Contents

CEH research programmes

Three events during the past year are already influencing, and will continue to influence the soils research within the Institute:

- ***restructuring of the science programmes within CEH***
- ***publication of the Royal Commission on Environmental Pollution's report* Sustainable use of soils**
- ***investment in staff and laboratory facilities for the application of molecular approaches in work on soil biota and biologically mediated processes.***

Soils

The addition of microbiological laboratories and expertise to existing ITE facilities for stable isotope, radionuclide, inorganic and organic chemical analysis, means that the Institute is well equipped for strategic and applied research across a broad range of soil-related topics.

The restructuring of the CEH science has created the programme on soils and soil/vegetation interactions. This is the first time that there has been a separate programme devoted to soil research within the Institute – an acknowledgment of the key role of soils in a number of the current environmental concerns, such as global change, pollution impacts and sustainable development. However, the whole of the soils-related research within CEH and ITE is not included within this programme. Rather the programme aims to bring together the strategic work on soil processes which underpins the topic or problem-oriented soils work carried out within a number of the other science programmes. The Royal Commission has stressed the need for research on these key processes. Programme 1 is divided into three main projects:

1.1 Physico-chemical processes affecting soil/water interactions
1.2 Biologically mediated soil processes
1.3 Physical and physiological processes controlling soil water balances.

The three articles presented here illustrate aspects of work in all three areas.

Decomposition of plant litter in soil is a key process controlling the cycling of nutrients in ecosystems and the accumulation of carbon in soils. Our ability to understand the functioning of ecosystems, and to predict and assess the impacts of pollution and global change on the sustainable functioning of these systems and on carbon budgets requires a knowledge and understanding of decomposition processes. Many studies have looked at decomposition of plant litters over the short term but the article by Howson reports a unique, 23-year study of the decomposition of three different plant litters at a site in the northern Pennines. It is the longest investigation of the decomposition of non-woody litter carried out to date.

The results show variations in the rate of decomposition over time and that extrapolation of the trends from short-term studies to make long-term predictions can lead to erroneous conclusions. They also show that, after 23 years, between 33% and 50% of the litter remained to form peat and accumulate carbon.

Atmospheric deposition of nitrogen has increased considerably in north-west Europe over the past 20 years, and there is considerable concern about the impacts on the functioning of terrestrial ecosystems and on linked aquatic systems. The second article by Emmett *et al* reports on a study, part of a large Europe-wide investigation, of the impacts on forest soils. It has clearly shown that the system under study has a finite capacity to utilise the deposited nitrogen and that current inputs to the study forest in north Wales are very close to that capacity. A significant proportion of any nitrogen added above that capacity was readily leached and, in the acid soils, mobilised aluminium, with potentially damaging consequences on aquatic biota. Emissions of 'greenhouse gases' from the soils also increased. The capacity of a system to utilise atmospheric inputs of nitrogen has been referred to as the critical load, a concept used in calculating acceptable levels of pollutant emissions. This study is helping to improve our understanding of the processes controlling the system response to increased nitrogen deposition and our ability to quantify the critical load.

The uptake of nutrients and water by plants from soil is controlled by a complex of below- and above-ground processes. Below ground, competition between roots for nutrients and water is a major influence on plants growing in mixtures. Agroforestry systems are seen as potentially sustainable sources of food, timber and fodder products. However, root competition between the tree and food crop plants can adversely affect the growth and production of one or both of the species. The third article by Deans *et al* considers the impacts of a number of factors, including root competition, on bean production in an experimental agroforestry system in Kenya. It shows a clear reduction in yield of beans growing close to one species of tree but a smaller impact by a second species. The study also underlines the complexity of the interactions between the tree and food crop. Later phases of the study will include detailed assessments of root growth and turnover.

As already noted, the soils research within the Institute is linked to a number of important, current environmental issues. The nitrogen study reported here is only one of a series of studies supporting the development and application of the critical loads concept in the UK and more broadly within Europe. Other pollution-related work is, for example, studying the controls on the mobility and transfer of radionuclides in terrestrial ecosystems, the degradation of pesticides, the influence of land use on heavy metal mobility, and the safe disposal, linked to biological remediation, of contaminated soils. Studies related to global change are investigating the controls on trace gas emissions from soils, quantifying soil carbon stocks and determining the influence of land use and climate change on these stocks. Studies such as that reported from Kenya are providing the underpinning science for the development of sustainable land use systems.

Our ability to understand how ecosystems function, and to predict and assess the impacts of pollution and global change requires knowledge and understanding of decomposition processes.

ITE studies are providing the underpinning science for the development of sustainable land use systems.

M Hornung

Long-term study of rates of decomposition

As concern grows about the anthropogenic emissions of CO_2 and the global carbon (C) cycle, attention is turning to terrestrial stores of C and how they can be protected or enhanced. The UK is one of the signatories to the Framework Convention on Climate Change and, as such, is committed to produce an inventory of terrestrial stores of C in the UK, and to protect these stores. These inventories have recently been compiled; they reveal the overwhelming importance of peats as soil C stores in the United Kingdom (Howard *et al.* 1995), and signal the need for more information on rates of peat formation and degradation.

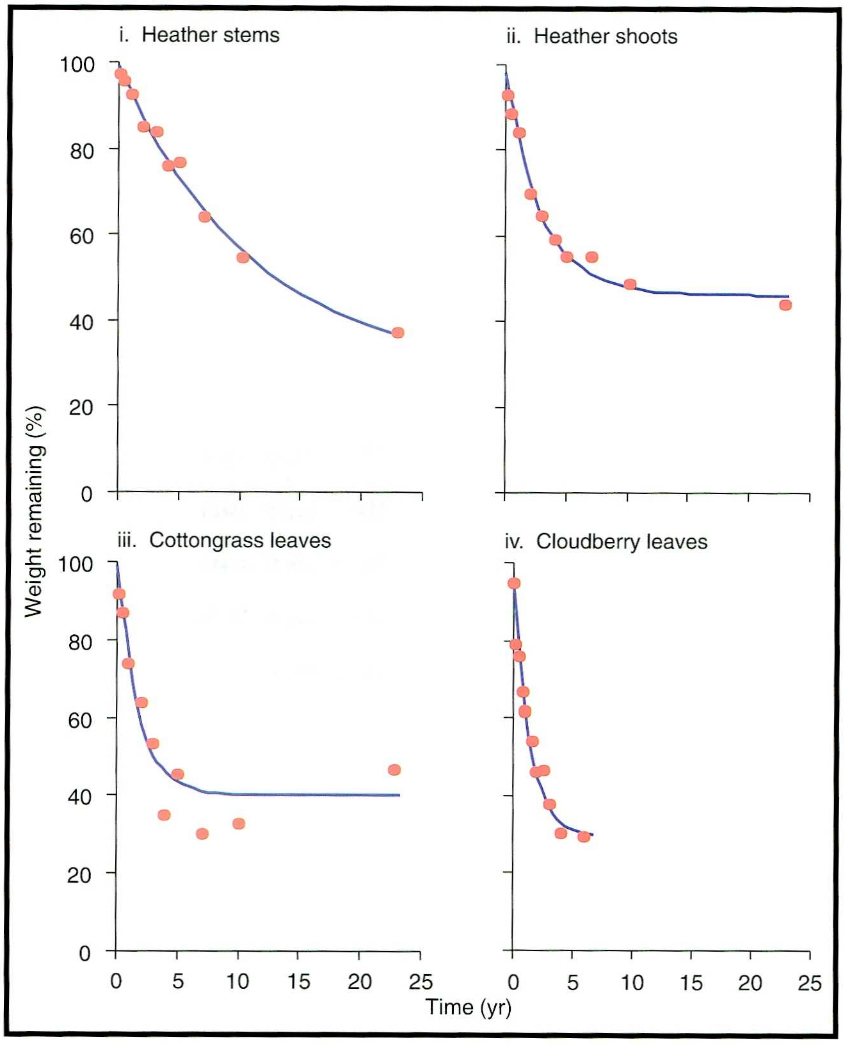

Figure 8. Decomposition expressed as % mean weight remaining for heather and cottongrass over 23 years, and over six years for cloudberry leaves (asymptotic curves fitted)

Peat is principally composed of partially decomposed plant remains, accumulated as the result of the imbalance between C gain in plant production and loss through decomposition; net accumulation rates of peats in Britain are commonly around 0.8–1.4 t ha^{-1} yr^{-1} (Clymo 1983). Although models of the process of C accumulation and peat development have been produced, no long-term decomposition data are available for verification. Most of the world's existing data on decomposition, in any terrestrial ecosystem, report on the early stages of decomposition (usually around one year, maximally three years), and estimates of the long-term dynamics of decomposition have been based on modelled extrapolation from these short-term studies. We report here on the results of what may be the longest decomposition experiment ever performed, established in 1966–67 at the Moor House National Nature Reserve in the northern Pennines (Plate 1) as part of the International Biological Programme; the peat at the site is approximately 1 m deep.

