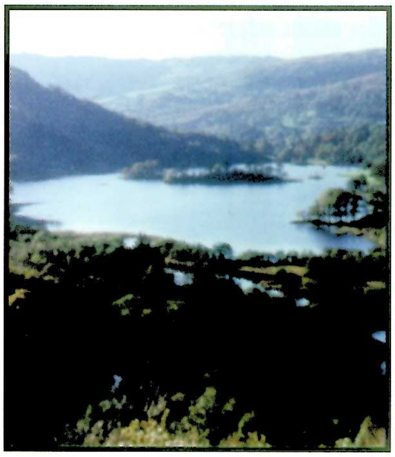
Contents



The Science Programme of CEH provides a base that underpins national and international requirements in the terrestrial and freshwater sciences. The Programme is wide-ranging and is divided into 10 component Programmes, all of which address issues of current environmental relevance and important scientific challenges. The Programme as a whole involves extensive collaboration with academic organisations throughout the world and with international research programmes.

CEH Science Programmes

1: Soils and Soil–Vegetation Interactions

This programme is designed to improve our understanding and ability to model key soil processes controlling the transformations of materials within soils and the flux of water through the soil–vegetation–atmosphere continuum.

2: Land Use Science

This is aimed at promoting an integrated approach to land use science that is applicable to the wide range of user community requirements. The programme's themes will be developed to provide the basis for large-scale, long-term analytical studies of major land use change.

3: The Urban Environment

This relatively new programme aims to extend the interdisciplinary knowledge base and to understand the key environmental patterns and processes in urban situations and particularly change due to human activities. This knowledge is required to plan more sustainable urban environments.

4: Freshwater Resources

Increasing demands on freshwater resources have resulted in the need for a scientific basis for the effective strategic and sustainable management of freshwater resources. This programme will address this by integrating CEH research in the areas of water quantity, water quality, and the ecological aspects of freshwater systems.

5: Biodiversity

Aimed at improving our understanding of microbiological and biological resources at a range of spatial scales. The research considers the underlying processes and resulting functions, and directs knowledge to the sustainable management of biodiversity.

6: Pest and Disease Control and Risk Assessment for GMOs

The primary aim of this programme is to undertake research in the provision of novel pest and disease control strategies whilst addressing any possible risk to the environment. The use of molecular biology is essential to maintain a novel and progressive approach to the themes of pest control and animal disease control.

7: Pollution

This programme is aimed at developing a better understanding of generic processes such as atmospheric transport, fluxes of pollutants and the fate of pollutants, in order to predict more accurately the likely impacts on environments and organisms.

8: Environmental Risks and Extreme Events

This research programme will develop understanding of how environmental extremes affect mankind and the natural environment, developing quantitative, predictive tools to describe these effects, and contributing to mitigating measures.

9: Global Change

This programme will help to reduce uncertainty in the magnitude of global change and its impacts. The research is focused on improving the accuracy of global change predictions through measurement programmes, the development of scaling-up methods and models, and the identification of ecosystem responses.

10: Integrating Generic Science

Programme 10 has been designed to provide a research framework for those areas of CEH science which underpin the nine other programmes (eg providing the data and technological support), as well as conducting its own fundamental research.

The following section of this Scientific Report describes some of the research which is currently being carried out in the ten Programmes by the Institute of Terrestrial Ecology. Further details of the Themes and Issues that make up each of the ten Science Programmes are listed in Appendix 3 of the CEH Annual Report.

Soil processes have a key role in maintaining nutrient cycles, breaking down pollutants and wastes and/or buffering their impacts, and controlling the release and consumption of 'greenhouse' gases.

Soils

The Institute has maintained a significant soils research programme since its formation in 1973 and now makes a major contribution to the CEH Strategic Science Programme 1 on soils and soil-vegetation interactions. This Programme has three main themes:

- physico-chemical processes affecting soil-water interactions
- biologically mediated processes
- physical and physiological processes controlling soil water balances.

Over the last 25 years the Institute has sought to maintain a balance between a number of strategic themes and, increasingly, applying its expertise in areas of environmental concern, such as pollution impacts, climate change and waste disposal. In parallel with the move from basic to strategic and more applied work, the nature and emphasis of the research has changed, reflecting the general shift in ecological research, from observational and descriptive to testing of hypotheses using experimental manipulation.

Decomposition and nutrient cycling processes – the role of fauna, bacteria and fungi

One of the consistent research themes has been the study of decomposition processes and the role of soil biota, particularly fungal and microbial communities in these and other biologically mediated processes. The work has ranged from method development to studies of particular organisms and a unique 25-year field study of litter breakdown rates. The strategic fungal research initially focussed on autecological studies, moving to elucidation of their role in nutrient cycling. It has included development of techniques for determination of fungal biomass, the first application of immunofluorescent methods in the study of fungi, one of the earliest uses of the molecular approach, and a 20-year study of population dynamics in the field.

Early microbiological work examined the relative roles of microbial and fungal populations in nutrient dynamics in different soils. The first energy budget for a UK woodland was developed under the International Biological Programme (IBP) and showed that the microbial population was effectively starving. Current microbial work is using molecular techniques to investigate populations involved in trace gas production and consumption. IBP studies on soil protozoa still provide keystone information and gave rise to a type protozoan collection which is still drawn upon today. Early faunal work focussed on earthworms and gave rise to a classification still employed today. Similarly, groupings of soil organisms on the basis of size formulated by Institute scientists, continue as the basis of the experimental design of research projects in many countries.

The role of fungi in the retention and cycling of pollutants

A very different aspect of work on fungi showed their importance in the cycling of atmospherically deposited pollutants Thus, saprophytic fungi were found to be important in the retention and cycling of radiocaesium in acid, soils while mycorrhizas sequestered the caesium and mediated plant uptake In contrast, decomposer fungi were shown to be the most sensitive components of soil-plant systems to SO_2, with the result that exposure to the gas could disrupt nutrient cycling

The importance of mycorrhizas in plant nutrition

ITE research helped demonstrate the crucial importance of mycorrhizas in plant nutrition, particularly in forests and nutrient poor soils The early focus was on P nutrition but later work provided one of the first indications that mycorrhizas could also utilise organic N Applied work developed mycorrhizal inoculation systems for introduction into tropical tree nurseries, with major beneficial impacts on establishment Current work shows that re-inoculation with mycorrhizal may be necessary after clearfelling of tropical forests

Isotopic approaches to plant nutrient demand, P dynamics and carbon turnover

A feature of our research has been the innovative application of isotopically based techniques Thus, work on P dynamics in the 1970s involved the first use of ^{32}P labelled RNA in this field A technique developed in the Institute determines plant nutrient status/demand by measuring uptake from labelled solutions by excised roots The technique is applied to phosphorus using ^{32}P, potassium using ^{86}R as an analogue for K, and N using ^{15}N The method has now been applied in over 14 countries in forest management, pollution and plant competition studies

The rate of carbon incorporation and turnover in soils has been modelled using the signal from ^{14}C from nuclear weapon tests The method is currently being applied across a transect of European forests Current work on carbon fluxes and transfers in soils, and the role of mesofauna and microbial populations, is exploiting the differing carbon isotope signatures of some soils and plant litters to track carbon transfers State of the art mass spectrometers are allowing ITE to determine the carbon isotope signal of individual compounds from individual invertebrates

Impacts of land use and pollution on element cycling and water quality

A 20-year series of studies has examined the impacts of afforestation, including subsequent forest management, and atmospheric pollution on soil processes and drainage water quality This provided the first clear evidence linking increased pollutant inputs due to canopy-atmosphere interactions, with changes in soil-solution interactions and subsequent acidification of drainage waters Related work showed the potential impacts of clearfelling on drainage water quality, in particular, large increases in nitrate leaching with potential short-term increases in acidification The results from the studies have influenced subsequent forest management guidelines

Global change – enhanced CO_2, increased temperature, trace gas sources and sinks

Our research has shown that enhanced CO_2 can impact on plant chemistry to reduce decomposition rates in conditions of nutrient stress Field experiments, involving a combination of heating *in situ* soils and transport of intact soil columns down an altitudinal gradient, have shown large increases in outputs of dissolved organic carbon with soil warming Older pools of soil carbon were broken down but meso-fauna had a crucial role in mediating the decomposition Research on trace gases has provided the first quantitative data on

- outputs from a number of habitats/land use systems
- information on the impact of wetland drainage on trace gas emissions
- clear evidence of interactions between N deposition and CH_4 oxidation rates

Waste disposal

Applied research related to decomposition has confirmed the rapid breakdown of hydrocarbons from oiled beach materials disposed of by deep burial or land farming Recommendations for the disposal of these materials have been developed

ITE research helped demonstrate the crucial importance of mycorrhizas in plant nutrition, particularly in forests and nutrient poor soils.

M Hornung

Plate 1. Clearfelling experiments at Beddgelert forest (in collaboration with the Forestry Commission)

Early studies of forest ecosystem N dynamics quantified the major N pools and the major flux pathways.

Developments in forest soil nitrogen dynamics

The International Biological Programme studies – definition of N pools and cycles

The International Biological Programme (IBP), which took place in the late 1960s and early 1970s, gave rise to a series of large scale, whole system studies in a wide range of natural and semi-natural ecosystems. The UK contribution included three major system studies, plus smaller supporting investigations, managed initially by the Nature Conservancy and subsequently ITE. The three major studies focused on blanket bog at Moor House in the northern Pennines, an upland grassland at Llyn Lydaw in Snowdonia and a lowland deciduous woodland at Meathop on the northern shores of Morecambe Bay. They provided the first detailed quantification of major nutrient element pools and transfers between those pools for semi-natural ecosystems in the UK. The three studies included quantification of the N pools in aboveground vegetation, roots, standing dead litter, soil, soil invertebrates, fungi, in some cases bacteria, sheep, sheep dung, dung invertebrates plus atmospheric inputs and an estimate of leaching losses at some sites (Perkins 1978, Martin & Holding 1978, Heal & Perkins 1976, Brown 1974). The woodland study also included one of the first attempts to quantify atmospheric inputs in detail, including a consideration of aerosol deposition to the canopy (Brown 1974, White & Turner 1970). The blanket bog work included one of the first attempts to estimate N losses via denitrification.

