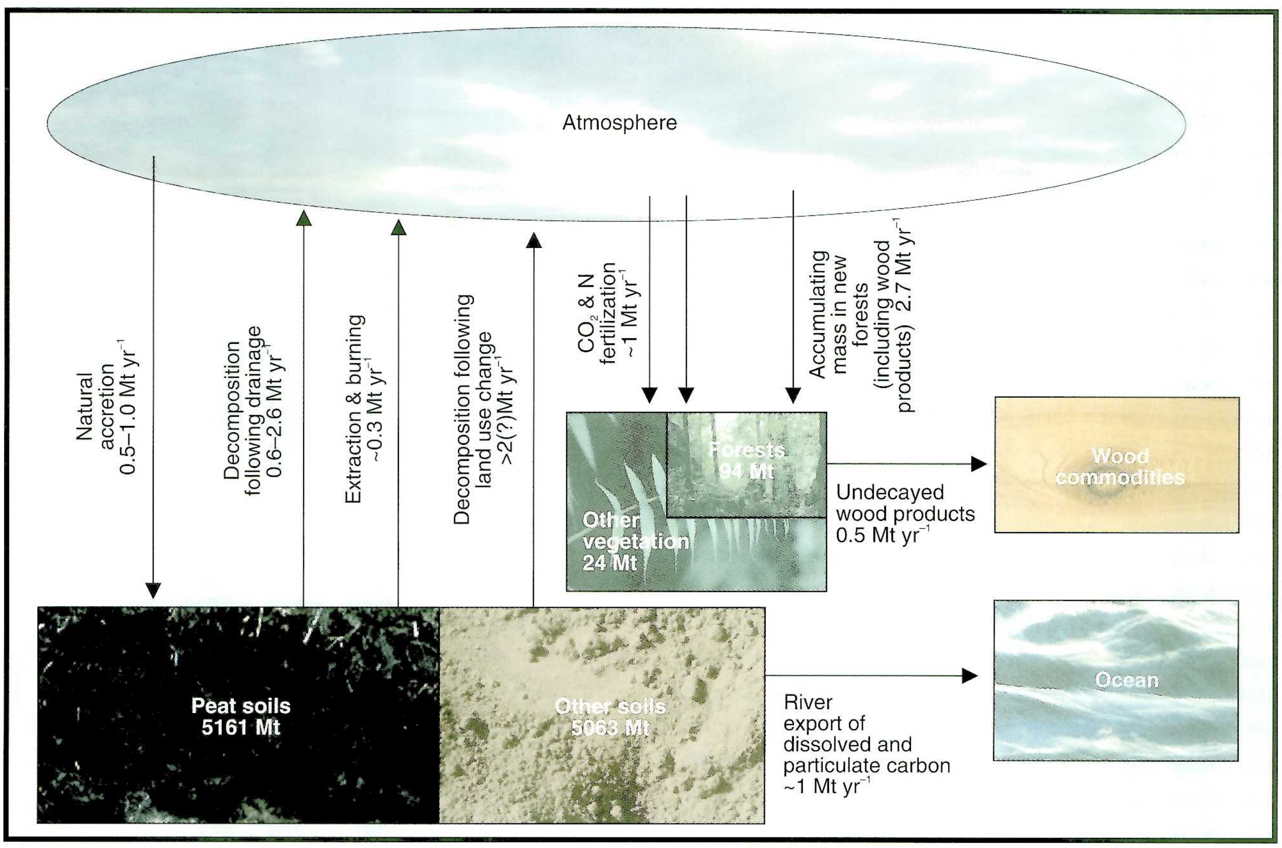

Figure 51. Pools and fluxes of carbon in UK vegetation and soils

Physiological response of plants to long-term CO_2 and temperature treatments

Most C3 species are capable of responding positively to elevated atmospheric CO_2 concentrations (↑[CO_2]), at least in the short term. The response is due to competitive inhibition of the oxygenase activity of the photosynthetic enzyme 'Rubisco' by CO_2, resulting in increased photosynthesis relative to photorespiration. However, in many species, the initial stimulation of photosynthesis at ↑[CO_2] is attenuated with time, resulting in what is often termed 'acclimation' of photosynthesis. Accumulation of non-structural carbohydrates and end-product inhibition of photosynthesis have been implicated in the loss of photosynthetic capacity at high CO_2, and, whilst the exact molecular signals are unclear, regulation of photosynthetic gene expression by increased soluble carbohydrates in leaves at ↑[CO_2] appears to be involved (Sheen 1994).

The extent of loss of photosynthetic capacity at ↑[CO_2] is dependent on the ability of plants to utilise assimilates in metabolism, storage and growth, ie on their sink capacity. Any factor, either genetic or environmental, which restricts sink capacity may accentuate the extent of acclimation of photosynthesis to high CO_2. Given the importance of sink capacity in determining the size and direction of the photosynthetic response to ↑[CO_2], we might expect that much of the variability between species in response to ↑[CO_2] could be accounted for by interspecific differences in sink capacity. The C-S-R model of plant growth strategies (Grime 1974) offers a potentially useful approach to categorising species according to sink capacity.

Plate 19. Long-term studies on the effects of climate change on a rye-grass sward

Vegetation is divided into three main functional types:

- competitors,
- stress-tolerators
- ruderals

according to the intensity of competition, stress and disturbance in the environment.

The solardomes at ITE Bangor provide a large-scale exposure facility for studying climate change impacts on native vegetation. The facility comprises eight hemispherical glasshouses, programmed to provide a factorial combination of two levels of CO_2 (ambient/ambient +340 ppm), two levels of temperature (ambient/ambient +3°C) with two replicates for each [CO_2] x temperature combination (Rafarel, Ashenden & Roberts 1995). Analysis of the response of a range of functional types to growth at ↑[CO_2] showed that, as might be expected from their ability to form sinks, only fast-growing competitive species responded positively to short-term exposure to ↑[CO_2] (Figure 52i). These results agree closely with earlier screening studies of a much wider range of species (Hunt *et al.*

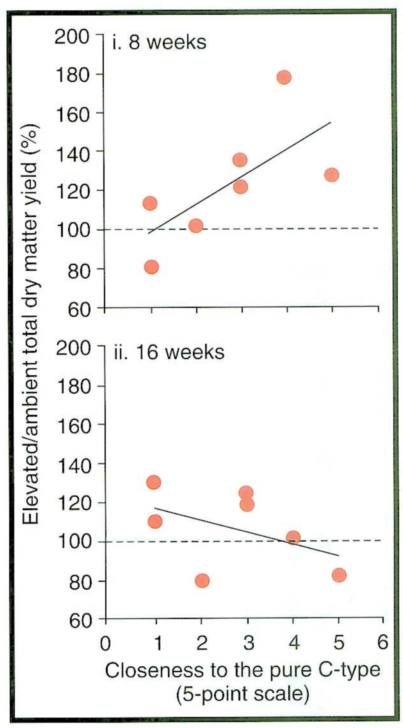

Figure 52. Percentage change in total dry matter of plants grown at elevated relative to ambient CO_2 concentrations after (i) eight and (ii) 16 weeks' growth. Data are plotted against a 'competitive' index on a five-point scale from 1 (pure S-strategist) to 5 (pure C-strategist). The data show a reversal of the initial increase in CO_2 response with competitive ability after 16 weeks

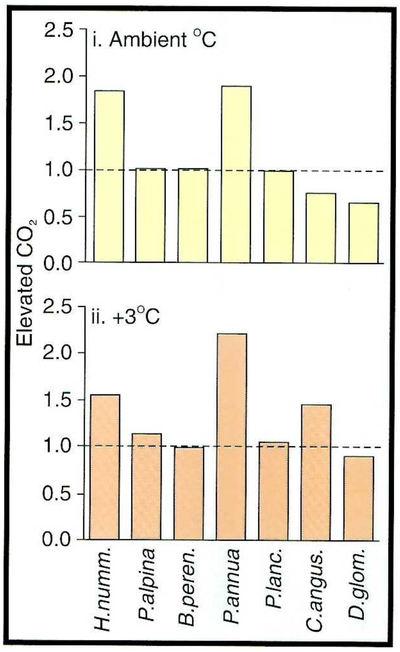

Figure 53. Acclimation index for photosynthesis of plants grown at elevated CO_2 concentrations and (i) ambient and (ii) elevated temperatures. Species are: *H.numm* = *Helianthemum nummularium*, *P.alpina* = *Poa alpina*, *B.peren* = *Bellis perennis*, *P.annua* = *Poa annua*, *P.lanc* = *Plantago lanceolata*, *C.angus* = *Chamerion angustifolium* and *D.glom* = *Dactylis glomerata*. The results show that after 80–100 days only the fast-growing competitive species (cock's-foot and rosebay willowherb) show a loss of photosynthetic capacity at elevated CO_2 and high nutrient inputs