Samples of the dominant vascular plant species on the blanket bog at the site – heather *(Calluna vulgaris)* shoots and stems, hare's-tail cottongrass (*Eriophorum vaginatum*) leaves, and leaves of a deciduous herb, cloudberry (*Rubus chamaemorus*) – were collected, air dried, sorted and placed in appropriate litter bags (Plate 2). The samples were then placed back in the field, in as near-natural conditions as possible, and the positions carefully noted to facilitate retrieval in future decades. Samples were retrieved at intervals over a 23-year period, with the exception of cloudberry leaves which had lost 73% of their original weight by year 6.

Variation between replicate samples increased during the 23 years, with some samples remaining almost intact while others were almost totally decomposed. At the end of the experiment, samples were being retrieved at depths of 14–15 cm in the peat, representing the rates of peat accumulation over the 23 years (Table 2). Detailed notes were made throughout the experiment of surrounding plant cover and the depth of the located samples in the peat profile. For the first four to five years, samples were retrieved annually, and more infrequently as the experiment continued. Samples were stored below 5°C prior to sorting and measurements made of weight remaining.

The weight remaining (WREM) of a litter sample over a time period is a useful integrated measurement of mass loss and includes losses due to respiration, leaching of soluble organic and inorganic matter, and the removal of material by soil fauna. WREM data are most frequently modelled using an exponential rate of weight loss over time and are currently used in many of the models of C cycling (eg Parton *et al.* 1987). These simple exponential equations most easily describe the weight loss data derived from short-term decomposition studies, but generate unrealistic outputs over the long term because of the assumption of almost complete decomposition of all litters. It is therefore important to identify more accurate equations to model the long-term process of litter decomposition, because it is over

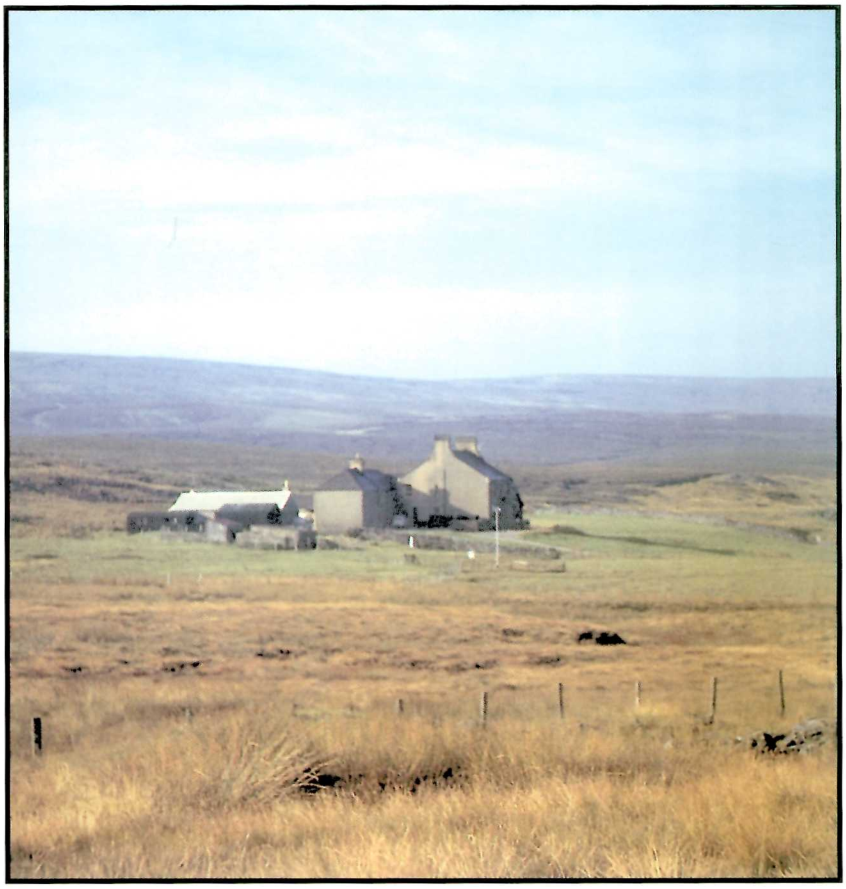

Plate 1. Moor House National Nature Reserve

long periods that major C sinks, such as peats, are important.

Figure 8 shows the mean weight remaining for the various litter types, and demonstrates that the initial litter quality is very important in determining decomposition rates. Decomposition was fastest for cloudberry leaves and slowest for heather stems. The data also show that decomposition of heather shoots and cottongrass leaves almost ceased after eight–ten years, and accounts for the accumulation of these tissues in peat.

There was great variability in decomposition rates within the four litter types, as well as between them, which may be explained by both initial resource quality and the initial position of the individual replicates. Differences in local

Results from the world's longest-running decomposition experiment throw into question existing models.

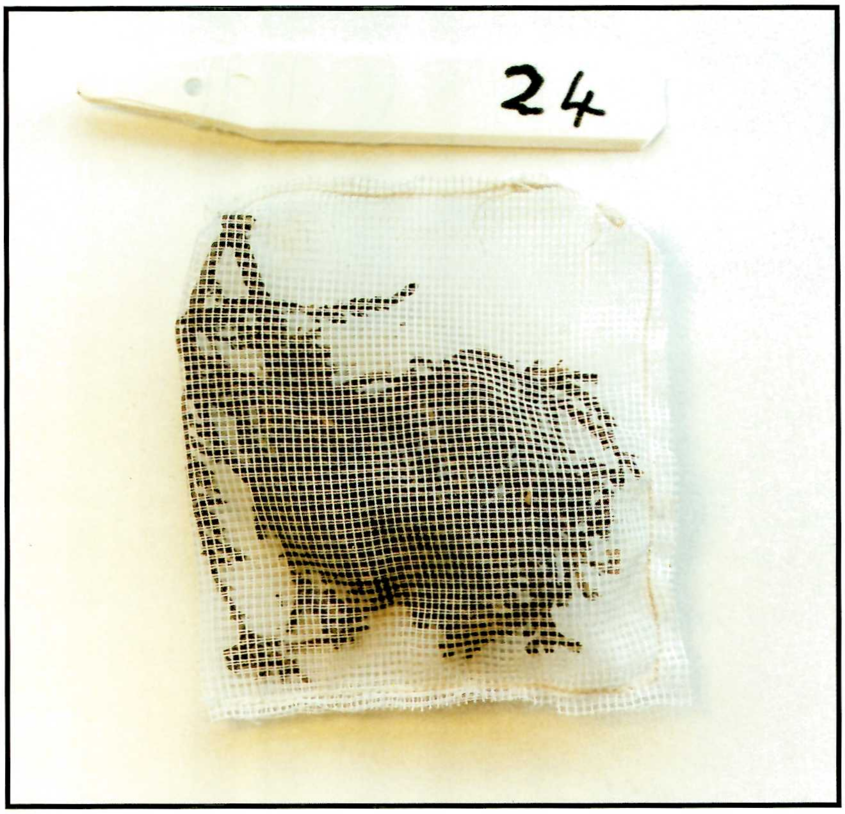

Plate 2. Litter bag used for heather shoots in the long-term decomposition study at Moor House

Table 2. Mean depth (cm) of the decomposed samples in the peat profile after 23 years for heather and cottongrass, and six years for cloudberry leaves (SEM=standard error of the mean)

	Depth (cm)	SEM
Heather shoots	15.39	1.34
Heather stems	12.57	1.37
Cottongrass leaves	14.07	1.21
Cloudberry leaves	4.33	0.67

microtopography have a strong effect on microclimate which, in turn, has a strong effect on decomposition rate.