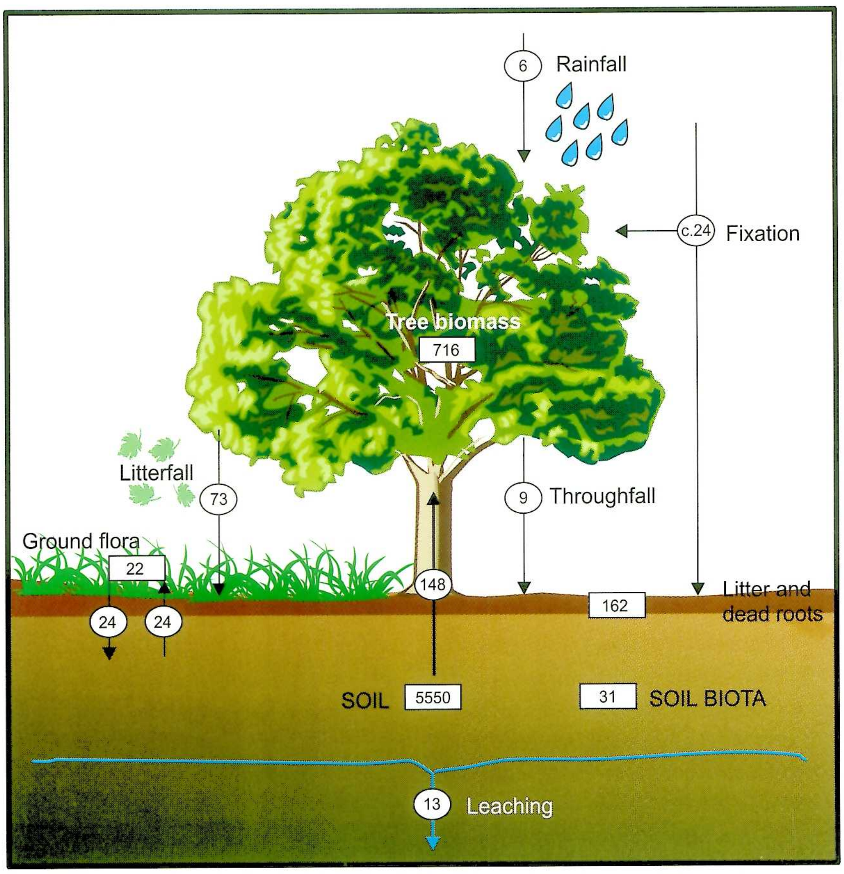


Figure 1. N pools (boxed), kg N ha^{-1}, and fluxes (circled), kg N ha^{-1} yr^{-1} for the Meathop Wood IBP site, Cumbria, (after Brown 1974, Harrison & Ineson 1987) showing the main N reservoirs and fluxes

The data enabled N cycles to be constructed for each of the sites (Figure 1). The results showed a large soil N pool at all the sites with only a small proportion of this pool 'active' and turning over relatively rapidly. The extreme case was in the blanket bog where it was calculated that in the top 30 cm, the 'active' soil organic N pool was only 100 kg out of a total soil pool of 3 400 kg N ha^{-1} (Martin & Holding 1978). The total amount of N in circulation annually in the bog system was estimated at 400–500 kg ha^{-1}, with the cycle between litter, the active pool, the microflora, the ammonium phase and plants probably taking "many years" (Heal & Perkins 1976). There were interesting contrasts between the ecosystems with regard to the pool of N in soil fauna and microflora. Thus, in the upland grassland in Snowdonia there was a larger pool of N in earthworms in the summer than in grazing sheep. The earthworms played an important role in N cycling. In contrast, the blanket bog contained a diverse microflora which also represented a significant pool of N. In the woodland soil the N pools in soil fungi and soil fauna were similar with a much smaller microbial biomass (Harrison & Ineson 1987). The results from all three UK sites suggested that atmospheric inputs of N, c. 2–10 kg N ha^{-1} yr^{-1}, were significant in terms of the annual N budget and similar to losses from the system (in sheep and/or leaching). The latter results were tentative, however, because of the large uncertainties in the quantification of the leaching losses.

In common with many of the IBP studies the range of elements and ions determined at the UK sites was rather restricted and it was not possible to investigate the inter-relationships between ions or the processes controlling solute transfers and leaching losses. The experimental and analytical techniques available also limited investigation of the fate of the atmospheric inputs of N, or more detailed studies of the distribution and transfer between soil pools. The studies were also largely observational and were not built around hypothesis testing. However, the IBP programme still represented a major step forward in the understanding of natural and semi-natural ecosystems and their functioning. The global series of IBP sites also showed that there could be major variations in element transfers and cycling, particularly in forest systems as they aggraded and reached a stable state.

Ecosystem disturbance/clearfelling – the impacts of management on N cycling and transfers

In the early 1970s there was growing interest and concern over the impact of disturbance, particularly forest management, on nutrient cycling and reserves within natural and semi-natural ecosystems. Partly as a result of these concerns a number of large-scale field manipulation experiments were developed, some based on earlier IBP studies, to explore the impact of the disturbance. These studies represented part of the change in field-based ecological research towards experimentation and the testing of hypotheses. There was, in parallel, a shift towards detailed consideration of soil solution and drainage water chemistry, and the processes controlling mobilisation and leaching of elements from soil. This stimulated the development of techniques for sampling soil and drainage waters. A number of manipulation studies focused on the impact of clearfelling mature forest. Perhaps the most famous of these was the study undertaken at the Hubbard Brook experimental catchments in New England, USA (Likens *et al.* 1977). Of particular concern, the results from these studies showed that following felling, a pulse of nitrate was generated within the catchment which was associated with either accelerated leaching of base cations or acidification of drainage waters. In the UK uplands, however, clearfelling was not expected to produce large quantities of nitrate in drainage waters (Heal *et al.* 1982). It was felt that the combination of high C/N ratios in the crop residues, low temperatures and wet, clay-rich soils would limit the mineralisation of organic matter and nitrification, whilst microbial immobilisation would further limit nitrate leaching losses.

Against this background, the Institute carried out three large clearfelling studies, in collaboration with the Institute of Hydrology (IH), Forestry

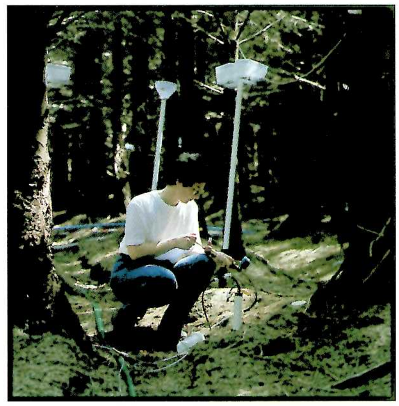


Plate 2. Studying the effects of nitrogen treatments on Sitka spruce at Aber forest (in collaboration with the Forest Authority)

Large-scale field studies showed that forest clearfelling increased nitrate-N losses to streamwaters.

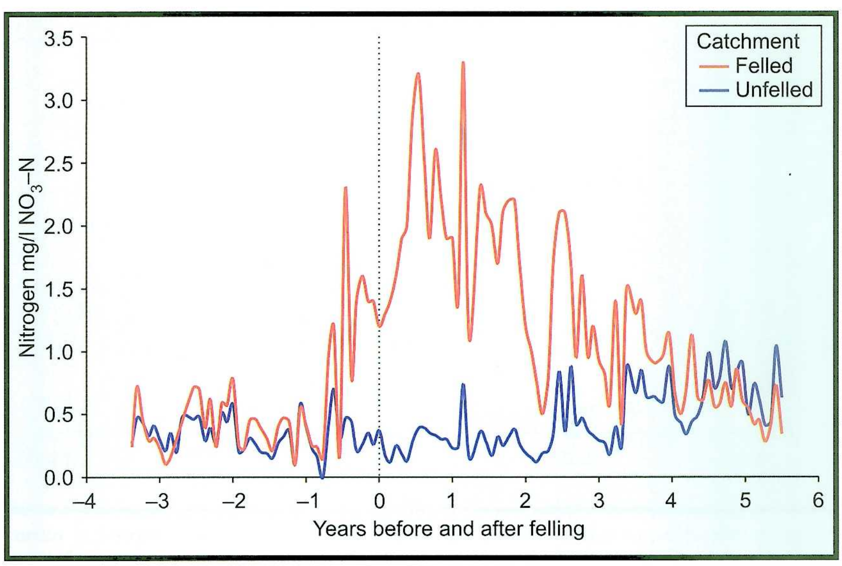


Figure 2. Stream water nitrate response to forest clearfelling in a small catchment at Plynlimon

Commission (FC) and universities, beginning in 1978. They were:

- Kershope in Cumbria (Adamson & Hornung 1990)
- Beddgelert in north Wales (Stevens & Hornung 1988, Stevens *et al.* 1995) (Plate 1)
- Plynlimon in mid-Wales (Reynolds *et al.* 1992).

All three involved monitoring of solute concentrations in atmospheric deposition, throughfall, stemflow, soil and drainage waters. A wide range of ions was measured to allow ion balances to be examined as well as interactions between ions and leaching processes. At all three sites, during the year following felling, nitrate concentrations increased in soil and stream waters draining the cleared forests, reaching a maximum between one and two years post felling (Figure 2). After five years nitrate concentrations at all clearfelled sites had returned close to, or below pre-felling levels. The additional nitrate was found to be caused by higher rates of N mineralisation and nitrification in the soil linked to an increase in soil temperature on removal of the tree canopy and the presence of readily decomposable fine root material. Furthermore, harvesting of the trees removed the vegetation sink for N.

Conventional harvesting practice for upland conifer plantations consists of clearfelling involving removal of the tree stem from the site leaving behind the stumps, branches and needles; replanting follows immediately afterwards. At Beddgelert forest, an experimental whole-tree harvesting treatment was also applied to compare the potential for site nutrient depletion between the two harvesting techniques. The whole-tree harvest experiment and lysimeter studies at Beddgelert forest demonstrated that the main control on the duration of the nitrate pulse was the re-establishment of vegetation, especially if this was dominated by grasses as at Beddgelert (Emmett *et al.* 1991, Stevens & Hornung 1990).