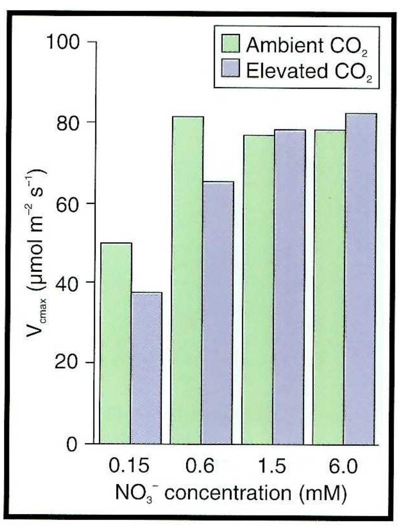

Figure 54. Effects of nitrogen concentration (NO_3^-) of the root medium on Rubisco activity (V_{cmax}) of cock's-foot grown at ambient and elevated CO_2 concentrations. The results indicate that the loss of photosynthetic capacity with decreasing $[NO_3^-]$ is more rapid at elevated $[CO_2]$

1991) and show that, in contrast to the fast-growing competitors, species with predominantly stress-tolerant (S) or ruderal (R) primary strategies show little or no response. However, this relationship was reversed when the duration of exposure was increased from eight to 16 weeks (Figure 52ii). Two important points emerge from these data. First, it appears that most species, irrespective of functional type, are capable of responding positively to $\uparrow[CO_2]$. Second, knowledge of the key processes underpinning relationships between species response and elevated $[CO_2]$ is essential for accurate extrapolation of results beyond the bounds of the experiment.

Light-saturated rates of photosynthesis were analysed in terms of an acclimation index ($A_{cc}I$). Values of unity indicate that no change in photosynthetic capacity has occurred and, consequently, an increase in CO_2 concentration would result in a more or less proportional increase in photosynthesis. If $A_{cc}I<1$ then photosynthetic capacity has been lost, and if $A_{cc}I>1$ growth at $\uparrow[CO_2]$ has actually increased photosynthetic capacity. The time-dependent decline in growth response of fast-growing competitive species to $\uparrow[CO_2]$ was associated with a loss in photosynthetic capacity, whereas there was no evidence of any loss in photosynthetic capacity amongst the S and R strategists after 80–100 days (Figure 53). There was no significant interaction between elevated $[CO_2]$ and elevated temperature ($\uparrow T°C$), with a 3°C increase in growth temperature generally having a less than additive effect on photosynthetic capacity at $\uparrow[CO_2]$. The sole exception was rosebay willowherb (*Chamerion angustifolium*), where the loss of photosynthetic capacity at $\uparrow[CO_2]$ was significantly reversed at elevated T°C (Figure 53ii). This response may be explained by the effects of $\uparrow T°C$ on sink capacity; the developmentally more advanced plants at the higher growth temperature had a greater number of reproductive sinks, resulting in relaxation of any sink limitations to photosynthesis at $\uparrow[CO_2]$.

We have found little evidence of any genetic constraint on the capacity of plants to respond to $\uparrow[CO_2]$, at least in the short term, and the loss of photosynthetic capacity in the fast-growing species, cock's-foot (*Dactylis glomerata*) and rosebay willowherb (Figure 53), is more likely to be explained by the more rapid depletion of nutrients at high $[CO_2]$. In support of this hypothesis, studies of the relationship between nitrogen (N) concentration and photosynthesis indicate that Rubisco activity declines more rapidly at elevated $[CO_2]$ (Figure 54). It may be that the initial stimulation of growth at elevated $[CO_2]$ results in N depletion within the plant and consequent allocation of N away from the primary carboxylase, Rubisco, thus resulting in a downward adjustment of photosynthesis. If N depletion is sufficiently severe, acclimation of photosynthesis is followed by a decline in growth.

A diminished or negative growth response to $\uparrow[CO_2]$ has occurred under high N inputs in longer-term experiments (Figure 55). Swards of rye-grass (*Lolium perenne*) (Plate 19) supplied with a balanced nutrient solution at a rate of 600 kg N ha^{-1} yr^{-1} showed the classic 10–15% increase in shoot yield during the first year of exposure. However, continued exposure not only diminished, but in some instance reversed, the response during the third and fourth year of growth (Figure 55). This effect was largely CO_2-driven as it was also observed in the elevated CO_2/T°C treatment. Elevated T°C continued to exert a positive effect on growth during the third and fourth year, except during the height of summer when higher growth temperatures may have promoted water/high temperature stress and so reduced growth (Figure 55). The decline in growth response to elevated [CO_2] was accompanied by a significant loss of photosynthetic capacity at the individual leaf level. Furthermore, there was no evidence of any change in below-ground biomass (live+dead root material) which, coupled with the decrease in canopy leaf area, suggests that less carbon was sequestered by the rye-grass swards at ↑[CO_2] after the second year of growth. This response was unexpected given the 'luxury' levels of N supplied, and it may be that other nutrients have become limiting with time. Further studies will be undertaken to elucidate the physiological processes responsible for the loss of productivity at elevated [CO_2].

These results emphasise the importance of long-term studies in determining the sensitivity of native plant communities to ↑[CO_2] and the extent to which vegetation will act as a future sink for carbon.

C M Stirling, H Harmens and T W Ashenden

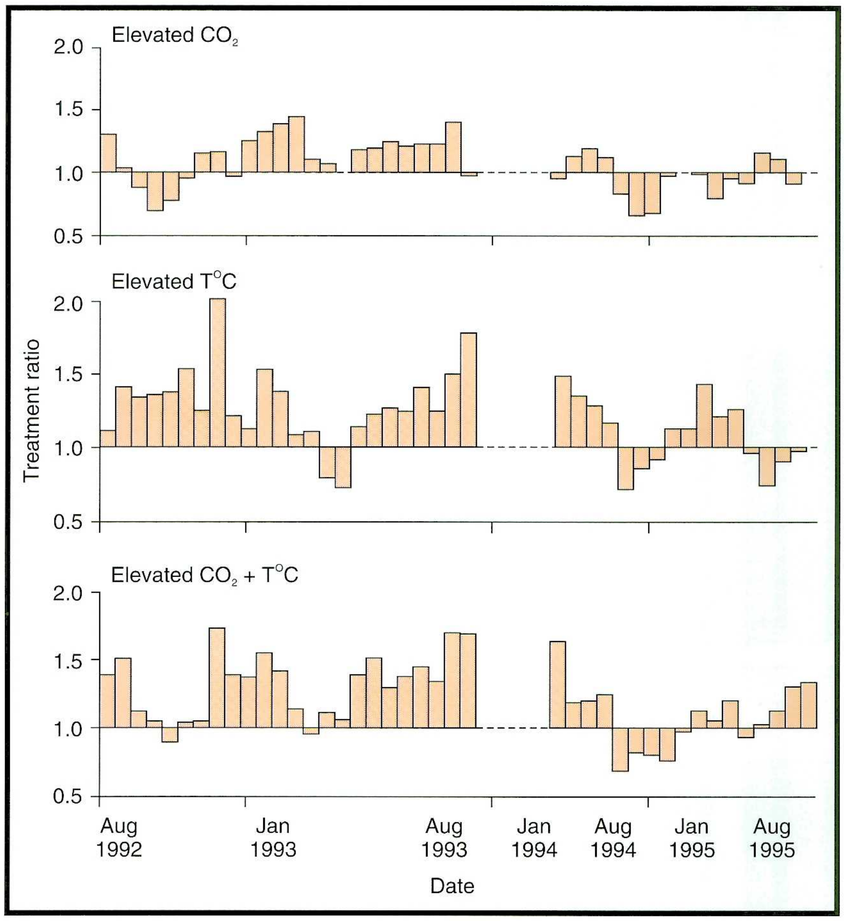

Figure 55. Treatment effects on shoot dry matter yield of rye-grass where the treatment ratio refers to shoot dry matter yields of treatments expressed relative to the control ambient CO_2/ambient temperature swards. The results show that stimulation of growth at elevated [CO_2] not only declines with time but may also be reversed during the third and fourth year

Long-term studies indicate that a diminished or negative growth response to elevated CO_2 may occur even under high nutrient inputs.

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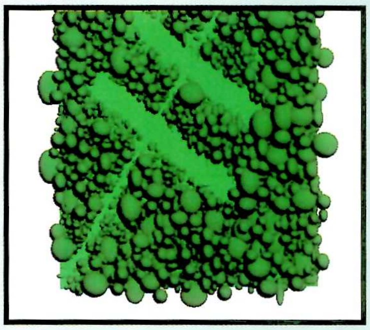
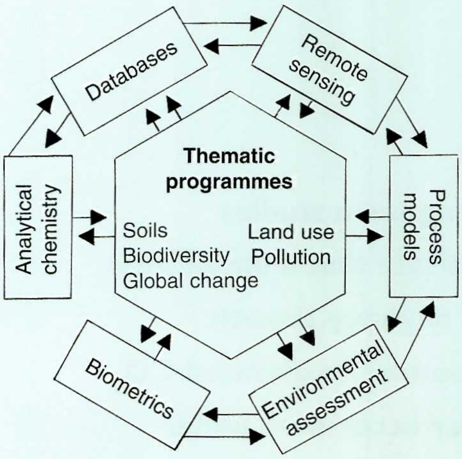
A number of specialist disciplines underpin the Institute's thematic programmes. The most important are:

- ***management of databases***
- ***remote sensing***
- ***analytical chemistry***
- ***biometrics***
- ***process modelling, including use of GIS***
- ***generic approaches to environmental assessment.***

Generic enabling science





Examples of the application of many of these techniques to specific scientific questions appear elsewhere in this Report. In this section, the focus is less on the applications and more on the enabling research needed to ensure that these disciplines deliver fully the needs of the Institute's science programme.