This long-term study has shown that existing global models of plant litter decomposition rate need to be modified if C accumulation rates in peats are to be estimated correctly. Existing models would not predict the large amounts of original plant litter remaining at these sites after 23 years (up to 50%), neither would they predict the observed cessation of weight loss. The contribution of litter remains in the accumulation of peat needs to be more accurately modelled because these soils represent one of the major C stores of the world (Gorham 1991).

G Howson

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Global models of plant litter decomposition rate need to be modified to estimate carbon accumulation in peat correctly.

Nitrogen dynamics in forest soils

The increase in atmospheric deposition of nitrogen in the UK and across Europe can cause acidification and eutrophication of soils in semi-natural ecosystems. Both are undesirable because of soil-mediated changes upon vegetation composition and streamwater quality. Other potential undesirable soil-mediated effects include a positive feedback on the net flux of 'greenhouse gases' from soils. Working together with European partners, ITE has been investigating the implications of enhanced nitrogen deposition as nitrate or ammonium on upland coniferous soils and the potential effects of these changes on both vegetation and surface waters.

Nitrogen can be deposited in either oxidised (NO_x) or reduced (NH_y) form as derived from industrial or agricultural sources. This nitrogen may be:

- assimilated into the trees,
- taken up by soil microbes,
- adsorbed on to the soil exchange complex,
- leached into drainage water, or
- transformed by microbes to gaseous forms of nitrogen and lost from the system (Figure 9).

It is generally difficult to follow these pathways because of the relatively small inputs of atmospheric deposition compared to the large pools of N in the soil and vegetation.

However, the stable isotope ^{15}N, which represents approximately 0.366% of the total N pool, can be accurately determined using mass spectrometry. Therefore, small changes to this pool, following application of ^{15}N-enriched nitrogen, can be more closely monitored enabling the fate of deposited nitrogen to be traced into the different soil and vegetation pools. This approach has been used to determine the relative impacts of oxidised and reduced nitrogen in a mature Sitka spruce (*Picea sitchensis*) stand in N Wales.

Trends in nitrogen fluxes

Each week ^{15}N-enriched nitrate-N or nitrate-N + ammonium-N was sprayed on to the forest floor of a spruce stand for one year following eighteen months of unlabelled nitrogen applications. Nitrogen applications represented a minimum of 125% increase in N deposition, simulating deposition loading currently observed in parts of The Netherlands and central Europe.

After one year, the ^{15}N enrichment in all soil and vegetation pools was determined and ^{15}N loss in collected drainage waters calculated. Results indicated that the trees retained 20–30% of incoming nitrogen, whilst 10–50% was retained in the forest floor horizons, depending on the mixture of nitrogen form applied. The lower mineral soil retained less than 10% of applied ^{15}N. The remaining nitrogen applied (27–56%) was leached directly into drainage water and was equivalent to the nitrate-N component of applied nitrogen only.

These results were compared to those observed by our European partners in experiments established across a nitrogen

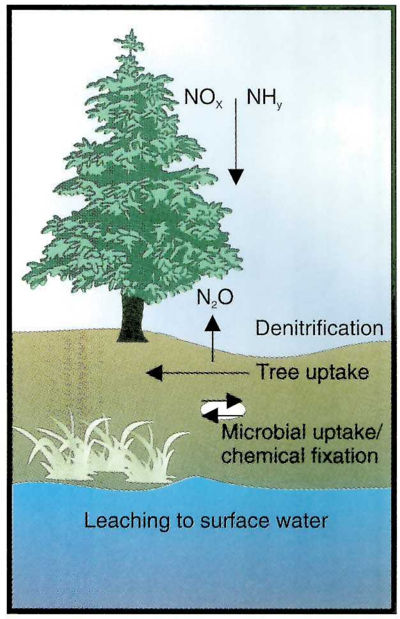

Figure 9. Fate of atmospheric nitrogen deposition in coniferous forests

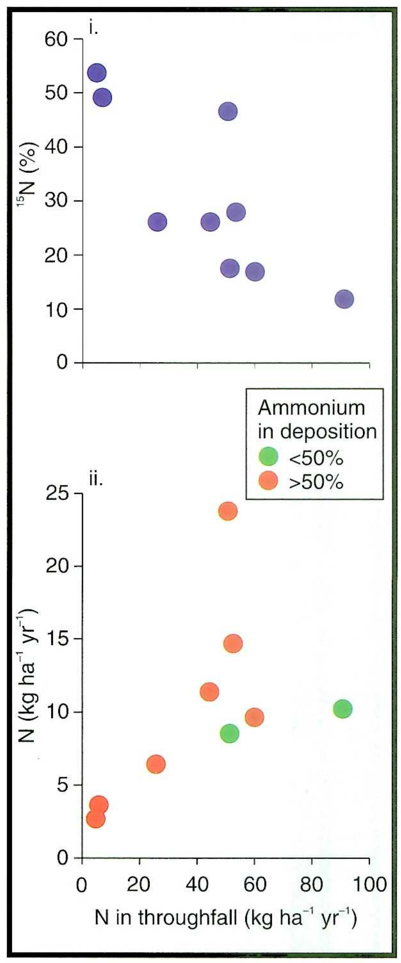

Figure 10. The amount of ^{15}N immobilised in the forest floor as (i) a percentage of inputs and (ii) flux

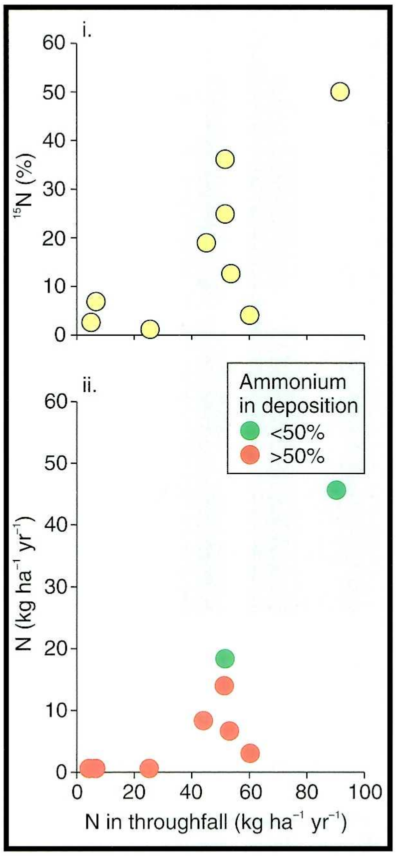

Figure 11. ^{15}N lost in drainage water after one year of application expressed as (i) a percentage of inputs and (ii) flux

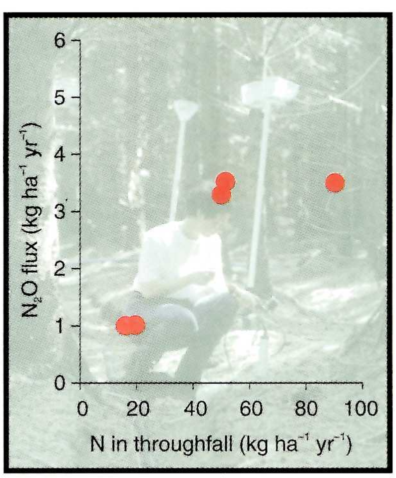

Figure 12. N_2O losses in relation to N in throughfall in a Sitka spruce stand in N Wales

deposition gradient from low-deposition countries in Scandinavia to high-deposition areas in The Netherlands. Retention of incoming ^{15}N in the soil was observed to decline from 75% to 20% of inputs, as nitrogen in throughfall increased from 5 kg ha^{-1} yr^{-1} to 90 kg ha^{-1} yr^{-1} (Figure 10i) This, however, represented an increase in absolute nitrogen retention from approximately 5 kg ha^{-1} yr^{-1} to 20–30 kg ha^{-1} yr^{-1} (Figure 10ii).