In more peaty soils at Kershope, a significant loss following felling was in gaseous form through the denitrification process (Dutch & Ineson 1990). In contrast to agricultural soils where the product of this process is inert N gas, this study identified the importance of acid forest soils as souces of nitrous oxide – an important greenhouse gas.

A later study of the impacts of clearfelling exploited one of the longest established field experiments under the stewardship of ITE (jointly with the FC) – the forest mixtures study established in Gisburn Forest, north Lancashire in 1954 (Brown 1992). The mixture study had shown that nitrate availability was a major factor influencing differences in growth between the mixtures and that this was linked to differences in the rates of organic matter turnover brought about by microbial and faunal activity. At felling, the results from the pure spruce and pine stands showed similar changes in soil water chemistry to those found in the earlier studies; increases in nitrate concentration but decreases in sulphate and chloride. Under alder, however, the concentrations of nitrate declined rapidly after felling.

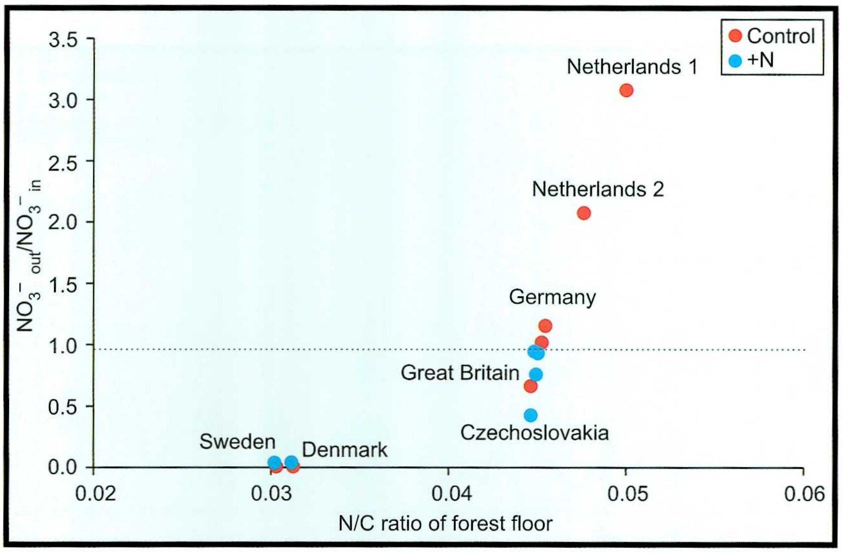


Figure 3. The effect of soil N status (N/C ratio) on the proportion of deposited nitrate leached to streamwater in a series of conifer stands across Europe. The proportion of inputs leached remains constant with respect to the N/C ratio irrespective of experimental N additions (Emmett *et al.* 1998)

Atmospheric N deposition and acidification

The acidification of soils and stream waters by acidic atmospheric deposition was clearly demonstrated in the late 1970s and early 1980s. The main driver was shown to be sulphate although the contribution of nitrate was recognised. However, during the later 1980s, and as sulphur emissions decreased, it became increasingly apparent that the deposition of inorganic N to forest ecosystems was likely to have deleterious consequences for forest health, soil and stream water acidification (Malanchuk & Nilsson 1989). The term 'nitrogen saturation' was coined to describe the condition of forest sites where the availability of N was in excess of the combined demands of the vegetation and soil microbial biomass, as well as other N sinks such as denitrification (Aber *et al.* 1989). As observed in the felling studies, enhanced leaching of nitrate from acidic, aluminium bearing soils results in stream acidification through increased aluminium leaching and a decline in acid neutralisation capacity (ANC). At Beddgelert forest, "nitrogen saturation" was observed in a small catchment dominated by 50-year old Sitka spruce (*Picea sitchensis*). Outputs of inorganic N in the stream, were also observed and, averaged 14.6 kg N ha^{-1} yr^{-1} over the period 1982–1990, compared to average inputs in bulk precipitation of 10.3 kg N ha^{-1} yr^{-1} (Stevens *et al.* 1993). Data from other Institute sites at Plynlimon and Llyn Brianne indicated that younger forests were not 'nitrogen saturated', leading to the hypothesis that conifer plantations become N saturated as they age, due to:

- increased atmospheric inputs of N to the taller canopies
- decreased demand for N by the trees, which, although taller, are no longer building biomass quickly
- increased rates of decomposition and release of N from forest floor litter and/or soil organic matter.

To examine these factors, a study was undertaken of 20 forest stands (all Sitka spruce) of varying ages up to 55 years old, and five moorland catchments. This work confirmed that virtually no nitrate was leached from plantations younger than 30 years, but that leaching progressively increased with stand age (Stevens *et al.* 1994). The main control on leaching was identified as tree uptake in younger stands (<30 years), but in older stands where tree uptake was reduced, the main control was N deposition and the N status of the site (Emmett *et al.* 1995a).

The clearfelling of forests can also lead to short term acidification of waters. Thus, recent analysis of the stream chemistry data from Kershope, Beddgelert and additional small catchment studies at Plynlimon has shown that the nitrate pulse generated at felling is directly and quantitatively linked to a decline in streamwater ANC. However, the decrease in stream water sulphate and chloride concentrations resulting from reduced atmospheric deposition and an increased water flux following felling, offsets the acidification effects of the nitrate pulse. The net acidification, in terms of ANC depression, is therefore finely balanced, and generally barely discernible from natural background variations. Under some circumstances, for example, during the first major rainfall following summer droughts, extremely large nitrate concentrations can be observed in streams draining recently felled sites where there is little or no vegetation cover. This can result in extreme, episodic stream acidification (Neal *et al.* in press).

Further detailed investigations of the processes controlling nitrate leaching from coniferous plantations have been subsequently undertaken, in a major plot scale experiment in Aber forest, near Bangor (Emmett *et al.* 1995b). The objective was to follow the fate and impact of increasing atmospheric N deposition by adding extra N through a forest floor spray system to a 30-year old Sitka spruce stand. The amount of N approximately doubled inputs but still represented only <0.5% of the total N stored within the trees and soil. To enable the fate of the applied N to be followed, the N spray solution was labelled with the tracer ^{15}N, which occurs in very small quantities under natural conditions. The results demonstrated that deposited nitrate was leached through the soil profile and directly contributed to eutrophication and acidification of the drainage waters (Figure 4). In contrast, ammonium was retained in the soil profile, contributing to a build-up of the soil N store.

The results from a series of similar studies conducted across a European N pollution gradient indicated that ammonium also contributes to N leaching in areas with histories of high N deposition loadings. This results from a build-up of the soil N store and the consequential effects on the rate of N cycling by soil microbes. In particular, an acceleration of the process called nitrification results in the transformation of ammonium to the more mobile nitrate form of N and the production of acidity. Combining information on the maturity of the stand, the soil N status and the amount of deposited nitrate and ammonium now enables current N leaching losses to be predicted in stands without extensive monitoring (Emmett *et al.* 1998). These empirical models along with dynamic models

Many forests in the UK are N saturated and additional inputs lead to eutrophication and acidification of the drainage waters.

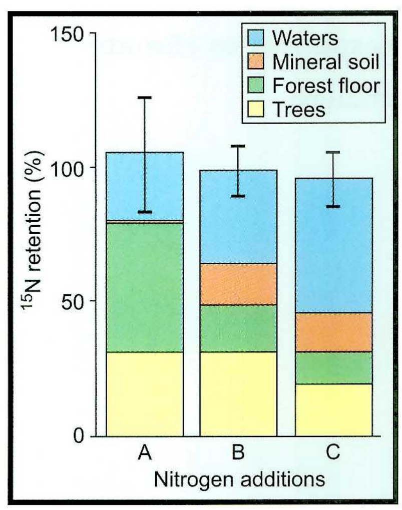


Figure 4. The fate of applied ^{15}N in the Aber forest experiment when applied as ammonium nitrate at (a) 35 kg N ha^{-1} yr^{-1} or sodium nitrate at (b) 35 or (c) 75 kg N ha^{-1} yr^{-1}

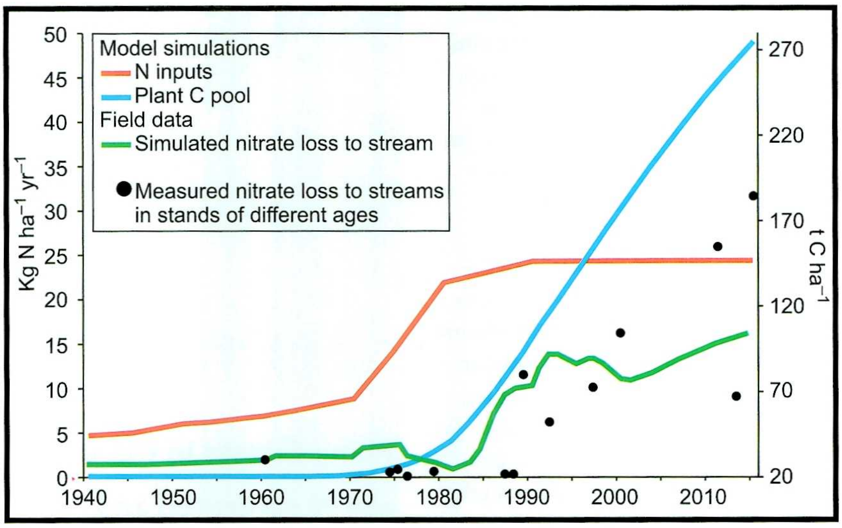


Figure 5. The effect of afforestation and forest growth on nitrate leaching to streamwater, as inferred from a survey of streams draining Sitka spruce stands in Wales of different ages and as simulated by the MERLIN model. The model simulates the nitrate leaching from mature forestes

There are important effects of N deposition on trace greenhouse gas fluxes and ecosystem responses to climate change.

such as MERLIN (Cosby *et al.* 1997), which are currently being developed, have greatly improved the ability to predict the impacts of enhanced N loading (Figure 5).