Management of databases

Arguably, the Institute's key resources comprise its staff and its repository of scientific data and knowledge. Management has recognised the long-term significance of its ecological datasets and the need to maintain and conserve them, and has established a distributed network, comprising the science teams responsible for the major corporate data holdings. The network is organised on both thematic and geographic principles. Thematic elements include:

- Environmental Change Network,
- national ecological survey data generated by the land use section,
- Data Centres which service thematic programmes, such as LOIS (Land/Ocean Interaction Study) and Environmental Diagnostics.

Specialists at each site are responsible for data generated locally. The Environmental Information Centre, established in 1989 at ITE Monks Wood, sits at the hub of this network. EIC is one of seven Data Centres designated by NERC under its Corporate Data Policy (NERC 1996), with overall responsibility for documentation, quality assurance, management, dissemination and custodianship of data relating to terrestrial and freshwater ecology.

Remote sensing

The physical, chemical and biological characteristics of terrestrial ecosystems change rapidly in space and time. Generic insights into the behaviour of these systems can be obtained from experimentation and from *in situ* studies. However, the only practicable means of acquiring extensive and continuous datasets describing the state of the land surface, material and energy fluxes between land, atmosphere, hydrosphere and biosphere, and the responses of terrestrial ecosystems, is by the use of remote sensing. The Institute has considerable expertise in this area of science (using both airborne and space platforms). Strong links to the wider national space programme have been forged with similar groups in other NERC Centres and Surveys, the academia, and through the NERC Remote Sensing Applications Development Unit ITE's core strategic research in remote sensing focuses on the development of methods to estimate biophysical variables, such as photosynthetic activity, evapotranspiration and canopy chemistry

Analytical chemistry

Many problems addressed in the Institute's programmes demand detailed understanding of the chemistry involved, its core strategic science programme in analytical chemistry is designed to meet this requirement The programme includes, for example, development of new methods, modifications to existing methods, evaluation of new techniques or instruments, and improvement of quality assurance and control procedures Applications are diverse, covering water chemistry, soil and plant chemistry and atmospheric chemistry, and encompassing organic and inorganic naturally occurring elements and compounds, as well as polluting and toxic substances The work is relevant to all ITE's programmes, Wright and Meharg illustrate the general approach

Biometrics

Biometrics – especially the use of multivariate techniques – is an important component of the Institute's core strategic science, as success in exploring ecological hypotheses is heavily dependent on good experimental design and a sound understanding of the underlying statistics To encourage effective dialogue between biometrician and ecologist, and to ensure the uniform adoption of best practice, ITE has established a network of statistical advice and support, with full-time biometricians located at most sites and accessible from all The article by Rothery describes the operation of this network in greater detail

Process modelling using GIS

Much of the work of the Institute is concerned with elucidating and explaining interactions in space and time which govern the relationships between individuals and populations and their environment Increasingly, we are able to represent these interactions in the form of mathematical models, which can be used predictively Analyses of spatial relationships are of particular importance for ecological research, these are operations for which geographical information systems (GIS) are designed and are particularly well suited GIS is now in routine use at every ITE site for applications as diverse as pollution transport, population ecology and impacts of changing land use The origins of current GIS packages lie in the requirement for mapping and analysis of data overlays In general, they are not well adapted to spatially distributed modelling of dynamic processes This is seen by ITE as a priority area for development, and current work, as described by Wadsworth, is directed towards rectifying these deficiencies

Environmental assessment

Currently, the Institute's work in environmental impact assessment, restoration and economic valuation is targeted towards strategic needs identified in the UK Government's environmental strategy (Department of the Environment 1996, Office of Science and Technology 1993) Recent EC Directives, eg concerning habitats, species conservation and ecological quality of surface waters, act as additional, political 'drivers' in this important and expanding area of environmental science Methods are needed to measure the ecological significance of identified impacts and to evaluate their importance in social or economic terms Current research in ITE seeks to develop a methodology that will ensure consistency in approach and deliver techniques for validation and quality assurance in what is usually a complex field of interrelated environmental issues The paper by Treweek, MacNally and Sheail provides an analysis of many of these issues

There has been growing interest in the valuation of natural assets, using a range of economic criteria Historically, the Institute has looked to the university community for socio-economic inputs We intend to continue such collaboration, but experience has taught us that some of the most effective developments in environmental economics have been made when economists work for extended periods with environmental scientists within the same organisation As a first step in the planned expansion of its core strategic science programme in this area, ITE has recently appointed a professional economist

The Institute's collected databases and libraries offer a unique opportunity to reconstruct the historical evolution of the natural environment and the development of policies for its management The discipline of environmental history provides vital insights to assist in the development and implementation of a more sustainable approach which avoids errors of the past It also provides an historical baseline against which recent changes can be assessed

B K Wyatt

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The unit is striving to improve the quality, efficiency and variety of its analyses to support research projects.

Analytical chemistry in LOIS

(This work was funded by the NERC Land/Ocean Interaction Study)

The analytical chemistry unit at ITE Monks Wood analyses a wide range of environmental samples for a variety of elements and organic compounds. Since 1994 the unit has been analysing water samples for the Land/Ocean Interaction Study (LOIS). Work for this study is an example of the way in which the unit is continually striving to improve the quality, efficiency and variety of its analyses to support research projects.

Initially, we were asked to look for polychlorinated biphenyl (PCB) congeners at weekly intervals in the rivers that discharge into the Humber estuary (Figure 56). The rivers were analysed for 16 PCB congeners by gas chromatography with electron capture detection (GC–ECD). The Rivers Aire, Calder, Don and Trent were chosen for weekly sampling, based upon their PCB congener and general organic pollution levels. Occasionally, samples are taken from all the rivers to monitor for any major changes.

Plate 20. Preparation of river water samples for analysis by GC-MS and GC-ECD

Development of analytical methods

In such a study the collection of samples is an enormous task and their preparation is as costly as the instrumental analysis itself. The opportunity to carry out a long-term detailed study of a river system is rare, and therefore it was decided to take the opportunity to obtain as much information from the samples as possible. A method was developed which enabled the analysis of PCB congeners, total PCB, organochlorine pesticides (OCs) by GC–ECD and chlorobenzenes (CBs) by gas chromatography–mass spectrometry (GC–MS) (Plate 20). The GC–MS was also used to determine what other organic compounds were present.

The PCB analysis showed the intermittent presence of a few PCB congeners at or slightly above the limits of detection for the method. However, the number of positive results for PCBs was not enough to give an accurate picture of the variation of PCB concentrations with time, and results near the limit of detection had a high level of uncertainty. The sensitivity of the analysis was increased by changing the sample clean-up procedure and employing a novel technique for the injection of the sample into the gas chromatographs. Increases in GC–ECD and GC–MS analysis of x50 and x20 respectively improved the quality of the data.

Average organic concentrations in the LOIS rivers

Figure 57 shows the average concentrations of chlorobenzenes in the Rivers Aire, Calder, Don and Trent. These levels are well below that which would have acute or chronic effects on aquatic organisms. The pattern of isomers is very similar in each of the four rivers, the major difference being the much higher level of hexachlorobenzene in the River Trent which may indicate that the input of hexachlorobenzene into the Trent is higher than for the other rivers. There are limited data to be found on the concentrations of all the CBs in surface waters, for comparison with the results. The pattern of CB isomers is also similar to that found in other surface waters, such as at Niagara-on-the-Lake in Canada (World Health Organization 1991) and the Forth Estuary in Scotland (Harper, Ridgeway & Leatherland 1992; Rogers, Crathorne & Leatherland 1989). The concentrations of CBs in the four rivers are much lower than those found in the Forth Estuary (Harper *et al.* 1992; Rogers *et al.* 1989) and the Rivers Besos and Llobregat in Spain (Gomez-Belinchon, Grimalt & Albaiges 1991). CB concentrations are of the same order of magnitude as those measured at Niagara-on-the-Lake. Differences in the pattern of isomers between different surface waters will be influenced by the types of source, such as industry or sewage treatments, and the factors that affect their environmental transport and transformation, such as the amount and type of sediment in the water, biological activity and climatological conditions. The main uses of CBs are as intermediates in the production of pesticides and other chemicals; 1,4 dichlorobenzene is a common contaminant of sewage (Rogers *et al.* 1989). CBs are moderately toxic, lipophylic and may be bioaccumulated up the food chain. The sources of CBs in the Aire, Calder, Don and Trent are yet to be established.