Maximum retention capacity was dependent on the form of nitrogen applied, with lower retention of only 20 kg ha^{-1} yr^{-1} if nitrogen was deposited as nitrate rather than ammonium (Figure 10ii). A major consequence of declining retention of N in the soil relative to the increase in N in throughfall was an accelerated loss of incoming nitrogen to drainage water, both in relative and absolute terms (Figure 11) (NITREX *et al.* 1996).

Leaching losses increased from 2% to 55% on inputs (or <1–50 kg N ha^{-1} yr^{-1}). This increase is due to saturation of the various sinks within the forest stand and accelerated nitrification rates in soils which have become enriched with nitrogen after prolonged exposure to high N deposition loadings (Emmett, Stevens & Reynolds 1995). The nitrification process can both mobilise nitrogen from the soil store and reduce the retention of incoming ammonium.

Emissions of trace greenhouse gases

Recovery rates of applied nitrogen within the trees, soil and drainage waters indicated that gaseous loss was not a large sink for incoming N at the Welsh site. This result was confirmed independently by measuring gaseous fluxes from the forest floor using gas sampling chambers. N_2O losses were 0.5 kg N ha^{-1} yr^{-1} under ambient conditions, increasing to only 3–4 kg N ha^{-1} yr^{-1} when exposed to a range of N deposition rates (Figure 12). As N_2O is an important greenhouse gas, there is a small, but positive, feedback between nitrogen pollution and production of this gas. No evidence of net changes in soil methane or carbon dioxide fluxes were observed.

Conclusion

These results indicated that increases in atmospheric-N deposition to European coniferous stands on similar soils are contributing directly to both enhanced nitrate leaching and increased net flux of an important greenhouse gas. New work is planned which will compare these responses in coniferous forests to those in non-afforested areas of the uplands.

B A Emmett, D Sleep, S A Brittain, C Quarmby

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Agroforestry in the semi-arid zone – a complex mix of above- and below-ground interactions

(This work is partly funded by the Overseas Development Administration)

In semi-arid regions, to satisfy their needs for timber and non-wood products, resource-poor farmers increasingly grow trees as well as crop plants on their farms. Thus, of necessity, the farmers are practising agroforesters, and for sustainability their practices need to be based on sound ecological principles. Some of the traditional agroforestry systems are extremely successful, and the *Faidherbia albida* traditional low-input/output parkland agroforestry system found in the semi-arid tropics is considered one of the most extensive and sustainable forms of tropical agriculture (Vandenbelt 1992). Attempts to introduce newer and potentially higher-yielding agroforestry techniques into semi-arid regions have so far met with little success. The greatest disappointments have occurred in systems where trees and crops occupy the land simultaneously, such as in alley cropping. Crop plants alone are incapable of utilising the entire annual rainfall (Ong, Black & Marshall 1996), and so, in these simultaneous systems, the assumption is that the presence of trees will enable fuller use of available water, thus increasing total productivity. In addition, it is expected that the presence of trees will also improve crop yield by improving soil fertility and microclimate. However, in practice, any overall increases in production have been associated with reduced crop yield through competition with the trees for light, water and nutrients. Even where early results with both indigenous and exotic tree species have shown promise, good initial crop yields have tended to decline as trees grow larger, usually within two or three years of tree planting (ICRAF 1995).

Most agroforestry studies have focused on competition for resources above ground, and have neglected the importance of below-ground competition which is crucial in drylands. In particular, although several authors have examined the spatial non-dynamic distributions of tree roots *vis-à-vis* their apparent suitability for simultaneous agroforestry, scant attention has been given to ecological principles, and the dynamics and functioning of roots have been largely ignored because of the formidable problems in both measurement and interpretation (Van Noordwijk & Purnomosidhi 1995). Where trees and crops simultaneously occupy land, knowledge of the dynamic interactive aspects of their growth phases and phenologies, both above and below ground, is an essential prerequisite for

The farmers are practising agroforesters, and for sustainability their practices need to be based on sound ecological principles.

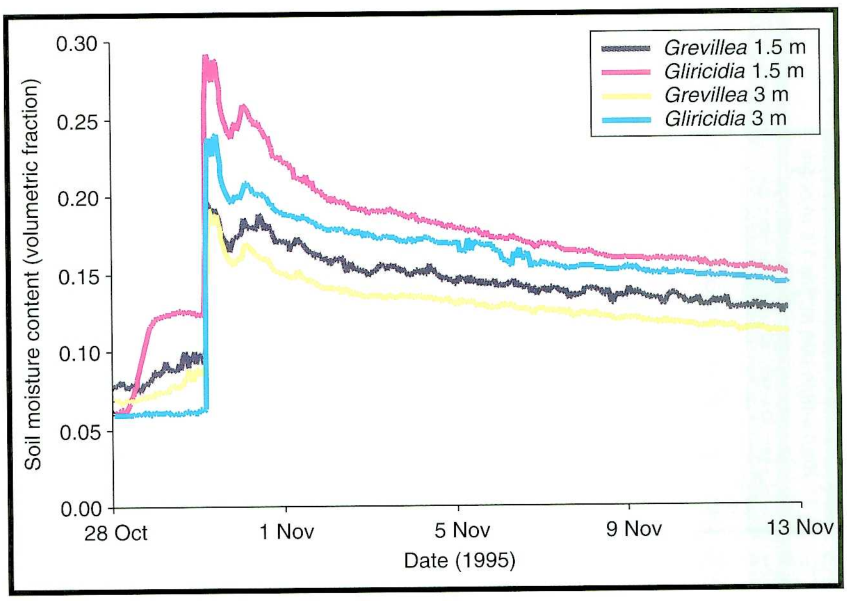

Figure 13. Soil moisture in 9 m x 9 m plots containing single (central) rows of *Grevillea robusta* and *Gliricidia sepium* trees immediately after the onset of the rains at Machakos in Kenya. Observations were made at 20 cm depth at distances of 1.5 m and 3 m from rows of trees

Plate 3. The competitive effect of trees on maize in an agroforestry alley cropping trial in Kenya. In stark contrast to plants in rows spatially separated from *Gliricidia* trees, maize plants close to trees have grown poorly and have wilted in the sunshine around mid-day

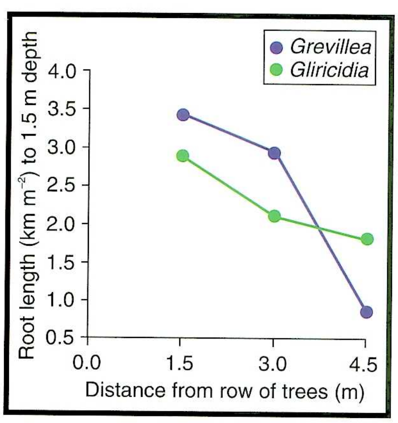

Figure 14. Total length of fine roots of *Grevillea robusta* and *Gliricidia sepium* recovered to a depth of 1.5 m at distances of 1.5 m, 3 m and 4.5 m from rows of trees in linear agroforestry plantings in Kenya

understanding competition. Failure to take dynamics into account is probably responsible for the overall lack of success in developing agroforestry mixtures, and for the conflicting results obtained for the same mixtures at different times and locations.