The lack of any promotion of tree growth due to N additions in the Aber experiment emphasised the absence of N limitation on tree growth due to increased N supply from the atmosphere. Indeed, an earlier study had shown that there was a response to applied phosphorus and hypothesised that the enhanced atmospheric inputs of N had induced a P deficiency. The absence of any negative effects of the N deposition on tree growth at Aber also indicated the tolerance of the major UK forestry tree species, Sitka spruce, to acidification. These results imply that the major concern in the uplands, with respect to impacts of N deposition on acidification, is the impacts on streamwater quality. In the lowlands, however, damage to trees and soils in response to N pollution may also be of concern when stands are located near point sources of N pollution, such as pig and chicken farms. For example, recent studies across natural gradients of deposition, downwind of intensive animal houses have demonstrated high foliar N concentrations but deficiencies of other nutrients, poor tree health, high concentrations of nitrate in drainage waters and soil acidification. This deterioration in tree health and growth can enhance breakdown of the soil N store through changes in microclimatic conditions and lowering of the C/N ratio of the tree litter. This fuels a destructive cycle of tree decline, soil and streamwater acidification (Berg *et al.* 1997).

Future research

New projects are expanding the research into more applied areas, other habitats and to explore the interaction between N deposition and environmental change. Thus, management options for reducing nitrate leaching from upland forests are being investigated, for example by managing stand structure to encourage ground flora, thus providing an additional sink for N.

Studies in Wales are assessing the impacts of N deposition on deciduous woodland and upland acid grasslands. The woodland research combines field survey and experimental studies. The grassland project is a major experimental study in mid-Wales. Preliminary results from the acid grasslands parallel those from the earlier forest study, with N added, as nitrate leaching but ammonium-N being retained. N deposition may also influence the flux of greenhouse gases. Examination of the relationship between methane oxidation and nitrate availability in soils, is suggesting depression of the oxidation in the presence of free nitrate. Work using solar domes is exploring the impacts of interactions between soil and plant N status and atmospheric CO_2 concentrations on decomposition rates and nutrient cycling. Current results suggest that N status is a key factor. In the absence of adequate available N, decomposition rates of litter from a high CO_2 environment are reduced compared with those of litter from ambient CO_2.

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Future research will focus on ecosystem eutrophication resulting from excess N deposition.

Plate 1. Forest/agriculture interface – on the margins of tropical forest in Brazil

Tropical forestry and agroforestry

Background

ITE Edinburgh Research Station was originally established in 1969 as a separate Institute of Tree Biology within the Natural Environment Research Council (NERC), to study fundamental problems in forestry both in the UK and overseas. After amalgamation into ITE in 1974/5, this station exploited its forestry expertise to address ITE-wide customer-funded issues concerning acid deposition, land use and climate change and, at the same time, developed a research programme on sustainable forestry and agroforestry in the tropics. The tropical research evolved in line with NERC policy to support overseas development, largely through the Department for International Development (DFID, formerly ODA). The aim is to provide underpinning generic information to help meet UK overseas aid objectives – most recently defined in the White Paper, *Eliminating World Poverty (DFID 1997)*.

Since 1974, ITE staff have worked in approximately 15 developing countries on forestry-related issues and five staff have been seconded to work in the tropics for 1–3 years (Figure 1). Work in the field has been supported by studies in tropical glasshouses and growth rooms at ITE Edinburgh, and by training.

The work has involved collaboration with most of the major international agencies supporting overseas research and with about 30 organisations in developing countries, most notably International

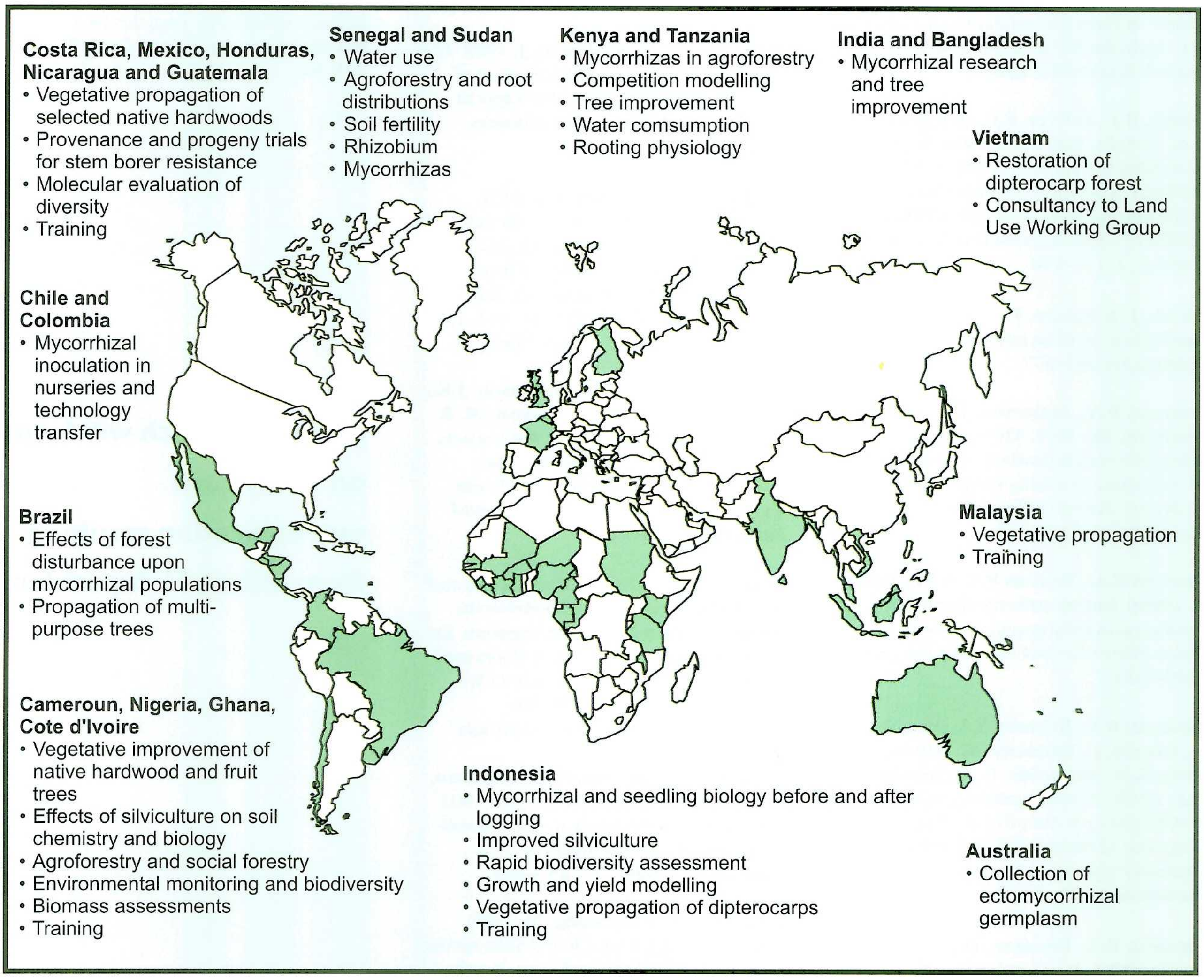

Figure 1. Country focus of the ITE Tropical Forestry Section at Edinburgh

Centre for Research in Agroforestry, (ICRAF, Kenya), Kenya Forestry Research Institute, (KEFRI, Kenya), Centro Agronómico Tropical de Investigación y Enseñanza, (CATIE, Costa Rica), Institut Sénégalais de Recherches Agricoles, (ISRA, Senegal), Institut Français de Recherche pour le Développement en Coopération, (ORSTOM, Senegal), Office National de Dévéloppement des Fôrets, (ONADEF, Cameroon), Centre for International Forestry Research (CIFOR, Indonesia) and Instituto Nacional de Pesquisas da Amazônia, (INPA, Brazil). In 1991, ITE co-founded the Edinburgh Centre for Tropical Forests (ECTF) – a consultancy, research and training consortium with the University of Edinburgh, Forestry Commission, Edinburgh Royal Botanic Gardens and LTS International Ltd.

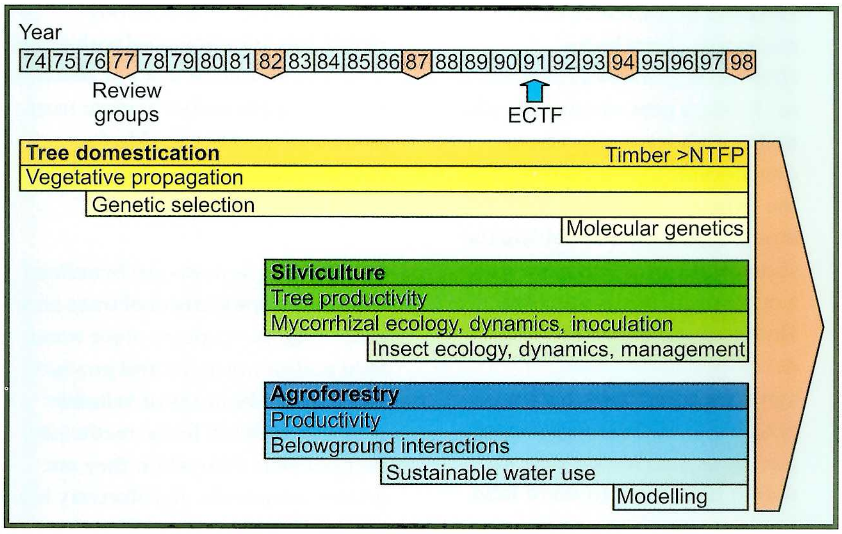

Figure 2. Development of ITE research themes in tropical forestry and agroforestry since the Institute of Tree Biology was amalgamated into ITE in 1974/75. NTFP are Non-Timber Forest Products and ECTF is the Edinburgh Centre for Tropical Forests

Issues and research themes

The overall aim has been to provide information and techniques that will reduce deforestation and environmental degradation. The approach has been to focus on ways to diversify man-made ecosystems and to improve the productivity of tropical forests and agroforests, so creating an incentive for better land management (Plate 1). There have been three main research themes, as shown in Figure 2.