Temporal patterns in concentration

The patterns within the different classes of compounds are fairly constant over time. Figure 58 shows the variation over time of 1,2,4-trichlorobenzene (a chlorobenzene), alpha-HCCH (an OC pesticide) and PCB congener 8. There is a close correlation between the different classes of compound, suggesting that the factors influencing their concentrations (ie similar sources such as contaminated sediments and agricultural and urban runoff) are the same. OCs, PCBs and CBs are closely related compounds in

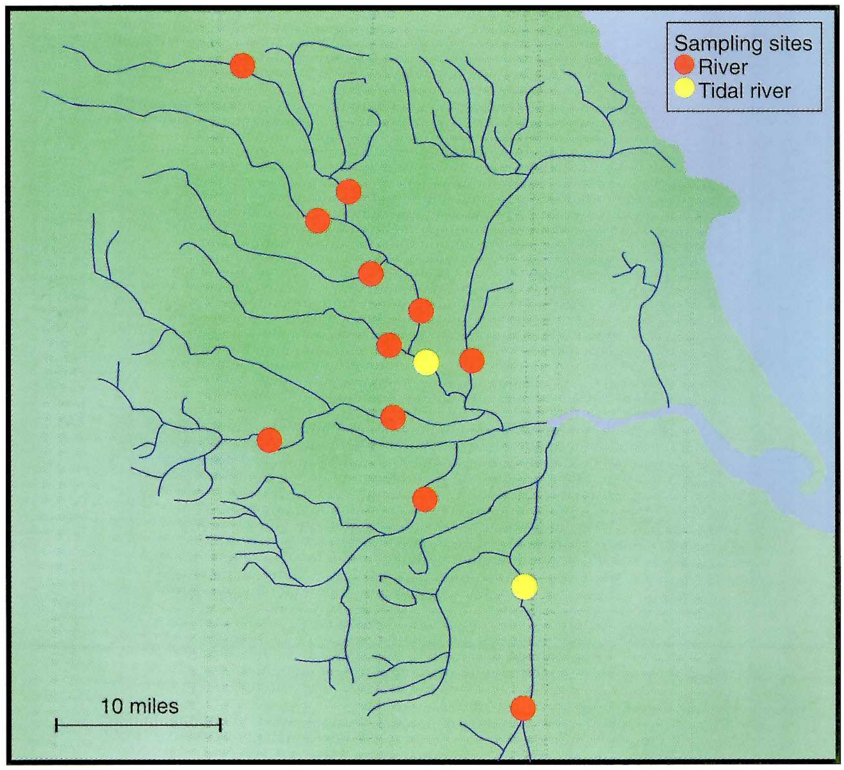

Figure 56. Map of the rivers discharging into the Humber Estuary showing the LOIS sampling sites

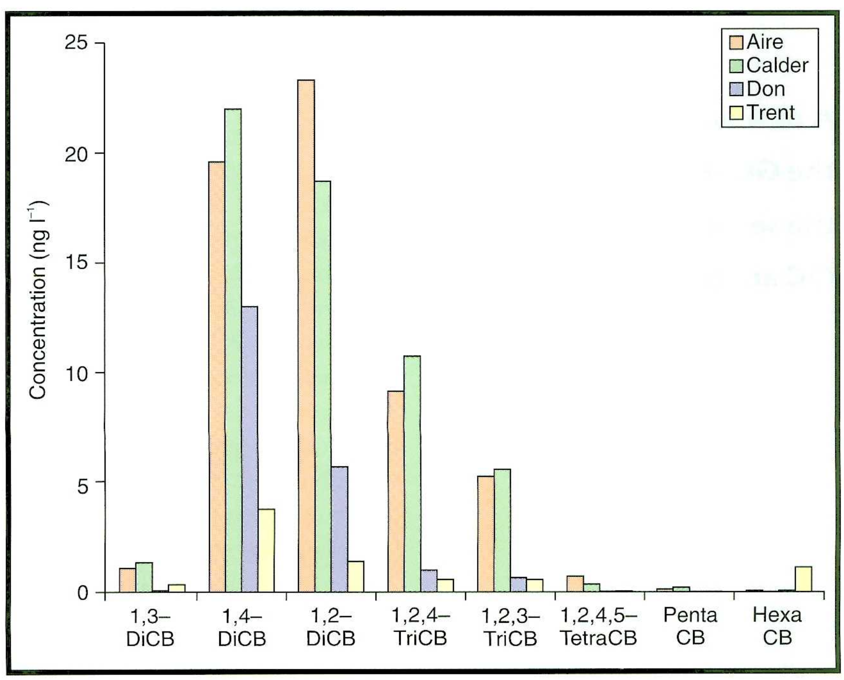

Figure 57. Average chlorobenzene concentrations in the Rivers Aire, Calder, Don and Trent

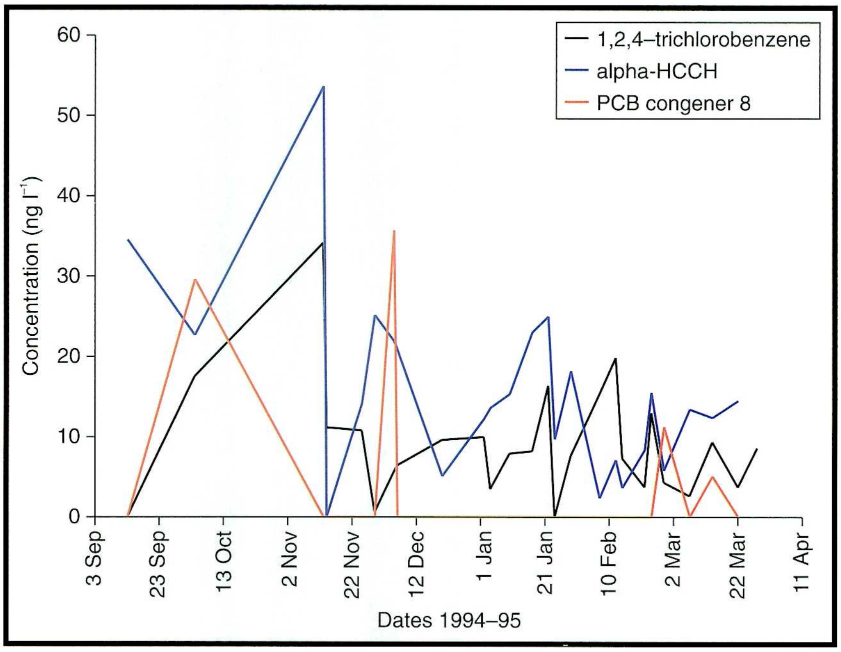

Figure 58. Variation in the concentrations of two OCs, two CBs and one PCB congener in the River Aire

terms of their physical and chemical properties; all are stable, semi-volatile, chlorinated organic compounds, and most of them have aryl or cyclic carbon skeletons. Other chemical and physical data collected by LOIS will be used to model the behaviour of OCs, PCBs and CBs and to give an indication of the total amount of these compounds going into the North Sea.

A new autosampler for the GC–ECD will increase the sensitivity of PCB and OC analysis.

Weekly sampling does not show the full picture of the behaviour of these compounds in a river system. During a spate the water flow increases and large amounts of sediments from the river bed are suspended in the water column. The river bed sediments are sinks for OCs, PCBs and CBs, especially for the more highly chlorinated ones. Therefore, spates may make a significant contribution to the mass flow of these compounds. Weekly sampling may miss spate events, and so the LOIS Laboratory at the University of York has set up automatic samplers to take samples during river spates, which the unit is currently analysing.

Development of the analytical methods used for this analysis is continuing. A new autosampler for the GC–ECD will increase the sensitivity of PCB and OC analysis further. The CB congeners that were not looked for at the start of the study will now be included. New fast sample preparation techniques will be assessed for analysis by GC–MS of compounds whose identity is unknown.

J Wright and A Meharg

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Developments in ITE biometrics

Biometrics is the application of mathematical models, statistics and computing in biology. In ITE, biometricians and biologists work in close collaboration to develop quantitative solutions to ecological problems. This article outlines the organisation of biometrics in ITE and presents example applications of some recent developments in biometrical methodology.

Role of the biometrician

The ITE biometricians form a dispersed group across the ITE stations in order to keep statistical expertise close to the ecological researchers. Scientists at ITE Banchory also collaborate with biometricians based at the Macaulay Land Use Research Institute. ITE biometricians work with a large number of scientists on a wide range of research and contract projects. The broad areas of work include:

- design and analysis of experiments and surveys,
- analysis of ITE datasets (especially long-term datasets),
- research in biometrical methods and their application,
- mathematical modelling, and
- statistical training for biologists.