We have recently begun examining water use, root growth, root distributions, phenologies of trees and associated crops, and the dynamics of their interactions in a collaborative study with the International Centre for Research in Agroforestry (ICRAF) in Kenya, at the Machakos Field Station. Competition with crops by two tree species, *Grevillea robusta* (evergreen) and *Gliricidia sepium* (deciduous) is being examined. The former is widely planted by farmers and considered to be much less competitive than the latter. Because the site at Machakos is relatively fertile, below-ground competition is largely for soil moisture rather than nutrients.

Machakos has bimodal rainfall distribution, receiving an average of 315 mm between October and January and about 345 mm between March and May. Beans (*Vicia faba*) were planted immediately after the first rain in October 1995. At that time, *Gliricidia* was leafless, and greater soil moisture recharge took place in plots containing *Gliricidia* than in plots containing *Grevillea* (Figure 13). Interestingly, and with both species, recharge at 1.5 m from the trees was greater than at 3 m from trees and also differed consistently with aspect, being greater on the northern than southern sides of the rows of trees. However, overall rainfall in this first cropping season (205 mm) was only about 65% of the long-term average.

Not unexpectedly, beans germinated faster, survived better and had greater early growth rates in the wetter parts of the plots. Growth was poorest close to the trees. Similar effects of the trees on a subsequent maize crop can be seen in Plate 3, where poor maize growth in close proximity to *Gliricidia* is evident. Whereas maize plants in rows closest to the trees had wilted by mid-day, plants in more distant rows remained turgid and became more advanced phenologically (Plate 4).

Although tree/crop competition was evident with both tree species, bean plants grew best initially with the leafless *Gliricidia*. However, by mid-December, the leaf area index of *Gliricidia* had reached about 80% of that of *Grevillea*, and thereafter interspecific differences in bean growth and development diminished as competition through transpiration by the *Gliricidia* increased.

At harvest, there was a distinct trend of gradually increasing bean dry weight with increasing distance from trees in the *Gliricidia* plot. A similar but more dramatic trend occurred in the plots occupied by *Grevillea*. In rows close to *Grevillea* trees, severe competition reduced bean yield almost to zero, but at distances in excess of 4.5 m from trees, bean yields exceeded those from *Gliricidia* plots by 25–50%. Bean yields from *Grevillea* and treeless 'beans only' control plots did not differ significantly, but both produced greater overall bean yields than plots occupied by *Gliricidia*.

The interspecific difference in trend of bean yield can probably be explained in terms of root competition for water. Although both tree species had similar total root lengths, the spatial distributions of roots differed between species (Figure 14). *Grevillea* had greater root length and concomitantly greater competitive effects on beans close to tree stems than *Gliricidia*, but *Grevillea* root concentrations diminished more rapidly with increasing distance from stems than those of *Gliricidia*. Therefore, competition by *Grevillea* was less intense at greater distances from trees. Additionally, whereas patterns of distribution of bean and *Gliricidia* roots with depth were similar, and would produce severe competition in the fertile and frequently wetted 0.3 m surface layer of the soil profile (Figure 15), *Grevillea* roots tended to be concentrated deeper, and thus would be less competitive with beans.

Results so far confirm farmers' views that *Grevillea* is less competitive with intercrops. However, these results also highlight the complexities of tree/crop interactions and the crucial need for detailed information on the dynamics of growth and phenologies. In future studies, it is planned to use real-time transpiration measurements in association with frequent light pruning of the trees to manipulate soil water extraction by the two tree species. Crop root and tree root phenologies, and their dynamics, will be examined in more detail using regular sequential coring and repeated non-destructive minirhizotron observations.

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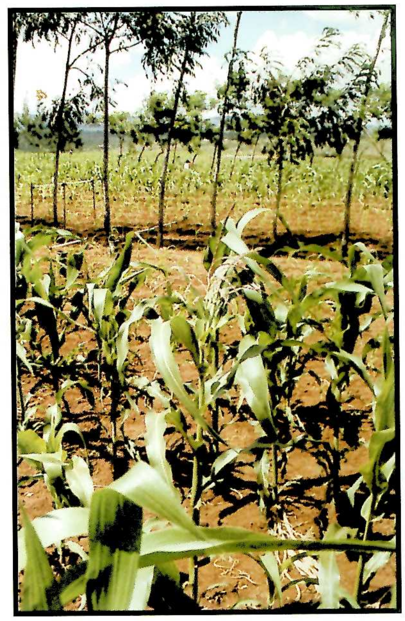


Plate 4. Phenological differences in maize caused by competition with trees in an alley cropping study in Kenya. One plant in the foreground has entered the reproductive phase while those closer to the trees have scarcely progressed beyond the seedling stage

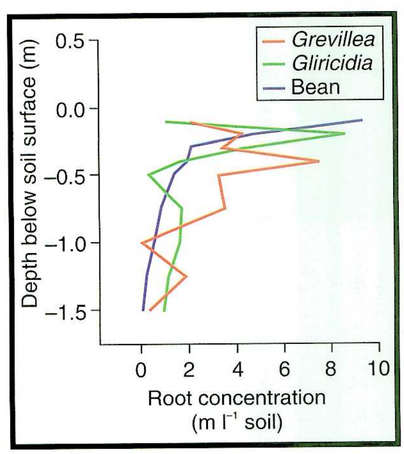
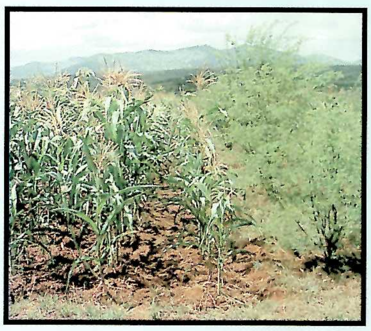


Figure 15. Changes in fine root concentrations for bean, *Grevillea robusta* and *Gliricidia sepium* at different soil depths in an alley cropping study at Machakos in Kenya

Land use research is by its very nature interdisciplinary and the Centre for Ecology and Hydrology's core programme draws on expertise in economics, hydrology and ecology. The new strategy is focused on five key areas – all involve significant input from ITE.



Land use

Land use is subject to continual change driven by economic, social, political and environmental pressures. The desire for more sustainable forms of land use, as expressed by the Rio Convention and a series of national White Papers and Strategies, can only be met if it is based on sound science. This is well expressed in the NERC mission in relation to land use:

- to ensure that environmental information on land use is available, accurate and comprehensive
- to develop the ability to predict the environmental consequences of major changes in land use
- to provide a basis on which policies may be formulated for ensuring that land use in the United Kingdom is efficient, flexible and environmentally sustainable.

The five key areas

- **Long-term land use monitoring and experimental studies**

The key challenge is to quantify and model environmental implications of land use and land use change over the long term. The key activities are long-term monitoring and experimental manipulations supplemented by shorter-term, intensive process studies, or more extensive, regional studies.

The key project here is the continuation of the Countryside Survey series. Surveys have been undertaken in 1978, 1984 and 1990, all based on the idea of repeated surveys of 1 km squares to monitor and analyse change in land cover, land use and biodiversity. The next survey is due in 1998, to be published in 2000 (Countryside Survey 2000). Another element in this theme is the continued monitoring and experimentation of the effects of grazing in the uplands.

- **Land use impacts**

The key challenge is to develop models of the impacts of a given land use practice, system or policy, thereby allowing its productivity to be increased and/or unwanted impacts to be reduced. The key activity is to conduct large-scale experiments and surveys into particular land use systems in order to develop and parameterise spatially explicit models of production and/or impacts.

The emphasis is to develop models from field data to help provide advice on the specific management of a particular landscape, land policy or land use. For example, one strand of this research is the assessment of environmental impacts of farming systems, and a second deals with the hydrological impact of land use change, with special reference to upland forestry (a close collaboration between ITE and the Institute of Hydrology).