- There has been a long-running programme of work on the "domestication" of indigenous tree species, including the development and dissemination of methods of vegetative propagation and early selection for growth and quality traits.
- The work on domestication has been carried through to improving *methods of tree establishment* in the field, exploiting microsymbionts, and determining optimal methods of forest logging and silviculture – most notably in DFID aid programmes in Cameroon and Indonesia.
- A research programme has developed on *tree-crop interactions* in agroforestry systems aimed at identifying optimal tree-crop combinations and practices.

In the past work on tree domestication has focussed on tropical hardwoods, but currently there is also an emphasis on trees producing non-timber forest products, many of which have been extracted from natural forests. About 1.5 billion local people (24% of the world population) depend on such trees for many of their daily needs that includes food and nutritional security, health and cash generation. The socioeconomic and policy issues surrounding domestication and commercialisation of non-timber forest products and Third World development issues, have been a focus of work since 1996–97 (Leakey & Tomich in press).

In recent years, three specific scientific initiatives have been developed (Figure 2).

- Molecular methods (RFLPs, RAPDs and microsatellites) have been used successfully to partition genetic diversity within natural populations of mahogany and other tropical tree species – providing guidelines for selection and conservation (Gillies *et al.* 1997).
- Studies of insect pests have led to the identification of host genetic

ITE has a major research commitment to sustainable tropical forest management and agroforestry.

ITE's tropical research has recently launched scientific initiatives in molecular genetics, insect pest ecology and ecosystem models.

variation in resistance to the mahogany shoot borer (*Hypsipyla grandella*) (Newton *et al.* 1998), a pest which currently makes mahogany plantations uneconomic throughout most of the tropics. These new genetics-based approaches to solving the shoot borer problem have led to a new international initiative.

- Mathematical models have been developed to simulate agroforestry systems, making it possible to address many more questions over longer periods than it is possible to do in field experiments.

Below, we present new findings from our research on agroforestry, starting with some basic concepts.

Agroforestry – some basic concepts

ITE research has had an impact on the way agroforestry is now viewed by international aid and research agencies and has contributed to the direction of the international research agenda (Sanchez *et al.* 1997). Whereas once it was regarded simply as a collective name for land use systems in which woody perennials are integrated with crops, it is now viewed as a set of practices which progressively integrate trees into farming systems, akin to succession in natural ecosystems (Leakey 1996).

Agroforestry systems are beneficial when the combination of trees and crops together capture more water, light and/or nutrients and produce more useful biomass or valuable products (timber, fruits, medicines, etc) per year than when they are grown separately. Agroforestry is a low input approach to the sustainable production of trees and crops. The benefits are both environmental and socioeconomic, including opportunities for poverty alleviation (Leakey & Simons 1998), the development of novel food crops (Leakey 1998a), and for increasing the biodiversity in agroecosystems (Leakey 1998b). In the biophysical domain, one of the hypotheses in favour of agroforestry boils down to a central tenet that "the benefits of growing trees with crops occur only when the trees are able to acquire resources of light, water and nutrients that the crops would not otherwise acquire" (Cannell *et al.* 1996). The problem is that, although the total resource use may be increased, some of the resources used by the trees are acquired at the expense of the crop so that the risk of crop failure may be increased. The objective is to define soil-climatic conditions and tree-crop combinations and systems that maximize resource use while minimizing tree-crop competition.

In agroforestry systems in the tropics, trees more often compete with crops for water and nutrients than for light. Particular effort has, therefore, been directed to define the nature of tree-crop competition belowground, using models, field observations and experiments.

Observations in the Sahel

Using very deep soil cores, it has been established that some trees in semi-arid regions send roots to the water table at over 30 m depth. Furthermore, there are N fixing bacteria at that great depth. Clearly, these tree species can withdraw water from the water table when the surface soil is dry. This lessens competition with crops, but the amount of water abstracted from the water table must not exceed the recharge rate, which may be no more than 15 mm per year, otherwise village water supplies may be jeopardized. Thus, it is important to determine whether tree species differ in water use.

Water use by individual trees has been measured directly, using sapflow gauges, on sunny days in the dry season in Senegal. *Acacia mellifera* and *A. laeta* were found to use more water *per unit leaf area* than *A. macrostachya* (a woody shrub) or *Prosopis juliflora* – which is a fast-growing exotic in Senegal (Figure 3). Sap flow in the latter two species began to decline in mid-morning, well in advance of maximum air temperatures and solar radiation, suggesting that their root systems were unable to supply enough water to satisfy atmospheric demand.

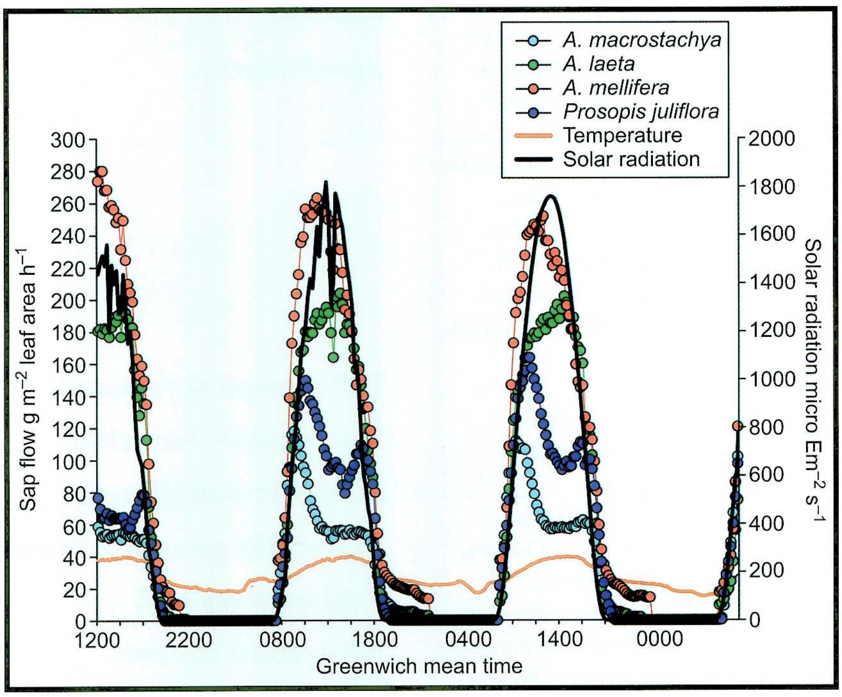

Figure 3. Direct measurements of the transpiration of trees over three days in Senegal, expressed as sapflow in the trunks per unit leaf area, shown in relation to solar radiation and air temperature. Data for three indigenous *Acacia* species are compared with an exotic *Prosopis* species and show that although the shrubby *Acacia macrostachya* used least water, the exotic species *Prosopis juliflora,* used less water than the other indigenous trees

Experiments in Kenya

Field experiments are in progress in a semi-arid climate in Kenya (Machakos, *ca.* 700 mm bimodal rainfall) with ICRAF to explore below ground interactions between trees and crops. Eight tree species were planted in 1993, as single lines across large plots (18 x 18 m), including a treeless control and interplanted with beans in the short rains (October–December) and maize in the long rains (March–June) (Plate 2). Just two years after planting, bean yields in the short rains 1995/96 were reduced by the presence of trees and in the following year the bean crop failed completely when less than 150 mm rain fell during the short rains (Figure 4). Crop yields did not approach those of the control plots again until the 1997/98 short rains, when there was higher than average precipitation of about 650 mm.

Belowground studies focussed on the trees silky oak (*Grevillea robusta*) and *Gliricidia sepium*. Root distribution, dynamics and function were all considered in conjunction with those of the crop roots. About 85% of bean roots occurred in the top 40 cm of soil compared with 63% of maize roots. Although tree root length density varied greatly from one rainy season to another, for both tree species, the zones of maximum root density were in the surface layers of soil, and overlapped with those of the crops. *Gliricidia* generally had greater root length density than *Grevillea,* particularly in the upper soil layers. Nevertheless, there was also extensive rooting of the tree species beneath the crop zone, so there was at least some potential for complementarity in root activity. Studies of sap flow (Figure 5) showed that during the dry season, the tap roots supplied about 80% of the water lost in transpiration by trees, whereas, in the wet season surface tree roots rapidly became active (before substantial amounts of new root could have developed) and contributed most of the water lost in transpiration (Ong *et al.* in press). Hence, regardless of tree root architecture, root activity can switch rapidly from one rooting zone to another to exploit zones of greatest moisture availability.

These results confirm that complementarity between trees and crops, exists up to a point as water is partly extracted below the crop rooting zone. However, the capacity of tree roots to switch their zones of activity suggests that as long as tree and crop roots overlap in their distribution, there will be competition for resources when the surface soil is wet.

Trees as reservoirs of mycorrhizal fungi

Although there is strong evidence of belowground competition between trees and crops, there are also beneficial interactions. Arbuscular mycorrhizal (AM) fungi form symbiotic associations with both trees and crops and, because such fungi tend to be non-specific, most trees and crops in the tropics commonly share the same AM fungi. Studies in Kenya demonstrated that maize plants became more extensively mycorrhizal near to trees which in turn resulted in the production of greater numbers of AM spores in the surrounding soil for future crops. In Senegal, considerable variation was observed in the amount of AM infection and inoculum associated with different tree species

Plate 2. Line planting system at Machakos, Kenya. *Grevillea robusta* trees planted with maize, showing strong competition in the first row

Although there is strong evidence of belowground competition between trees and crops, there are also beneficial interactions.