Contributions to the wider ecological community include serving on scientific committees and editorial boards, and refereeing papers for publication. The latter role is becoming increasingly important as more and more papers appearing in ecological journals contain mathematical models or statistical data analysis.

The biometrics network

The biometrics network is one of the seven scientific networks set up when ITE North and South were re-united in 1994. The network is co-ordinated from ITE Monks Wood and meets twice a year. Its key functions are:

- to ensure effective communication between biometrical staff across ITE,
- to document and develop specialist expertise to ensure appropriate deployment,
- to develop research links with university departments,
- to formulate a statistical training policy for ITE, and
- to develop and implement a strategy for biometrical research.

The network's catalogue of expertise and experience includes a comprehensive list of biometrical methods, statistical computing, biometrical research, mathematical modelling and a wide range of ecological areas of involvement. The network has links with universities and other research institutes, and the list of external collaborators is growing. A new statistical training programme has been started and a course in Minitab Release 10 was presented recently at ITE Monks Wood and ITE Bangor. Network members are collaborating in a project to produce a book on *Introductory statistics for ecotoxicology*.

Computer-intensive statistical methods

The advent of fast and cheap computing has led to important developments in statistical analysis. Many methods can now be routinely applied using packages running on personal microcomputers. Moreover, new computer-intensive techniques have been developed in which computing power replaces or supplements theoretical analysis. This section gives some ecological applications of a computer-intensive technique referred to as the resampling method, which includes randomisation tests of statistical hypotheses and bootstrapping for assessing the precision of estimates

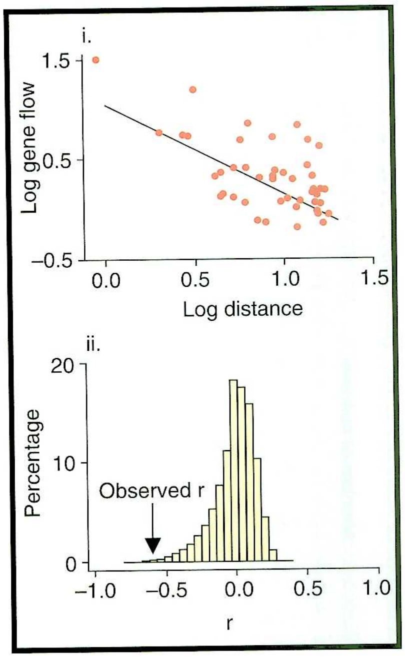

Figure 59i. Log gene flow against log distance (km) between ten pairs of sea beet populations using restriction fragment length polymorphisms. Fitted line: log (gene flow)=1.05–0.82 log distance
Pearson correlation coefficient r=–0.63
ii. Randomisation distribution of r for a Mantel test of association between gene flow and distance ($r \leq$ observed value of –0.63 in only eight out of 10 000 randomisations, ie P=0.0008)

ITE biometricians and biologists work in close collaboration to develop quantitative solutions to ecological problems.

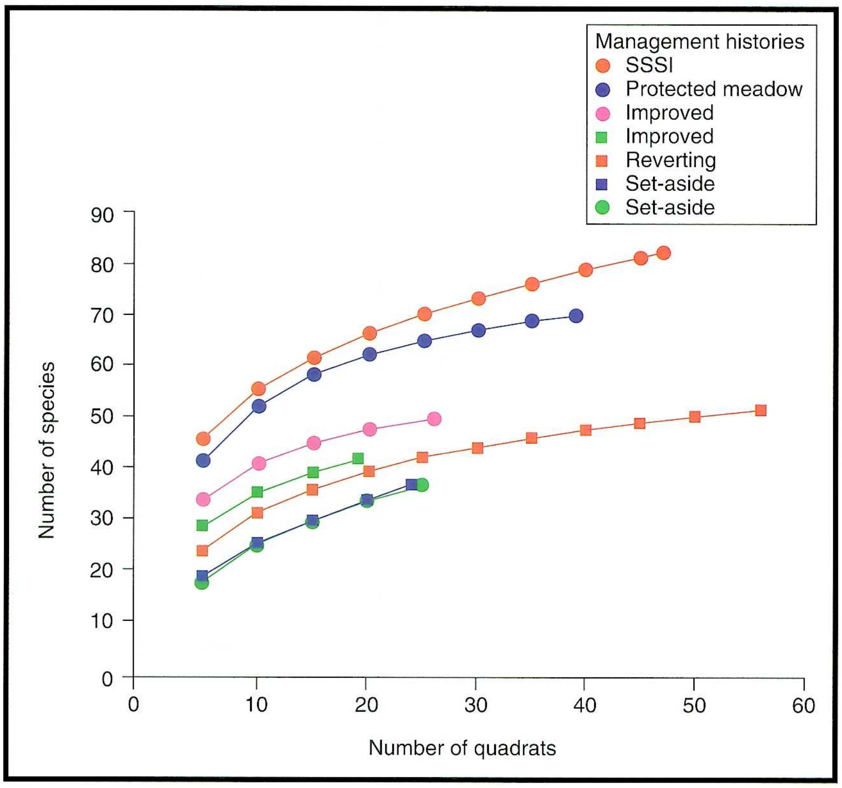

Figure 60. Estimated species area curves obtained by random subsampling of quadrats taken in grass fields from the River Ray catchment, 1993

(Manly 1991). Some examples in ecotoxicology are discussed by Sparks and Rothery (1996).

- **Gene flow and geographical distance in a population of sea beet**

Raybould, Mogg and Clarke (1996) report on a study of the genetic structure of sea beet (*Beta vulgaris* ssp. *maritima*) populations to compare patterns of gene flow in isozymes with those in single-copy nuclear restriction fragment length polymorphisms (SCN RFLPs). Isolation effects can be quantified by the regression of log gene flow on log distance, using values calculated between all the pairs of several populations (Figure 59i). Because the pairs of values were not independent of each other (each population is represented more than once), the statistical significance of the trend was calculated using a randomisation test, which randomly shuffled the populations and not the pairs of observations. Figure 59ii gives a histogram of the randomisation distribution of the sample correlation coefficient and shows strong evidence of a decline in gene flow with increased geographical distance. In a similar analysis for isozymes, there was no detectable decline with distance.

Table 11. Number of species recorded in field walks and random quadrats in seven fields of the River Ray catchment, 1993. Estimated sample size required to detect 90% of the species identified in field walks

Field	Area (ha)	No. of quadrats	No. of species walks	No. of species quadrats	Estimated sample size quadrats	Estimated sample size area (%)
SSSI	3.80	47	100	81	86	0.23
Protected	3.50	39	81	69	49	0.14
Improved	2.07	26	55	49	26	0.13
Improved	1.43	19	52	41	36	0.25
Reverting	7.22	56	62	50	95	0.13
Set-aside	3.78	25	60	36	124	0.33
Set-aside	6.03	24	55	36	88	0.15

- **Sample sizes for estimating species lists in vegetation surveys**

Vegetation surveys often involve locating quadrats within some area of interest and recording the species present in each quadrat. Grassland surveys typically use 1 m^2 quadrats, recording other information such as ground cover, vegetation height and flowering status. Invariably, some species are likely to be missed, which raises the question of how many quadrats to take in order to record a specified fraction of the total species present in the area. In general, the answer is not straightforward because it depends in a complex way on the spatial distribution and abundance levels of all the species present. One empirical approach is to analyse quadrat data from existing studies where a complete species list is available from a separate intensive search (Sparks *et al.* 1997). The approach is to draw random samples, without replacement, from the observed sample in order to estimate the distribution of the number of species found in samples of different sizes. In particular, the mean number of species plotted against the cumulative number of quadrats estimates the species area curve (Figure 60). In this example, the species area curves are approximately linear in log number of quadrats so that an estimate of the number of quadrats required to detect 90% of the species list can be obtained by extrapolating the fitted straight line. Over a wide range of management regimes, the estimated sampling fraction varies between 0.13% and 0.33% of the total area of the population (Table 11). Similar analyses using data from other populations help to provide guidelines for the design of future studies.

- **Estimating otter diet from spraint samples**
  The diet of wild carnivores is often inferred from the remains of prey items found in their faeces. Eels (*Anguilla anguilla*) are a major prey item of the otter (*Lutra lutra*), and studies in Scotland are estimating the distribution of eel lengths in the diet. Experiments on captive otters show that eel length can be predicted from the width of eel vertebrae, and that vertebrae of different sizes are recovered at different rates in the spraints. An empirically derived relationship between the width of the partially digested vertebrae and the eel length is then applied to vertebrae found in field samples of spraints to estimate the frequency distribution of eel sizes in the diet (Figure 61). Estimation errors arise from the natural variation of the amount of eel represented in each spraint and measurement error in estimating eel length from the partially digested vertebrae, but these errors cannot be easily calculated using analytical methods. Instead, a computer-intensive method called bootstrapping is used to estimate the error in the estimated length frequency distribution (Carss & Elston 1996). The approach draws random samples with replacement from the field sample of spraints, and in each case calculates an eel length frequency distribution. A confidence interval for the population length frequency distribution is calculated from the percentiles of a large number of these so-called 'bootstrap samples' (Figure 61).