- **Landscape level interactions**

The key challenge is to develop and apply models of fluxes between elements within landscape mosaics The key activity is to study the processes involved in the fluxes of organisms, water, nutrients, energy and pollutants between land units

Over the past decade there has been an increase in studies looking at fluxes of water, nutrients, pollutants and organisms across landscape units A full understanding of these fluxes and their response to changes in land cover and management is essential to the development of holistic land use models, but such understanding is not yet available The NERC Thematic Programme on Large-Scale Processes in Ecology and Hydrology covers some, but by no means all, of the biodiversity issues

Particular studies will involve the fluxes of nutrients, water, pollutants and organisms across forest edges, landscape ecological theories will be developed and validated and the roles of buffer zones and corridors will be assessed The mathematics and visualisation of interactions between land use units will be developed

- **Management of particular land uses and sensitive ecosystems**

The key challenge is to develop and apply the scientific basis of sustainable management of individual land uses The key activity is to conduct monitoring, experimental, modelling and dissemination programmes relating to the management of single land uses within the wider land use context

Sustainable development requires that land can be managed in ways that can continue in the long term whilst maintaining or increasing levels of natural and human capital The optimum management of a land unit for a particular purpose is frequently location-specific, and depends upon other land uses in the vicinity The core/strategic emphasis is therefore to develop models of the processes involved which can be parameterised to the local conditions ITE's large overseas forest management and restoration work is centred within this theme, and research also addresses the management of wetlands, drylands, uplands and saltmarshes

- **Holistic land use strategies**

The key challenge is to develop models to assist with the development of land use and water resource management strategies The key activity is focused on interdisciplinary modelling and field studies at the landscape, catchment and country scale

Strategic land use planning involves making decisions on the basis of best-available knowledge, implying that the knowledge must be tightly organised The National Technology Foresight Panel on 'Agriculture, natural resources and environment' placed priority on combining environmental and social data and models within common frameworks There is great potential value in integrated information and management systems Particular studies include the integrated modelling of land use processes including social and economic variables, and plans are being developed for an holistic study of a lowland catchment which will integrate human and environmental processes

Current research illustrated in the following papers contributes to three of these themes The first theme is 'monitoring the impacts of land use change', as exemplified by the use of long-term field studies on the effects of upland grazing The second theme is 'modelling the processes and effects of land use change', and the papers on chalk grassland and upland grazing show well how analysis based on long-term data can be used to model systems to help develop appropriate management strategies The third theme, 'optimising land use', is shown by the development of a geographical information system for wetlands which can be used to relate site management to the species present and the hydrology of the area in a very explicit way

Strategic land use planning involves making decisions on the basis of best-available knowledge.

L G Firbank and B W Staines

Grazing pressure is the principal influence on British upland vegetation.

Long-term effects of grazing on upland habitats

Grazing pressure is the principal influence on British upland vegetation. Herbivores alter the competitive balance between plant species by their selective feeding, and so cause changes in vegetation composition and structure (Plate 5).

The main herbivores present in the British uplands – cattle, sheep and red deer (*Cervus elaphus*) – are selective not only in which plants they consume but also in where they choose to graze. Generally, herbaceous plants such as grasses and sedges are preferred to dwarf shrubs such as heather (*Calluna vulgaris*) and cross-leaved heath (*Erica tetralix*). Amongst the grasses the less-coarse species such as bents (*Agrostis* spp.) and fescues (*Festuca* spp.) are grazed in preference to fibrous species such as mat-grass (*Nardus stricta*) and purple moor-grass (*Molinia caerulea*). Grasses are tolerant of defoliation, growing from the stem bases, whereas species such as heather which grow from above-ground buds suffer more severely. Tree saplings are particularly vulnerable to being grazed, and a major effect of herbivores in the uplands is to restrict woodland. The loss of heather and other dwarf shrubs causes concern to conservationists, and heather-dominated moorland is now a protected habitat under the EC Habitats Directive having a bird assemblage of international importance.

Plate 5. Sheep selectively graze newly burnt areas of heather moorland and promote the invasion of grasses

Effects of grazing on heather/grass balance

Welch (1984a), measuring both vegetation composition and herbivore occupance at a representative series of 32 sites in NE Scotland, established that heather moorland is replaced by graminoid communities above a threshold stocking of 2.7 sheep ha^{-1}. When the heather is growing badly, as on wet soils or at higher altitudes, the threshold densities are much less. Continued monitoring at a subset of sites has shown that change from heather dominance to grass dominance can occur in 8–10 years when stocking rates are high (Welch & Scott 1995), and for these sites cover changes are plotted against herbivore occupance in Figure 16. Losses in heather cover were proportional to the occupance index, the site with the greatest loss having a decrease of 61% from 85% to 24% cover. Gains in heather cover were smaller averaging 15%, and occurred mainly when the occupance index estimated from dung deposition was below 140 ml m^{-2} yr^{-1}, which is equivalent to 2.7 sheep ha^{-1}.

Changes in grasses and other subsidiary species of moorland were found to be less closely correlated with herbivore occupance than the changes in heather. The explanation is partly that the heather dominates the graminoids so that they are dependent on its performance and state, and partly that the graminoid species compete among themselves, certain ones being favoured by particular soil conditions (eg mat-grass by wet soils).

Mat-grass is a key species as it is of virtually no value to livestock, and there has been concern that it is spreading in the uplands and could become dominant over large areas. At the sites with continued monitoring since 1969, a significant increase in mat-grass over 25-year periods only occurred on sites where heather condition (index obtained from the product of % cover and height in cm) was poor (Figure 17 – site A). However, at sites where heather was less heavily grazed and in better condition, mat-grass cover actually declined (Figure 17 – site B), the losses mainly occurring when heather height exceeded 15 cm and the state index was greater than 1000.

A key finding is that the effects of heavy grazing on mat-grass expansion are reversible, at least if some heather is still present in the sward. The growth of individual mat-grass plants was measured for three years at four sites in NE Scotland, each having fenced and unfenced plots (Hartley 1997). Although there was a significant site effect, mat-grass performed best in the unfenced plots at the site with the heaviest grazing, where the heather canopy was most open. In the fenced areas heather attained an average height of 28 cm and its canopy closed above the mat-grass plants, subjecting them to increased litter fall. As a result, over a third of the individual plants died back and a quarter died. Heather ground cover increased in all the fenced plots within two years of the fences being erected; the most marked difference in cover between fenced and unfenced plots occurred at the site with the highest levels of sheep grazing. Fencing also led to significant increases in the height of the heather canopy and in heather canopy cover; again, there were significant differences in the rate of increase between sites (Figure 18) (Hartley 1997). An objective for future work is to define grazing thresholds permitting heather increase which take account of the main site conditions influencing the growth of heather and its competitors.

Effects of grazing on plant species diversity

Diversity in plant species in the British uplands is more strongly influenced by soil nutrient status than by whether heather or graminoids are dominant. For the 32 moorland sites reported by Welch (1984b), the mean number of higher plants, bryophytes and lichens recorded in 800 point quadrats was 57 at base-rich sites (8) and 39 at base-poor sites (24). At the subset of sites where monitoring has continued, the average trends over periods of 10–13 years (Figure 16) in the number of species recorded were:

- +5.4 species when heather lost more than 15% cover,
- +1.3 species when heather gained more than 15% cover, and
- –5.4 species when heather dominance was unchanged.

It appears that, when the vegetation is relatively static, less-competitive species are gradually lost but changes in dominance allow new species to colonise.

Effects of grazing on invertebrates

Grazing impacts which alter the vegetation composition and structure may have consequential effects on the diversity of other organisms. Pitfall trapping was used to monitor the ground beetle (Carabidae) assemblage in heather moorlands subjected to different grazing pressures. In ungrazed areas, the age of the heather plants was an important determinant of carabid abundance (Table 3). Under grazing, the loss of more than 60% of the current year's shoots had significant impacts on heather biomass, height, and shoot structure,

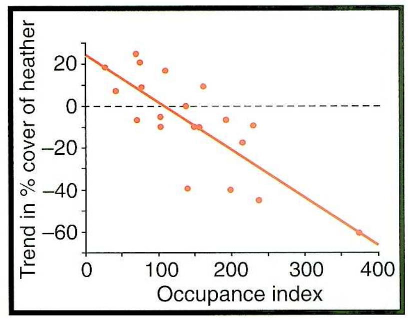


Figure 16. Heather cover trends over 10–13 year periods in relation to an index of herbivore occupance estimated from volumes of dung deposited (ml m^{-2} yr^{-1})

The effects of heavy grazing on mat-grass expansion are reversible.