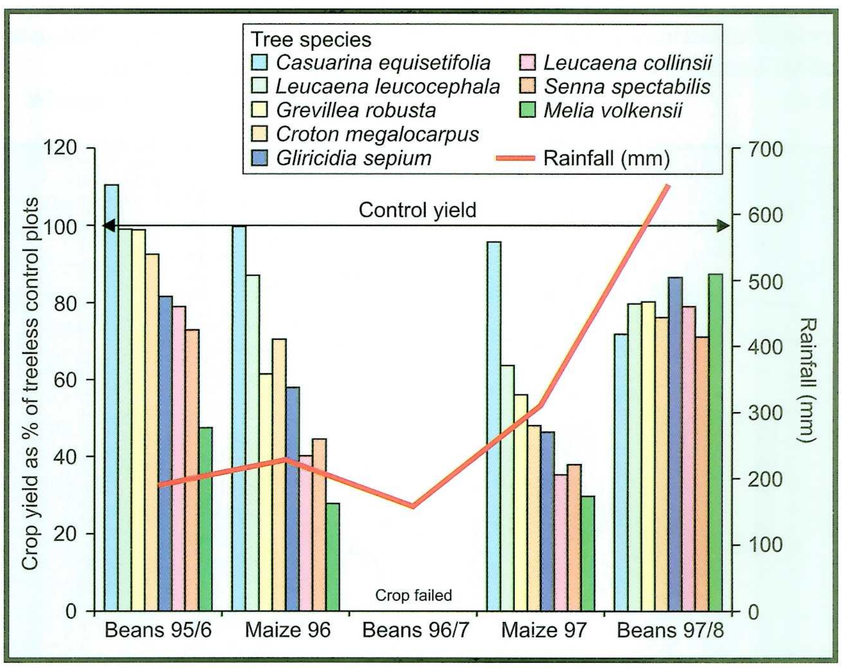

Figure 4. Yields of intercrops in an alley-cropping experiment at Machakos, Kenya, with hedgerows of different tree species. Beans are grown in the short rains (Sept–Dec) and maize in the long rains (March–July). Crop yields (histograms) are shown in relation to rainfall (points and line) in each cropping season. Crop yield was reduced by the presence of some tree species more than others and was also determined by the seasonal rainfall

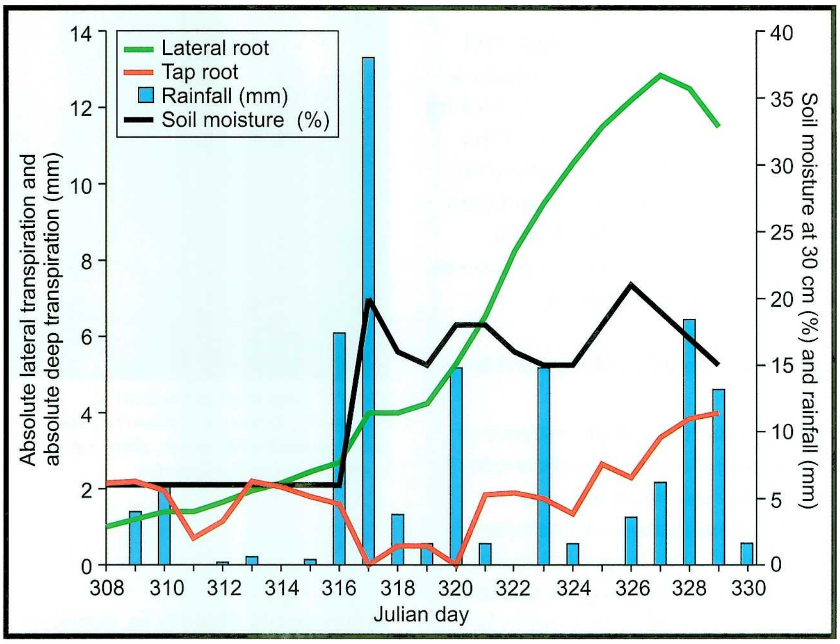

Figure 5. Rainfall (histograms) at the start of the short rains at Machakos, Kenya, showing the sudden increase in wetting of the surface soil and a large increase in the amount of water taken up by the lateral roots (compared with the tap root) of *Grevillea robusta* trees. Sapflows were measured directly in the lateral and tap roots

(Ingleby *et al.*, 1997), and soil collected from under tree species with the most inoculum produced the greatest infection and growth of millet plants. These studies suggest that trees in agroforestry systems provide a perennial reservoir of inoculum for interplanted crops and indicate the potential benefit to crop yield of maintaining large amounts of AM inoculum in alley-cropping soils.

Work in Cameroon and Cote d'Ivoire has demonstrated that forest clearance can lead to a short-term fall in the abundance of mycorrhiza. However, amounts of AM inoculum can soon recover when weeds colonize sites or when crops are planted. Longer-term changes in the species composition of AM spore populations also occur following forest clearance (Mason & Wilson 1994). However, the consequences of such changes for subsequent tree and crop growth are still unknown.

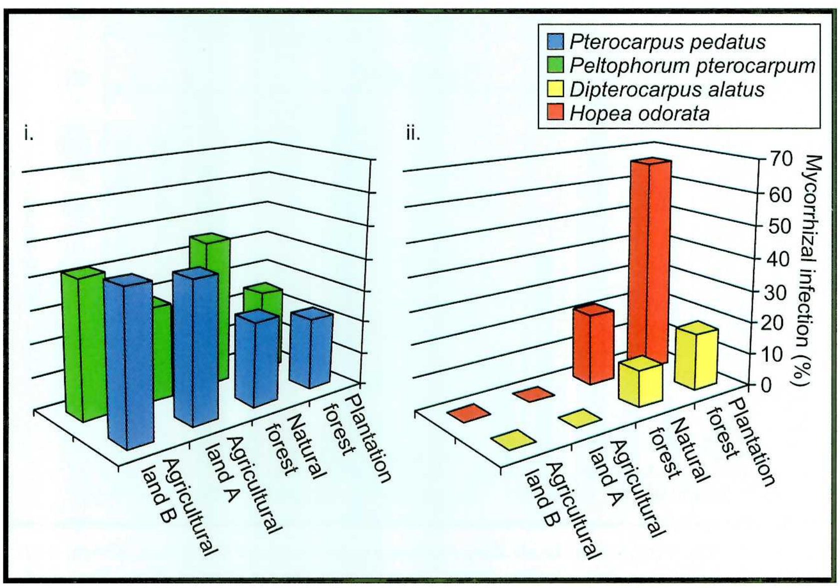

Figure 6. Mycorrhizal inoculum present in soils in Vietnam assessed from the extent of infection on plant roots 5 weeks after planting. Four indigenous tree species, *i.* arbuscular mycorrhizal, *ii.* ectomycorrhizal, were grown in soil from 4 sites with different land use histories

Several important groups of tropical timber trees like Dipterocarps in SE Asia form associations with ectomycorrhizal (ECM) fungi. Work in Indonesia has shown that ECM populations are severely depleted by logging and that more careful logging methods are needed to minimise losses of ECM fungi (van Gardingen *et al.* 1998). In Vietnam, ex-agricultural sites scheduled for reafforestation possessed adequate amounts of AM inoculum but were devoid of ECM fungi (Figure 6). These studies indicate that ECM fungi are more sensitive to disturbance than AM fungi and that the re-establishment of ECM tree species will require that nursery seedlings scheduled for outplanting are adequately mycorrhizal.

Agroforestry modelling

The simplest agroforestry systems to model are sequential ones, where cropping alternates with years of forest fallow, during which soil fertility is restored. The full rotation has two components:

- the 'cycle length' in years of cropping plus tree fallow
- and the fraction of years in each cycle occupied by trees as opposed to crops.

A model was constructed, based on *Acacia* and sorghum, which simulated the accumulation of soil organic N during a tree fallow period and its depletion during cropping. Optimal values of the two components occurred because the rate of increase in soil organic N slowed as the tree fallow progressed, until a time was reached when the benefits in subsequent crop yield of further soil improvement were outweighed by crop yield foregone. The optimum cycle was about 50 years with half the time in trees, which implied that current tree fallow periods may be too short – gaining short-term benefits at the expense of long-term sustained yield (Mobbs & Cannell 1995).

A more ambitious generic, process-based model is under development, which combines a forest and crop model to simulate agroforestry systems.

This has been used to estimate 50-year mean potential sorghum grain yields and overstorey tree annual net biomass productivities in climates ranging from arid Mali to the humid Nigerian coast (Cannell *et al* 1998) It was concluded that, in regions with less than about 800 mm rainfall, simultaneous agroforestry may enable more light and rainfall to be captured than sole cropping, but is unlikely to increase total site productivity without jeopardizing food security One reason is that, in dry climates, C3 trees have very low water use efficiencies compared with C4 crops such as sorghum However, in such dry situations, increased site productivity/ economic yield can occur where tree roots are able to tap the water table, or where trees improve soil fertility and/or where trees produce biomass of high value, which they undoubtedly can These factors are included in the latest versions of the model

The future

Many of these studies are ongoing, and are developing in line with priorities identified by DFID, and the international community

New work planned in Senegal, Burkina Faso and Mali will aim to minimise competitive effects of trees on crops by defining tree-crop combinations where competition is least Research will also focus on identifying useful trees which use water sparingly, and that possess small root competition indices Further studies on rooting depth and the source and extent of subterranean nitrate are also planned

In Indonesia, a biophysical model of tree competition is being applied to growth and yield data from SE Asia to examine the implications of differing harvesting strategies for long-term forest sustainability In Kenya previous agroforestry work will be followed by studies of crown and root pruning, which respectively reduce overall transpiration demand and tree root activity in the crop rooting zone In Cameroon emphasis is being placed upon the evaluation of socioeconomic aspects of forestry and agroforestry, and work has already commenced on a project to investigate the opportunities and constraints faced by farmers investing in planting and improvement of indigenous trees

A further need will be to investigate tree-crop interactions on a farm or catchment scale, in much more complex mixtures, and with multiple strata canopies These pose research challenges more associated with forest ecology than with agronomy

M G R Cannell, J Wilson, J D Deans, G J Lawson, D C Mobbs and R R B Leakey

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Future research aims to integrate biophysical models of tree-crop competition with field experiments on water use and nutrient cycling.