Biometrics and population modelling

The many applications of mathematical models in ITE include large-scale physical and chemical models, biological process models, dynamic population models and

The advent of fast and cheap computing has led to the development of new computer-intensive statistical methods.

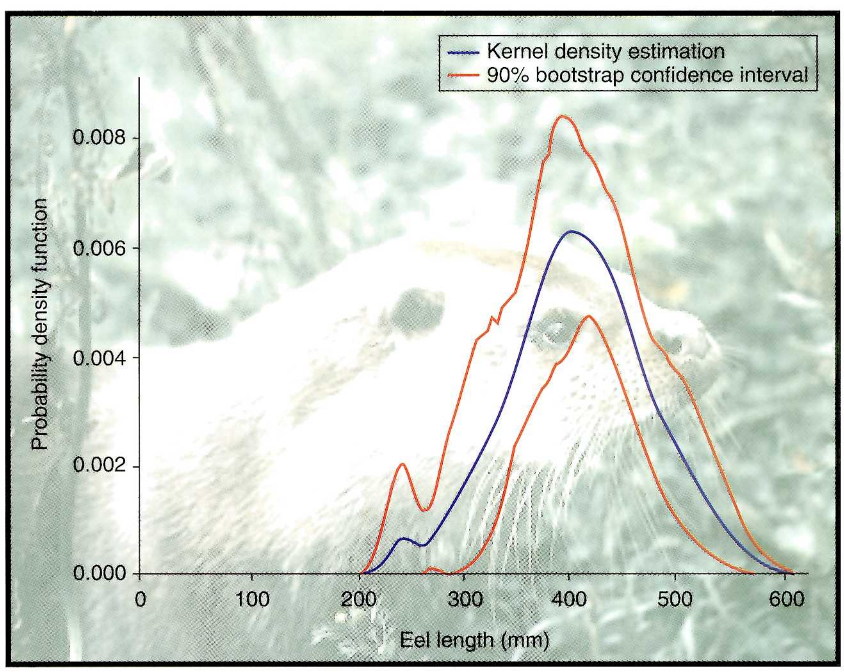

Figure 61. Estimate of eel length distribution in otter diet from 54 vertebrae in a sample of 96 otter spraints

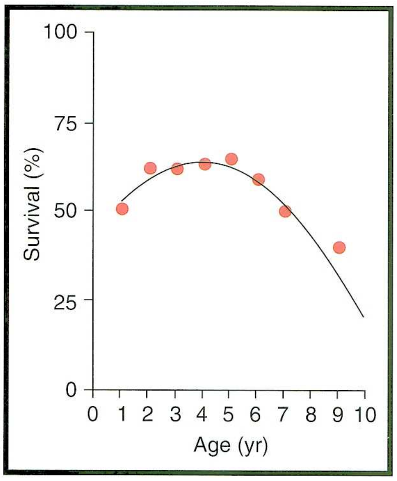

Figure 62. Age-dependent survival in female sparrowhawks, Eskdale. Estimates obtained from capture/ recapture data using a model with age and year effects for the recapture rate. Solid line shows a fitted quadratic in age (on a logistic scale) to test for senescence

The current pace of methodological developments emphasises the value of collaboration with other research institutes and universities for future developments.

Plate 21. Sparrowhawk and young

spatial models. Because of the inherent variability of biological material, the emphasis of biometrics has been on statistical methods for analysing data and as a basis for designing experiments and surveys. However, biometricians are becoming more involved in mathematical modelling of populations and processes, and in applying statistical models to estimate population parameters and describe relationships for input to models. This approach is exemplified by current work at ITE Furzebrook which uses a game theory distribution model of oystercatchers (*Haematopus ostralegus*) feeding on mussels (*Mytilus edulis*), and estimates model parameters using field data.

Another example is in a long-term study of the sparrowhawk (*Accipiter nisus*) in Eskdale, Dumfries and Galloway (Plate 21). Data have been used to estimate age-dependent survival applying some recent developments in models for capture/ recapture data (Lebreton, Burnham & Anderson 1992). The analysis shows an improvement in annual survival up to the third year of life, and a decline from the fifth year on, in the maximum ten-year lifespan (Figure 62). These results have been used to estimate the reproductive value of female sparrowhawks in Eskdale, and will be used to model changes in the surplus non-breeding population.

Conclusions

The studies mentioned above are a small sample of the work undertaken recently by the ITE biometricians. Many other studies, on a wide range of issues, are in progress. Some areas of increasing importance are:

- measuring uncertainty in spatial data,
- non-linear dynamic models and analysis of ecological time-series data,
- modelling species distribution on different spatial scales,
- generalised linear mixed models.

Other more recent computer-intensive methods such as neural networks and Markov chain Monte Carlo need to be evaluated for ecological data. The current pace of methodological developments emphasises the value of collaboration with other research institutes and universities for future developments in ITE biometrics.

P Rothery, T H Sparks, R T Clarke and D Elston

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Dynamic models and GIS

The integration of spatial and stochastic processes has become a developing area of research in many areas of science investigated by ITE, such as ecotoxicology (Meharg *et al.* 1995) and landscape ecology (Treweek *et al.* 1996). The requirements of these investigations are many and varied; they include producing tools to assist in managing a resource, to help formulate policy and to provide increased understanding. Research is taking place at a range of spatial scales, from local (a few fields on an individual farm) through regional (a river catchment) to national and international scales. Temporal scales at which spatial processes operate can vary from a few minutes (for some pollution events) to decades (ecological response to climate change). A research project for understanding spatial ecological processes at a regional scale is described below.

Geographical information systems (GIS) are being developed, from tools for the passive display of data to a means for the active simulation of spatial processes. While the ability to carry out sophisticated modelling within a GIS is still fairly constrained, the ease with which external programs may be linked has significantly increased recently. There are three typical approaches to developing integrated models of dynamic spatial processes:

- create them entirely within the GIS,
- call an external program to do some of the processing, or
- call a GIS from within an external program.

Because of the capability of GIS for the display of information and the ease with which simple graphical user interfaces (GUI) may be developed using a GIS, the first two approaches are more widely used within ITE's Environmental Information Centre. The approach of developing a model within a GIS can be illustrated by reference to work currently being developed as part of an NERC Thematic Programme on Large-Scale Processes in Ecology and Hydrology, with the University of Durham and the National Rivers Authority (NRA) (now part of the Environment Agency), on the dynamics of invasive species along river corridors.

Several plant species originally introduced to this country as garden ornamentals have escaped cultivation and are spreading along river banks across the country. In places they are forming dominant patches and preventing native species from growing. The suite of species being studied has a wide variety of growth habits and methods of dispersing. Two of the species – Himalayan balsam (*Impatiens glandulifera*) and giant hogweed (*Heracleum mantegazzianum*) – are shown in Figures 63 and 64, where differences

The integration of spatial and stochastic processes has become a developing area of research in many areas of science investigated.

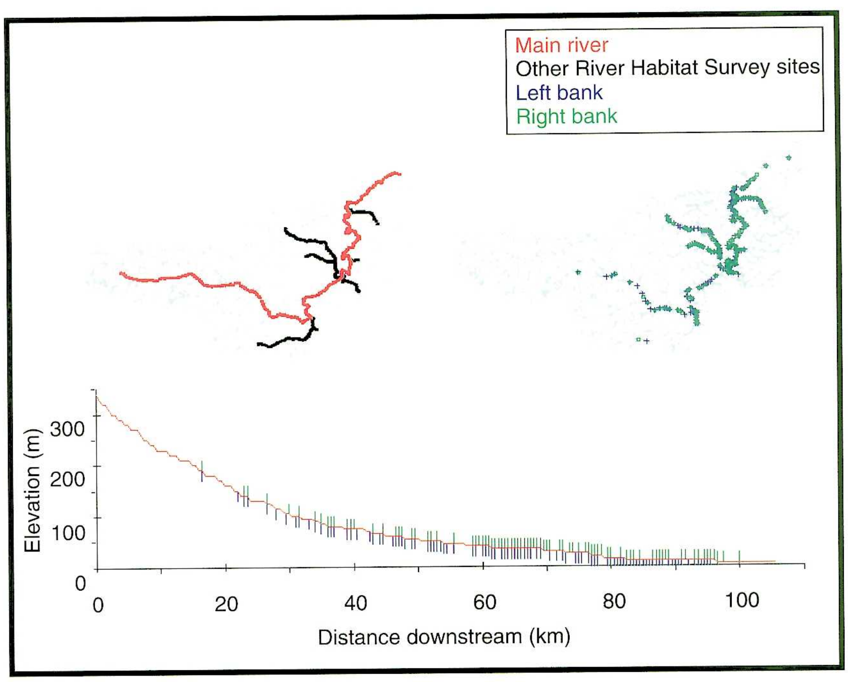

Figure 63. Observed distribution of Himalayan balsam (*Impatiens glandulifera*) estimated from data collected in the River Habitat Survey of the River Wear