Table 3. Species richness and abundance (mean number/10 pitfall traps/week) of carabid beetles on ungrazed and grazed heather moorland. Typical species are those characteristic of upland and moorland habitats

Vegetation abundance	Species richness	Number of typical species	Mean
Unbrowsed			
pioneer heather	27	12	151.1
building heather	30	16	39.6
Shoots browsed			
45%	26	14	10.1
52%	22	11	21.6
64%	17	7	52.4

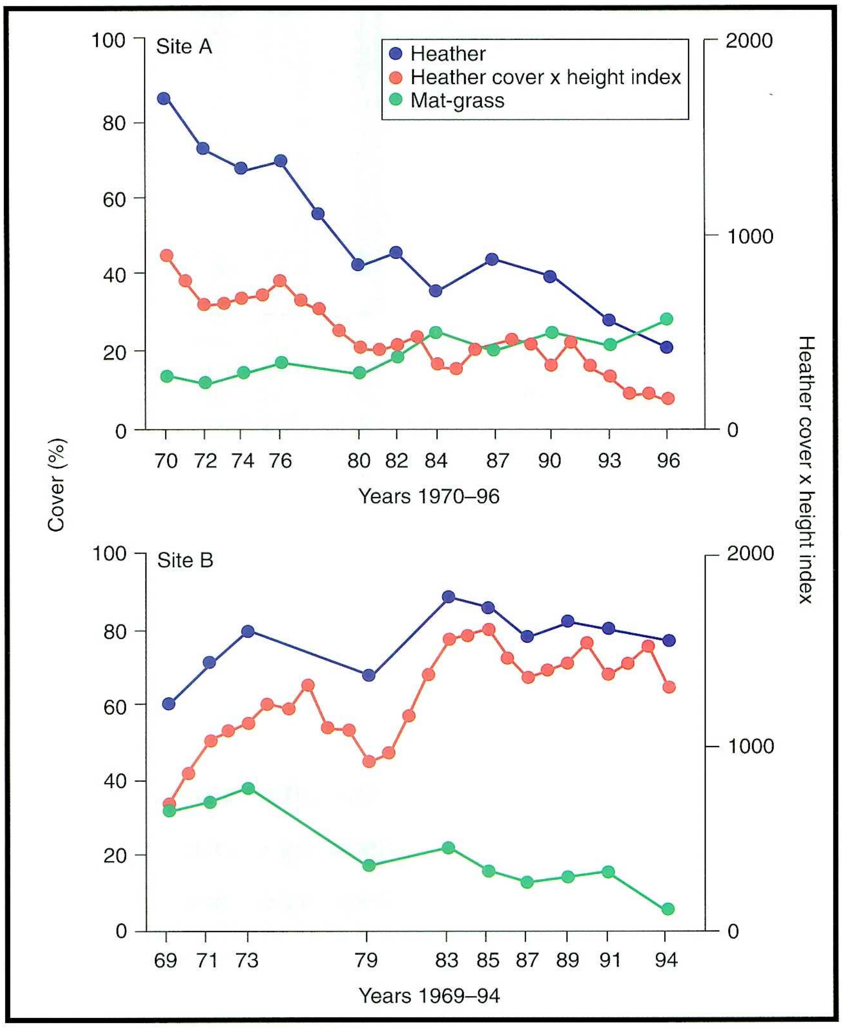


Figure 17. Mat-grass cover trends over 25 years in relation to heather cover and state; state is expressed by an index calculated from % cover and height (cm). At site A heavy grazing from cattle and sheep much reduced heather, while at site B moderate grazing from sheep and red deer allowed a slow increase of heather

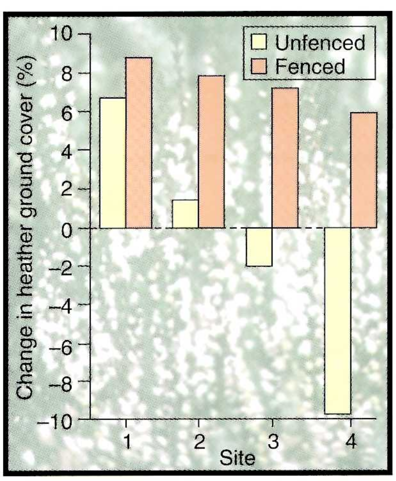


Figure 18. The change in heather ground cover (%; mean values) between 1993 and 1995 on fenced and unfenced plots at four sites in NE Scotland

causing a significant change in the composition of the carabid community (Gardner *et al.* 1996). Carabids associated with shady vegetated ground were less abundant at the most heavily grazed sites, whilst species associated with open ground increased in number. Species richness was much lower at the sites with heaviest utilisation (Table 3), species characteristic of heather-dominated moorland being absent.

Studies at ITE Bangor have shown similar effects of grazing on spiders: a reduction in grazing led to an increase in species diversity associated with the development of structurally more varied vegetation. Also, spider numbers peaked in the treatments with reduced grazing.

Conclusions

These studies have shown that grazing pressure controls heather dominance, by removal of biomass, and that the structure and height of the heather sward in turn controls the abundance and diversity of other plants and invertebrates. Current information indicates that the effects of overgrazing are at least partially reversible, but site factors greatly influence the timescale of this process. To gain a full understanding of upland vegetation dynamics and its consequences for species diversity, the long-term monitoring of both sward characteristics and key groups of plants and animals will continue.

D Welch, S E Hartley, D Scott and A Buse

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Review of effects of management of calcareous grassland

(This work was partly funded by the Ministry of Agriculture, Fisheries and Food)

Land use and biodiversity of calcareous grassland

Calcareous grassland is the product of many centuries of human use, typically involving grazing and cutting. Changes in the type or intensity of management will affect the composition and structure of the vegetation. Such changes are extremely important because calcareous grasslands are a resource of great value for ecology and nature conservation (Plate 6). They have a high diversity (up to 40–50 plant species m^{-2}) and contain many species which are largely restricted to this habitat (eg pasque flower (*Pulsatilla vulgaris*), early spider orchid (*Ophrys sphegodes*), chalkhill blue butterfly (*Lysandra coridon*), skylark (*Alauda arvensis*)).

Environmental land management schemes, such as Environmentally Sensitive Areas (ESAs) and Countryside Stewardship, seek to provide advice and financial incentives for management practices that maintain and enhance existing wildlife habitats. Of the current ESAs, the South Downs, South Wessex Downs, and the Cotswold Hills contain large areas of calcareous grassland. These schemes require detailed information on appropriate management practices and their effects on calcareous grasslands. However, such information is rare, especially in terms of the long-term dynamics of grasslands.

Long-term management experiments and monitoring

ITE has carried out long-term studies to determine the effects of management on the composition and structure of calcareous grasslands on a wide range of sites in Britain (Table 4). This has used a dual approach of (i) monitoring managed grasslands for up to 50 years, and (ii) establishing replicated management experiments (Wells & Cox 1993; Wells, Pywell & Welch 1994; Pywell *et al.* 1995). The objectives were to:

- compare the effects of different management techniques on the

Plate 6. Species-rich chalk grassland

Precise management rules depend on geographical position, soil type and fertility, climate and land use history.