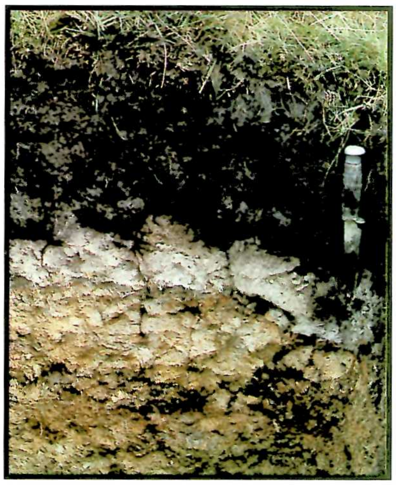

Plate 1. Typical upland soil profile showing organic and mineral horizons

ITE has maintained an international reputation for research into soil biodiversity and the functional significance of soil organisms.

Biodiversity and function: soil ecology research in ITE

Since its inception, ITE has maintained an international reputation for research into the ecology of soil biodiversity. The first ITE Annual Report of 1974 contained numerous articles about the ecology of soil organisms, with a strong conservation perspective. The papers ranged from the effects of sheep grazing on the beetle fauna of chalk grasslands, through to assessments of the effects of human trampling on major groups of soil invertebrates. Detailed studies on the autecology of a number of soil animals were described and the reader was provided with rare glimpses into the life-cycles of specific organisms. However, an understanding of the importance of these organisms to the functioning of the ecosystem was rarely considered at that time.

A section in the same report described some of the activities of the pot-worm (*Cognettia sphagnetorum* – an Enchytraeid), illustrating how it intimately burrowed into leaf litter as it selectively fed on carbon-rich detritus with low crude fibre content. ITE staff had identified this worm, in terms of biomass, as the most abundant animal in the peat areas of the Pennines, reaching populations of up to 200 000 m^{-2}, with a mass approaching 5 g m^{-2}. For comparison, the biomass of sheep on the site averaged 3.2 g m^{-2}. It was apparent that management treatments which increased or decreased the activity of this worm could be as important as those which altered the grazing intensity of the sheep. These pot-worms are clearly extremely important in these systems but, again, the question was left open as to exactly what they did in functional terms.

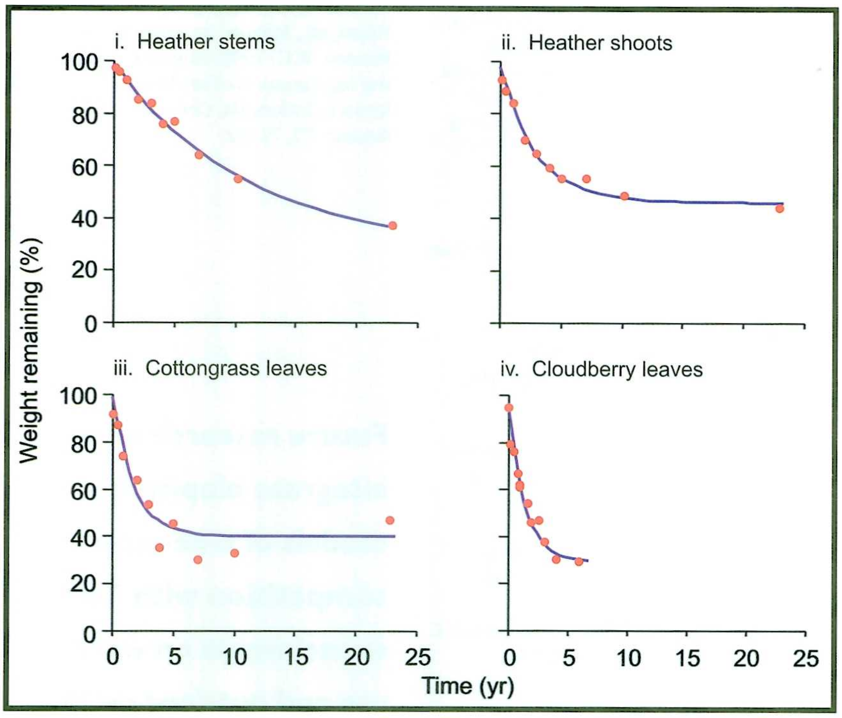

Figure 1. Decomposition curves for four types of litter decomposed on a Pennine moorland. Note that the relationship for long-term decomposition over time is an asymptotic curve and not an exponential decline as predicted from shorter-term studies. The implication is that this model predicts a greater amount of inert organic material will remain

At that time, studies of the decomposition of leaf litter by ITE soil ecologists were amongst the first quantitative investigations of decomposition rates in the field. This led to the establishment of the worlds' longest decomposition experiment, running for 23 years (Latter *et al*. 1998). Figure 1 shows the results of this work, with the surprising conclusion that samples taken after short-term intervals provided misleading data on the long-term fate of the litter. Such detail is extremely important when modelling potential carbon storage in soils, particularly within the context of current debates on sequestration of excess carbon dioxide from the atmosphere.

With hindsight, we can see the emerging struggle to relate the early detailed autecological studies to the ecological processes for which the organisms were responsible. Much research was carried out on the autecology and role in the ecosystem function of the millipede (*Glomeris marginata*), the earthworm (*Lumbricus terrestris*) and the decomposer fungus (*Mycena galopus*) (Satchell 1983, Frankland 1984). However, linking the fascinating detail of the thousands of soil organisms and the complex environment (Plate 1) to the essential ecosystem services that these organisms provide, still remains a major challenge today (Royal Commission on Environmental Pollution 1995).

One of the first attempts to integrate diversity and function came from the International Biological Programme (IBP) project at Meathop Wood, co-ordinated by ITE. By assembling, for the first time, unique and complementary datasets on the biomass of soil micro-organisms and the energy balance for this Cumbrian woodland, it became obvious that the 'books' simply did not balance. New techniques for counting and assessing soil microbial biomass by direct observation (eg fluorescent staining, phase contrast microscopy, 'Jones and Mollison' slide techniques; see, for example, Frankland *et al.* 1978) revealed the incredible disparity between traditional plate counts and the actual numbers of micro-organisms present in soil. The new estimates of soil microbial populations were too large to be supported by the energy coming into the system, with the inevitable conclusion that the majority of soil micro-organisms must be starved for most of the year. Information on the energetics and efficiency of fungi and bacteria, largely gained from laboratory culture, was almost irrelevant in this context, and this research opened the eyes of microbial ecologists around the world to how micro-organisms live in soil.

These data also indicated that the unculturable species vastly exceeded the tiny proportion of species that could be grown on petri dishes. New techniques were clearly needed to unravel these discrepancies and to increase understanding of the functional role of organisms within the soil. One such technique involved the development of a specific monoclonal antibody for detecting mycelium of the fungus *Mycena galopus*, a key litter decomposer in north temperate forests, in field material (Figure 2). A long-term investigation, originating from the IBP, used a variety of approaches to understand this particular fungus, and how it becomes established and distributed in soils and litters. We also now appreciate the community status and nutrient cycling role of this organism and how it interacts with other biota in the forest floor (Frankland 1982, 1998, Hitchcock *et al.* 1997).

It has taken a revolution in molecular techniques in the 1990s to side-step the need for traditional culture methods. Work within ITE has developed the application of new DNA analyses for distinguishing mycelia of fungal decomposers in simple mixed communities (Conway 1998). Soil is now recognised, along with tropical rainforests, as the habitat showing the highest undiscovered biodiversity (National Science Foundation 1994).

Five years after the publication of the first Annual Report, in 1979, recommendations from the Advisory Board for the Research Councils led to an increase in geochemical cycling studies. The recognition of the need to understand the behaviour of soils in terms of the chemical and physical sciences swung the research pendulum from basic observations on the ecology of soil organisms, to a more quantitative assessment of ecological systems. ITE was rapid to respond to these recommendations and the resulting

Figure 2. Novel monoclonal antibody-fluorescence technique applied to visualise the location of hyphae of the fungus *Mycena galopus* in decomposing spruce litter. This soil fungus plays a key role in decomposition in many forest and woodland soils. Diameter of hyphae: approximately 2.5 mm (Frankland 1978)

It has taken a revolution in the application of molecular techniques to soil biodiversity, to avoid, artifacts produced by plate culture methods.

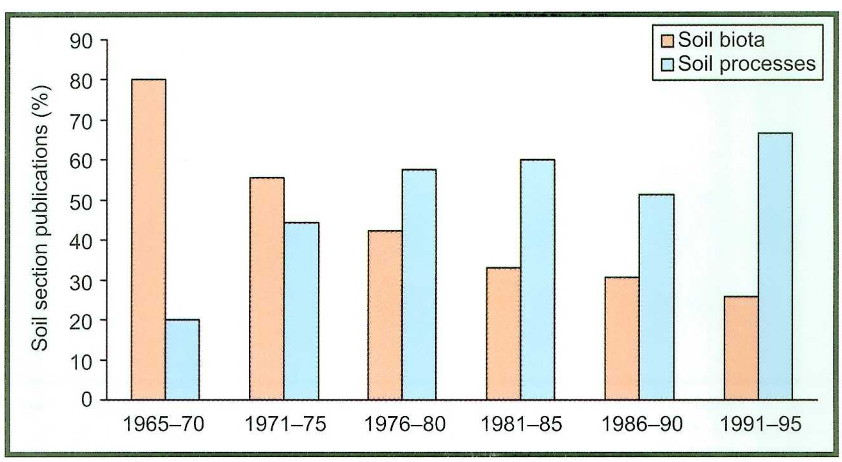

Figure 3. Analysis of publications arising from the Soil Section at ITE Merlewood between 1965 and 1995