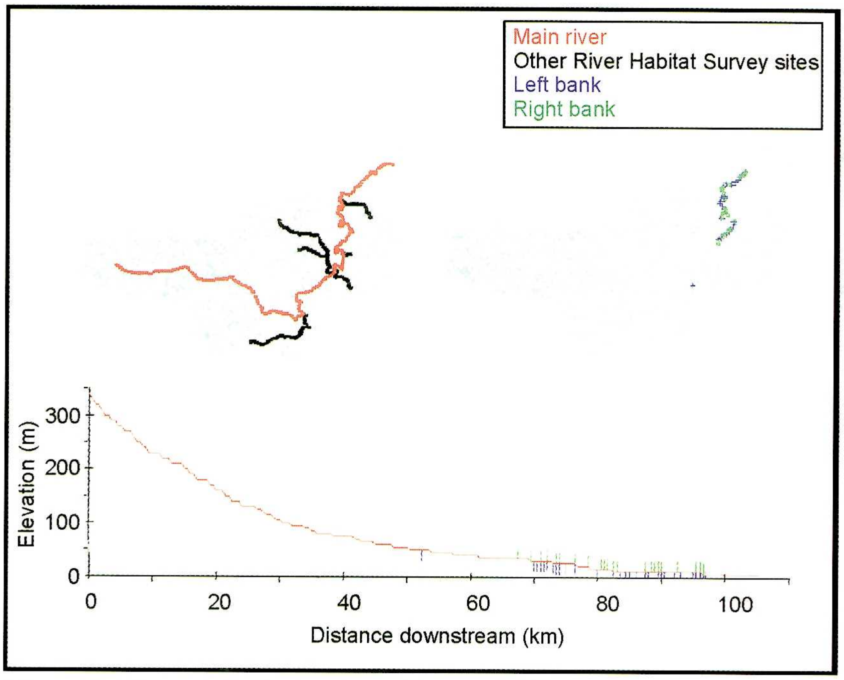

Figure 64. Observed distribution of giant hogweed (*Heracleum mantegazzianum*) estimated from data collected in the River Habitat Survey of the River Wear

between the two distributions (during 1994–95) are clearly visible. A major source of information for this study is the River Habitat Survey carried out by the NRA. This survey was carried out for 0.5 km sections of designated main river corridor and provides a description of the physical and ecological conditions (which have been characterised into 106 variables). Unfortunately, large amounts of potential habitat were not designated as main rivers and so have not been surveyed (this can be seen by referring to Figures 63 & 64). Other data sources are the Institute of Hydrology's river network, digital elevation model and river flow records and ITE's Land Cover Map.

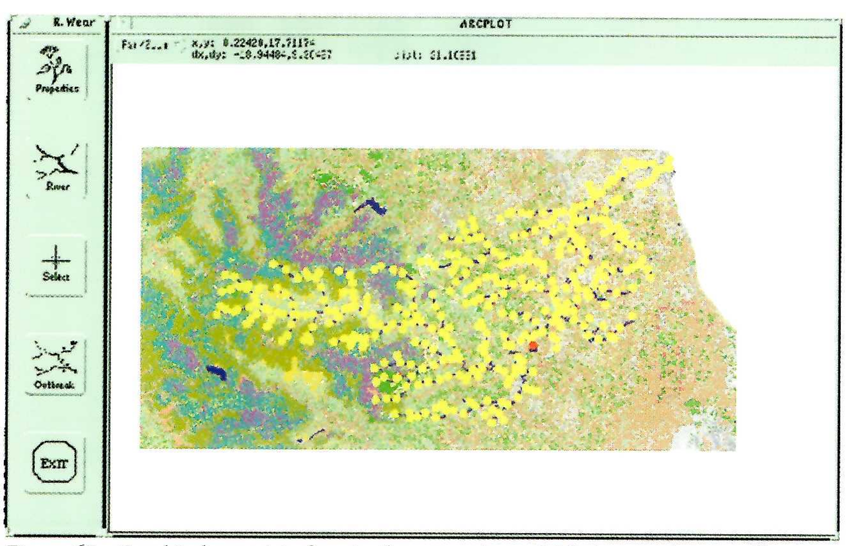

Figure 65. Graphical user interface to the network model being used to specify an initial starting point (shown in red) for an invasion

The spread of a each species has been modelled as a two-stage process: the large-scale dispersal of propagules along the river channels, and the local exploitation (or otherwise) of the river bank when a propagule is deposited. In GIS terms, the river can be considered as a network of nodes and links, and travel along that network may be impeded at each node and along each link. Along a river reach (network link), the magnitude of the impedance will be much lower downstream than upstream. Some movement upstream must be allowed (a large but non-infinite impedance) because of the various backwater and flood flow conditions which can move debris (and propagules) upstream. Within the network model, a plant is described by a very limited set of characteristics:

- how long a propagule remains viable when released,
- at what age propagules are released from the plant,
- how easily a propagule can be deposited on a bank.

At its simplest, the model estimates the time it would take a propagule to travel from a 'source' node to any other node; if the time is less than the viability period of the propagule, the 'empty' node is deemed to have been reached. Figure 65 shows the graphical user interface to the model being used to select an initial node to act as a source of propagules. Figures 66 and 67 show the effect of varying the plant parameters on the spread from the initial outbreak site over a three-year period.

Information on the flow regime and the geometry of the river banks is being used to estimate the probability that a propagule reaching a particular node will establish successfully. The establishment of the plant along each bank on a reach is being modelled at a fine resolution by a raster-based model under development at the University of Durham. The two models can be linked so that long-distance dispersal by water and short-distance dispersal on land can work in tandem. Data to verify the linked models are being collected for the River Wear in the summer of 1996, and the study area will be extended to cover the River Tyne and River Tees in 1997.

The network model has demonstrated that a very parsimonious system may be sufficient to simulate different patterns of distribution, corresponding to different dispersal mechanisms employed by riparian weeds. The project is now investigating what combination of physical conditions (soils, geology, bank geometry, frequency of flooding, etc), presence of other species and management practices (cutting, grazing and other disturbance) determines the success rate of propagules. If the sensitivity of each species to these different factors is known, then the potential range of the species and methods for their management may be determined.

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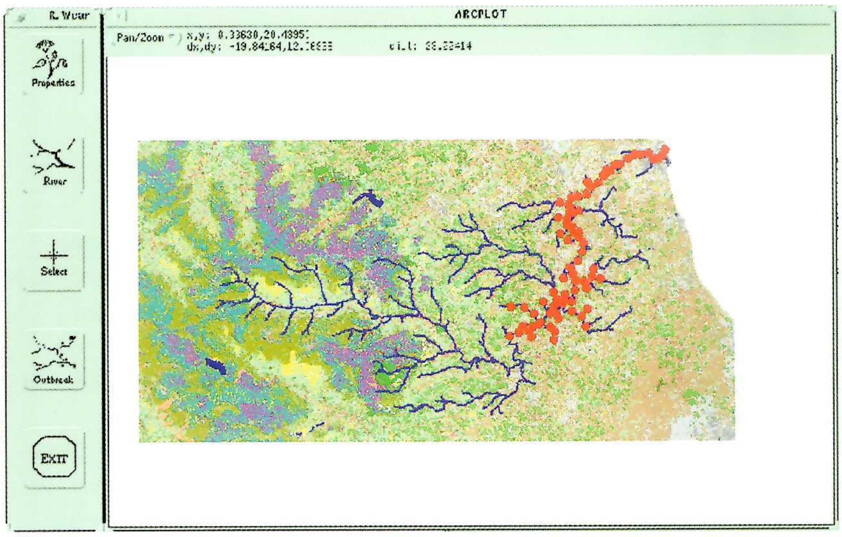

Figure 66. Results of the network model simulating the spread for a species with a high rate of dispersion

Data to verify the linked models are being collected for the River Wear in the summer of 1996, and the study area will be extended to cover the River Tyne and River Tees in 1997.

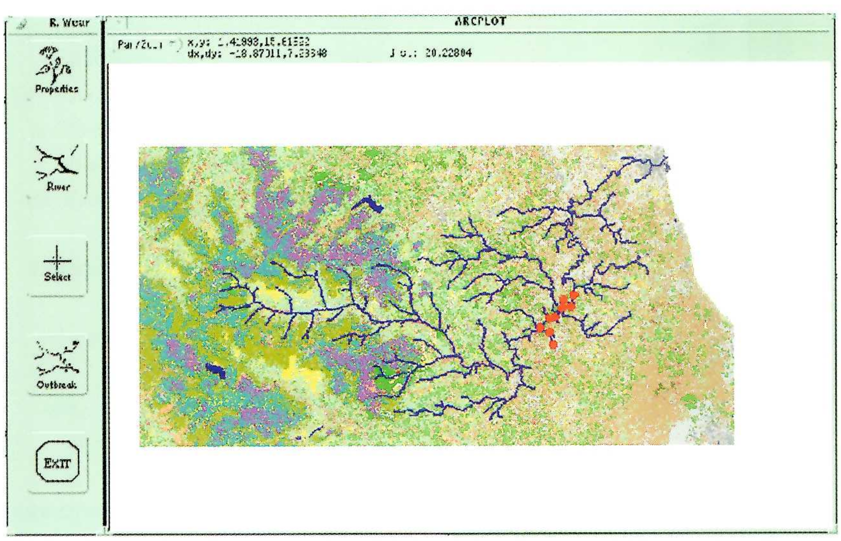

Figure 67. Results of the network model simulating the spread of a species with a lower rate of dispersion

The integrated application of ecological and economic techniques to development planning and decision-making is essential.

Ecological and economic aspects of environmental assessment: the role of mitigation in sustainable development

The achievement of sustainable development requires a balance to be struck 'between environmental preservation and economic development' 'to reap the benefits of growth without significant degradation of the natural resource base' (United Nations Environment Programme 1986). The integrated application of ecological and economic techniques to development planning and decision-making is essential.

Legislation for environmental assessment (EA) worldwide reflects heightened perceptions of the need to develop sustainably and has provided particular demand for the integration of ecological and economic techniques. Assessment of ecological impacts is fundamental to the EA process and has an important part to play in ensuring that conservation of biological diversity is compatible with development (Treweek 1996). Theoretically, EA provides opportunities for the avoidance of adverse environmental effects through environmentally sensitive siting and design and the early identification of potentially damaging environmental impacts. EA may generate physical measures of the environmental benefits and disbenefits of a proposal which can be converted into economic measures for inclusion in standard social cost/benefit analyses. Development options can then be considered in terms of their economic efficiency, actions only being approved if their benefits exceed their costs. However, in circumstances where impacts cannot be monetised, the extent to which economic instruments can be used to internalise environmental impacts in the decision-making process becomes much more limited (Lee & Kirkpatrick 1996).

There are many definitions of 'sustainability', but most are based on the premise that it is inequitable to advance the well-being of the current generation at the expense of future generations (Barbier, Markandya & Pearce 1990). Most EA legislation makes provision for the mitigation of adverse impacts to ensure the maintenance of a constant stock of 'natural capital' (Forbes & Heath 1990), while at the same time allowing development to take place. The Department of the Environment's guide to the procedures for EA in the UK specifies that 'where significant adverse effects are identified, a description of the measures to be taken to avoid, reduce or remedy those effects' (DOE 1989) should also be included in the environmental statement (ES) which summarises the findings of EAs for proposed development projects.

In researching the role of ecological mitigation in sustainable development, it has to be assumed that ecological impacts are predicted accurately in the first place. However, there is evidence to suggest that important ecological impacts are often neglected. Common criticisms of the ecological content of ESs are listed below (from Treweek 1996):

- failure to mention presence of designated areas and/or protected species,
- failure to consider resources important for conservation of biological diversity which are not designated or lie outside the actual site of a proposed development,
- failure to characterise baseline conditions or identify nature conservation constraints,

- failure to provide the data needed to identify or predict ecological impacts,
- failure to measure explanatory variables,
- failure to quantify ecological impacts (even simple, direct impacts like habitat loss),
- failure to measure cumulative, indirect and trans-boundary effects,
- weak prediction,
- over-reliance on descriptive and subjective methods,
- bias towards easily surveyed and charismatic taxonomic groups,
- over-reliance on superficial 'walk-over' surveys,
- inadequate replication,
- failure to estimate ecological significance,
- failure to describe limitations of survey methodology or to quantify levels of uncertainty attached to predictions,
- recommendations for mitigation measures which do not match impacts,
- recommendations for mitigation measures which are untested and unreliable

In a study undertaken by ITE in conjunction with Oxford Brookes University, ITE reviewed 192 ESs produced for a variety of development projects, representing approximately 10% of all statements known to have been produced between July 1988 and September 1993 (Frost *et al* 1993) The results suggest a failure to ensure that ecological impacts are mitigated effectively with a view to sustainable management of natural resources There appears to be no clear, objective basis for deciding whether to mitigate and, if so, which potentially adverse impacts should be mitigated The mitigation measures proposed do not always relate directly to the ecological impacts identified, and there are many ecological impacts for which no mitigation is recommended This results in a high risk of residual adverse effects and the erosion of natural capital

Overall, the extent to which measures were recommended to offset losses of wildlife habitat was very low (11%), and it did not appear to be influenced by the nature conservation value of the habitat affected Of 112 Sites of Special Scientific Interest (SSSI) subject to possible direct effects, specific mitigation measures were only recommended for nine (approximately 8%) More seriously, however, in the cases where internationally designated areas were affected, including one UNESCO World Heritage Site, nine RAMSAR sites and four Special Protection Areas, no specific mitigation measures were listed at all Although avoidance of ecological damage is generally accepted to be the most effective form of mitigation, only 3% of statements referred to the siting of development proposals based on 'least-damage criteria' with respect to ecological parameters Avoidance of key periods such as bird-nesting periods was only recommended in 7% of statements This implies a general failure to take account of ecological constraints in planning the siting, timing and scheduling of development

Review of 192 ESs suggests failure to take account of ecological constraints.

Where modification to project siting and design fails to ensure avoidance of damage, replacement through ecological restoration is commonly recommended to maintain a constant stock, but the extent to which new or replacement habitat substitutes for that which has been lost must be considered carefully Considerably more research is needed into the techniques, costs and effectiveness of restoring or replacing damaged ecosystems Results from other studies suggest that translocations of habitat, for example, generally result in the loss of some key species

Evaluating the effectiveness of ecological mitigation is essential in pursuing sustainability objectives.

No mitigation measure should be proposed without some indication of its effectiveness, and DOE gives a clear recommendation (DOE 1989) that an 'assessment of the likely effectiveness' of mitigation measures should be included in ESs Evaluating the effectiveness of ecological mitigation is essential in pursuing sustainability objectives There is a need to know how far mitigation can be relied upon to offset damage of losses resulting from development proposals In the majority of the ESs reviewed by ITE and Oxford Brookes University, it was impossible to determine whether the mitigation measures proposed would be effective either quantitatively or qualitatively for example, whether an equivalent area of land would be restored to compensate for habitat loss or whether it could be assumed to have equivalent wildlife value

To enhance the transparency of policy, there needs to be more guidance as to when mitigation must take place Gillespie and Shepherd (1995) argue that 'critical natural capital' should be treated as inviolable While 'constant natural assets' may be traded in issues of land use change, their loss should be fully and directly compensated to give no overall loss Undertaking mitigation in accordance with the principle of 'no net loss' for every adverse ecological impact could be unduly restrictive, however, and Barbier *et al* (1990) suggest that it might be preferable to offset the cumulative impacts of portfolios of projects through mitigation, rather than undertaking a 'shadow project' to offset every adverse impact

It may be important to estimate the costs of mitigation so that these can be incorporated into cost/benefit analyses of proposals, particularly where it is considered acceptable to use 'replacement cost' as a proxy for the value of the environmental damage associated with them In addition, it is relevant to assess the distributional impact of mitigation measures, particularly where habitat restoration is undertaken to mitigate loss Some complex habitats may take decades to be restored to their pre-damage state Thus, while sustainability is assured in the long run, it is achieved at the expense of the current generation which is effectively denied access to the resource Where use value forms an important part of total economic value, it is vital to consider this issue of inter-generational equity

However, it was clear from the review that there is no generally accepted method for evaluating the feasibility, effectiveness, costs and redistributional effects of ecological mitigation measures This means that the costs associated with failure to implement mitigation measures are not properly taken into account in development planning

Hence, key issues are

- the value of the resources which are to be damaged or lost,
- the extent to which they can actually be restored or replaced using available technology,
- the time this will take, and
- the cost of achieving an acceptable degree of mitigation

On the basis of the review of ESs, there are several recommendations which would make mitigation in EA consistent with the concept of sustainability

- Mitigation proposals should be more rigorous and comprehensive where potential impacts on designated sites and protected species have been predicted
- Mitigation proposals should be sufficiently detailed for their effectiveness to be evaluated

- Some indication should be given of the effectiveness of the proposed measures, based on similar experience elsewhere
- Where untested techniques are proposed, this should be made clear
- The extent of residual impact with and without mitigation should be estimated
- Contingency measures should be included with respect to possible mitigation failures
- The costs of failure to implement mitigation effectively should be explicit

Post-project monitoring of ecological impacts is absolutely essential (Treweek 1996) Without monitoring it will not be possible to measure or evaluate the effectiveness of mitigation in practice Whatever view is taken about the extent to which mitigation should be undertaken, 'sustainability' policies will be more credible if there are measures in place to enforce and monitor commitments by developers to mitigate specified ecological impacts

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