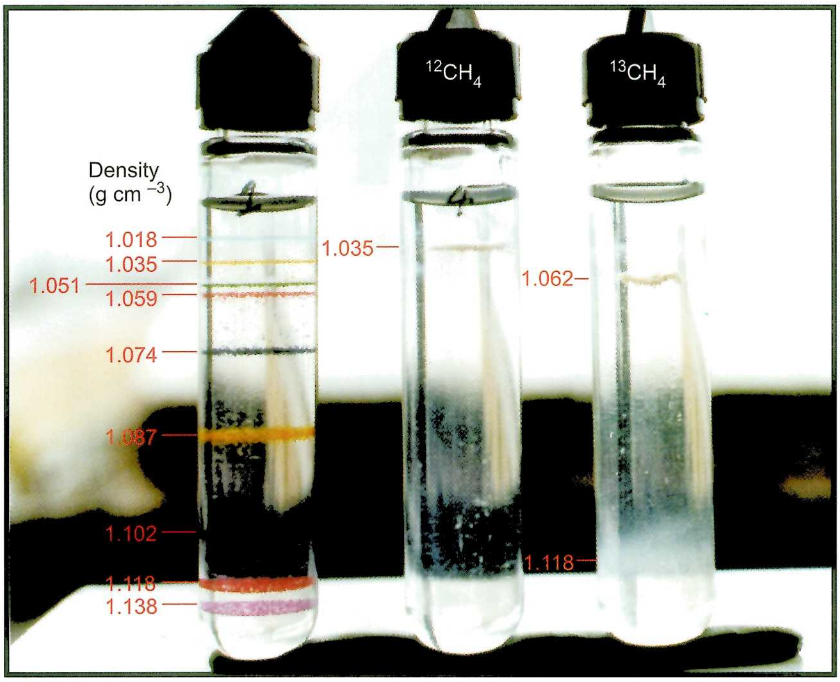

Figure 4. Use of density centrifugation to separate methane oxidising bacteria (methanotrophs) utilising isotopically labelled $^{13}CH_4$. The tube on the left contains density marker beads; the other tubes contain a pure culture of the methanotroph *Methylomonas methanica* S1 grown under either unlabelled or labelled CH_4

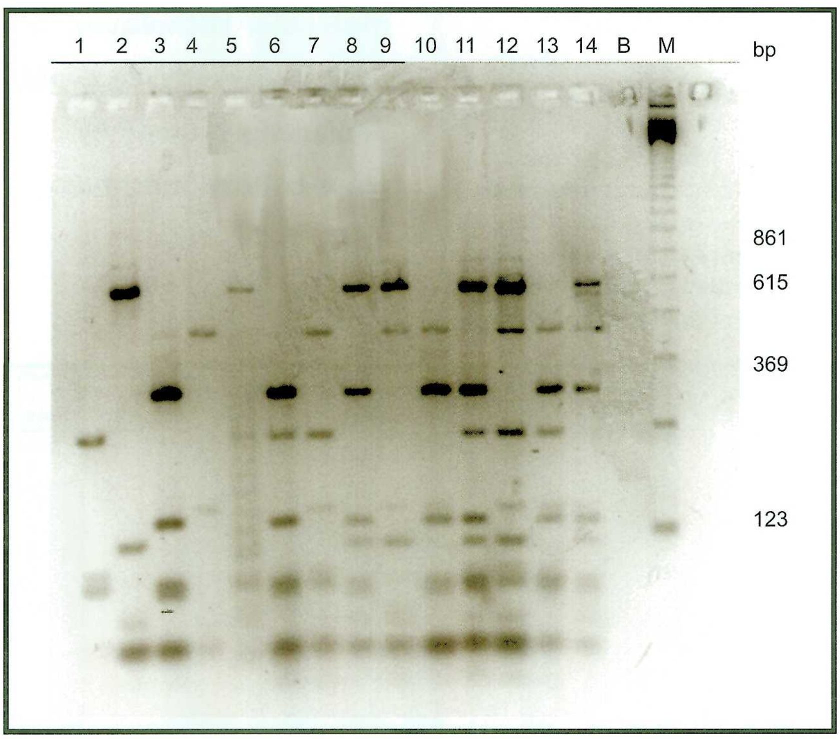

Figure 5. Restriction digests of PCR-amplified rDNA ITS region of mixtures of selected soil fungi. Lane 13 shows a digest from a mixture of *Chaetomium globosum; Mucor hiemalis* and *Agrocybe gibberosa;* lane 14 is identical except that *Chaetomium globosum* has been replaced by *Sphaerobolus stellatus*. The technique is being used to identify individual species within simple species mixtures

changes in emphasis are reflected in the profile of published research within ITE. For example, Figure 3 reflects these changes showing a breakdown of publications from the Soil Section at ITE Merlewood, classified into studies on soil processes and studies on the organisms responsible. The trend is clear and, in some senses, regrettable. The initial emphasis on characterising the soil biota, developing the painstakingly slow understanding of the jigsaw of species within the soil, was replaced by an emphasis on processes. The 'black box' approach was adopted, with more interest in the overall functioning of soil systems, rather than interpreting the role of individual species or organisms within the system. At the time, this re-direction of approach was necessary but now it is clear that studies of soil organisms and processes should go hand-in-hand.

The 1980s were characterised by a keen interest in chemical ecology, with the realisation that the impact of man on natural ecosystems through the release of novel organic chemicals and the global disruption of inorganic biogeochemical cycles, was both globally pervasive and non-trivial. Soil organisms were among the suite of impacted organisms, with observed changes in soil microbial and faunal populations and activity being frequently related to pesticides and air pollutants. During this period ITE staff were involved in a host of applied projects, from demonstrating the high accumulation rates of fluoride by woodlice (*Isopoda* spp.) and millipedes, the toxic effects of sulphur dioxide on specific soil fungi, through to helping decontaminate the anthrax polluted soils of Gruinard Island. They also produced the first major review on the scientific principles of soil protection in the UK (Howard *et al.* 1989). The few detailed studies on individual soil organisms revealed the importance of specific mycorrhizal fungi in maintaining tree productivity, with inoculation being shown to be an important potential management option in certain situations. Mycologists within ITE quantified the important role of mycorrhizae in nutrient uptake by trees using novel field isotope approaches (Dighton *et al.* 1990).

The 1990s brought a new global environmental concern; the causes and potential impacts of climate change. The importance of this issue was marked by the establishment of the NERC funded Terrestrial Initiative in Global Environmental Research (TIGER) programme. Soils were considered to have a central role, as major sources and sinks of the 'greenhouse' gases. Work funded under TIGER within the Institute quantified the role of soils in the release of nitrous oxide and the consumption of methane, whilst identifying the positive interactions between elevated CO_2 and other trace gases (Ineson *et al.* 1998). The TIGER programme clearly identified the importance of methane consumption by soils as a major component of the global methane cycle, highlighting our inability to isolate the key organisms involved. It appears that the organisms responsible for methane oxidation, at low atmospheric concentrations, belong to the group of unculturable soil bacteria. New techniques, utilising the carbon isotope ^{13}C, are being applied to the separation and characterisation of these methanotrophs. The ability of these bacteria to utilise artificially enriched $^{13}CH_4$ as a principal carbon source is being used to produce dense cells that can be isolated on a density gradient (Figure 4).

Work under TIGER also demonstrated that plant materials grown under elevated CO_2 frequently decomposed more slowly. New DNA techniques have been developed to identify the soil fungi involved (Figure 5). A major

Plate 2. The impact of warming treatments on the dissolved organic carbon in water. This is due to changes in the behaviour and activities of pot-worm (*Cognettia sphagnetorum*) an enchytraeid which accelerates litter decomposition in warmer soils

ecosystem warming experiment also demonstrated the large losses of carbon that would result from anticipated climate change in the UK uplands, implicating pot-worms in the observed effects. Not only is the population size and behaviour of this organism dramatically affected by small changes in surface soil temperatures, but the burrowing activities of this animal play a major role in the production of coloured water draining from these important catchment areas (Plate 2). The fundamental studies reported in the ITE Annual Report 1974, are underpinning our understanding of specific environmental questions relevant to the next Millennium.

Ecosystem warming experiments have shown greater peat decomposition and organic matter loss into surface waters.

Plate 3. Sub-culturing soil bacteria on Agar plates in a sterile laminar flow cabinet

Plate 4. Purification of DNA extracted from soil in the molecular microbiology laboratory

Recent research using stable isotopes and molecular methods, has characterised the methane oxidising bacteria in soils that remove this important trace greenhouse gas from the atmosphere.

So, what can we expect over the next 25 years? For the Institute, we are confident that the international reputation for soil ecological work will continue. The recent award to ITE of management responsibility for the £6 million NERC Thematic Programme on Soil Biodiversity will ensure that the Institute is at the leading edge of active research in this area. The Institute is also now responsible for investigating soil biodiversity across the UK, linking into the current Countryside Survey 2000. A project assessing soil biota associated with contaminated land in urban environments has been initiated as part of the NERC Urban Regeneration and the Environment (URGENT) Thematic Programme. Advances are also being made in the use of bacterial biosensors in soil to assess the toxicity of common aromatic pollutants, utilising genes cloned from marine bioluminescent bacteria into the genome of terrestrial bacteria (Boyd *et al.* 1997) (Plate 3). ITE scientists are using soil fauna to evaluate soil contamination, with the responses of earthworm lysosome membranes and immune systems being developed as soil diagnostic tools (ITE 1997). There is clearly remarkable potential in the use of the soil biota in the evaluation of soils and the development of quantitative indices of soil health.

Plate 5. Application of mass spectrometry to analysis of stable isotopes in environmental samples at ITE Merlewood

In more general terms, we can be confident that the polymerase chain reaction (PCR) technique will become a vital complement to the petri dish in soil microbiological studies (Plate 4). Novel multi-substrate utilisation test systems (BIOLOG plates) will enable the study of the functional diversity of the microbial community and are currently being used to assess the impacts of intensive agriculture on soil bacteria. Stable isotopes are also playing an increasing role in tracing trophic interactions in soils, with carbon and nitrogen transfers being followed by the use of the 'heavy' isotopes ^{13}C and ^{15}N at enriched and natural abundance levels (Plate 5). Recent technical advances in the analysis of both soil organisms and soil organic matter using solid-state Nuclear Magnetic Resonance and individual compound mass spectrometry are enabling the fate of carbon in soil to be closely tracked.

The role of specific organisms in processing soil organic matter will become clear and central to the manipulation of soil populations as a fundamental component within soil remediation or improvement programmes Perhaps most important of all, the genetic diversity within soil organisms will be exploited for both industrial and *in situ* processes The soil will become increasingly recognised as a fundamental resource of long-term environmental quality

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