Table 4. Calcareous grassland sites studied by ITE, either in experiments or by long-term monitoring of sites under different mangements

Grassland site studied	Experiment or monitoring Monitoring period	Managements
Aston Rowant NNR, Oxon	Experiment 30 years	Sheep grazing at different seasons and intensities
Knocking Hoe NNR, Beds	Experiment/monitoring 30–45 years	Horse, cattle and sheep grazing and cutting at different frequencies
Radcot, Oxon	Monitoring 8 years	Cattle and sheep grazing and cutting at different frequencies
Martin Down NNR, Dorset	Monitoring 18 years	Sheep grazing at different seasons and intensities
Parsonage Down NNR, Wilts	Monitoring 20 years	Cattle and sheep grazing at different seasons and intensities
Wylye Down NNR, Wilts	Monitoring 20 years	Cattle and sheep grazing at different seasons and intensities
Barton Hills NNR, Beds	Monitoring 30 years	Cattle and sheep grazing at different seasons and intensities
Barnack Hills and Holes, Cambs	Monitoring 50 years	Sheep grazing and scrub clearance
Old Wincester Hill, Hants	Monitoring 50 years	Sheep grazing at different intensities

Plate 7. Clustered bellflower which established in the grazed plots at Aston Rowant

structure and diversity of calcareous grassland in a variety of sites;
- identify and evaluate management procedures for the maintenance and enhancement of the botanical diversity of these habitats;
- derive effective, practical guidelines for managing calcareous grasslands (eg within the ESA and Countryside Stewardship schemes).

Monitoring of a variety of sites (see Table 4) has shown that precise management rules will depend on geographical position, soil type and fertility, climate and land use history. Two of the experiments illustrate the complex responses to different management systems.

Knocking Hoe NNR cutting experiment

A replicated experiment was set up in 1964 to determine the responses of the sheep's-fescue/meadow oat-grass (*Festuca ovina/Avenula pratensis*) grassland to four treatments:

- cut every year in May
- cut in May and June
- cut in May, June and July
- no management.

A survey 23 years later was used to assess effects on species composition (as % of total biomass). In order to measure the course of changes in the unmanaged plots, a third were harvested after seven years, another third after 16 years, and the remainder after 23 years. Under no management, the grassland became rank and herb and grass species were gradually lost until hawthorn scrub (*Crataegus monogyna*) and dog-rose (*Rosa canina*) became dominant after 23 years (Figure 19). Upright brome (*Bromus erectus*) dominated in all the cutting treatments after 23 years, but increased cutting frequency (ie a greater number of cuts in a year) decreased its dominance and increased the contribution of other species to the biomass. However, there were more subtle differences among cutting treatments. For instance, lady's bedstraw *(Galium verum)* increased only in the plots cut once annually in May, whereas squinancywort (*Asperula cynanchica*) and oxeye daisy (*Leucanthemum vulgare*) increased only under the most frequent cutting. Despite these differences, the different cutting treatments had similar species numbers (*c* 30 per plot), although there were significantly more species than in the unmanaged plots (*c* 15 per plot).

These plots were compared to adjacent grassland which had been grazed by sheep for many centuries. This grazed area had a markedly different vegetation to any of the experimental plots, having many more species (33 m^{-2}), a more equitable composition and a high abundance of forbs.

Aston Rowant NNR grazing experiment

When this experiment was set up in 1963, the sheep's-fescue/meadow oat-grass grassland was becoming degraded through a lack of management. Two grazing intensities of 2.5 sheep ha^{-1} and 7.4 sheep ha^{-1} (grazing season October–June) and ungrazed controls were imposed in a replicated experiment. These three treatments continued until 1973, after which the treatments ceased and all plots were grazed subsequently at roughly similar intensities. However, monitoring continued in order to determine the long-term consequences of re-establishing grazing on the site.

Surveys in 1973, after ten years, showed treatment effects on the frequencies of a number of species (Figure 20). Several forbs increased in the grazed plots compared to declines or smaller increases in the controls. These species also showed greater increases in the more heavily grazed plots. *Pseudoscleropodium purum*, an important moss of chalk grassland, showed similar responses to the treatments. In contrast, the grasses did not respond to grazing. False brome (*Brachypodium sylvaticum*) increased in all plots, indicating that grazing is not sufficient to control this problem species. New species established in all plots over the ten years, but the increase in species number was greater ($P<0.05$) in the grazed plots (by 12 and 10 species in the lightly and heavily grazed plots respectively) than in the controls (by three species). The new species included agrimony (*Agrimonia eupatoria*), cowslip (*Primula veris*) and clustered bellflower (*Campanula glomerata*) (Plate 7). A census in 1993 showed the grazed plots had similar species compositions as 20 years earlier, suggesting that the community had stabilised.

Conclusions

As seen at Knocking Hoe, scrub will gradually invade unmanaged grassland and cutting can halt this process. However, cutting has markedly different effects to grazing. Mowing is non-selective and does not create the valuable mosaic of gaps in the sward associated with livestock. For these reasons, cutting produced a coarser and less species-rich grassland than grazing. If cutting is used, the number of cuts in a year will strongly influence the species richness and composition of the sward.

The degraded grassland at Aston Rowant responded rapidly to the grazing treatments over the first ten years. By opening gaps and decreasing vegetation height, grazing

Scrub gradually invades unmanaged grassland but cutting halts this process.

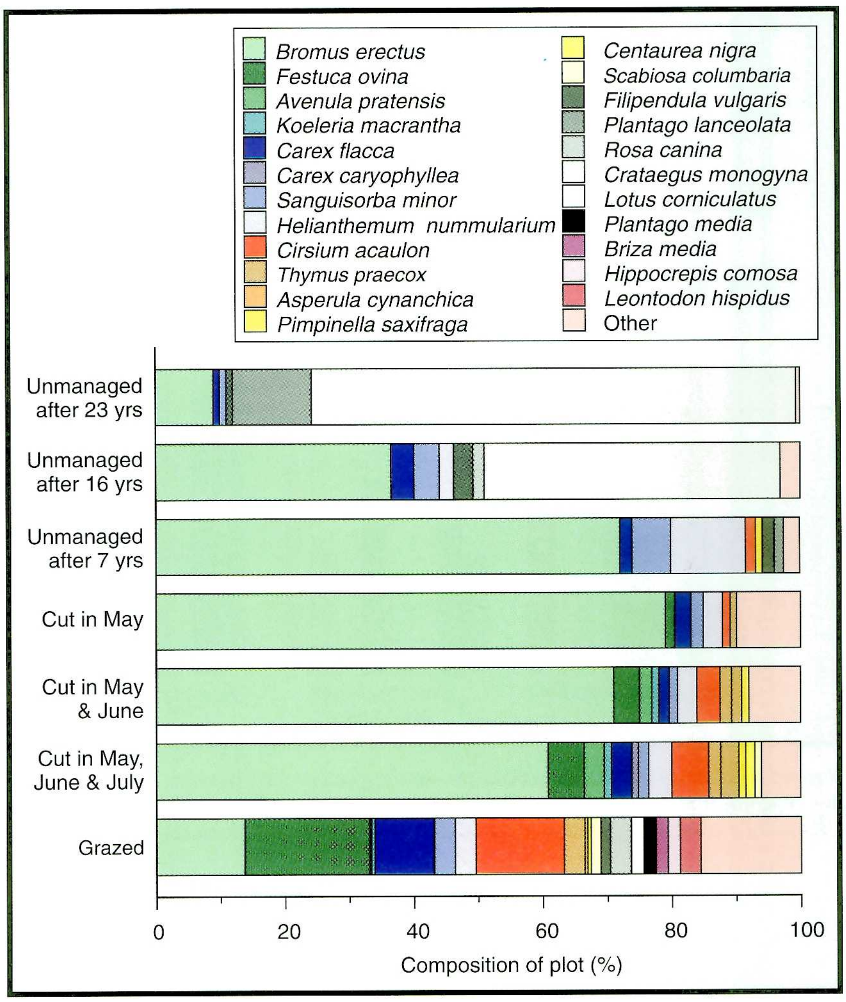

Figure 19. Effects of management on the composition of chalk grassland at Knocking Hoe

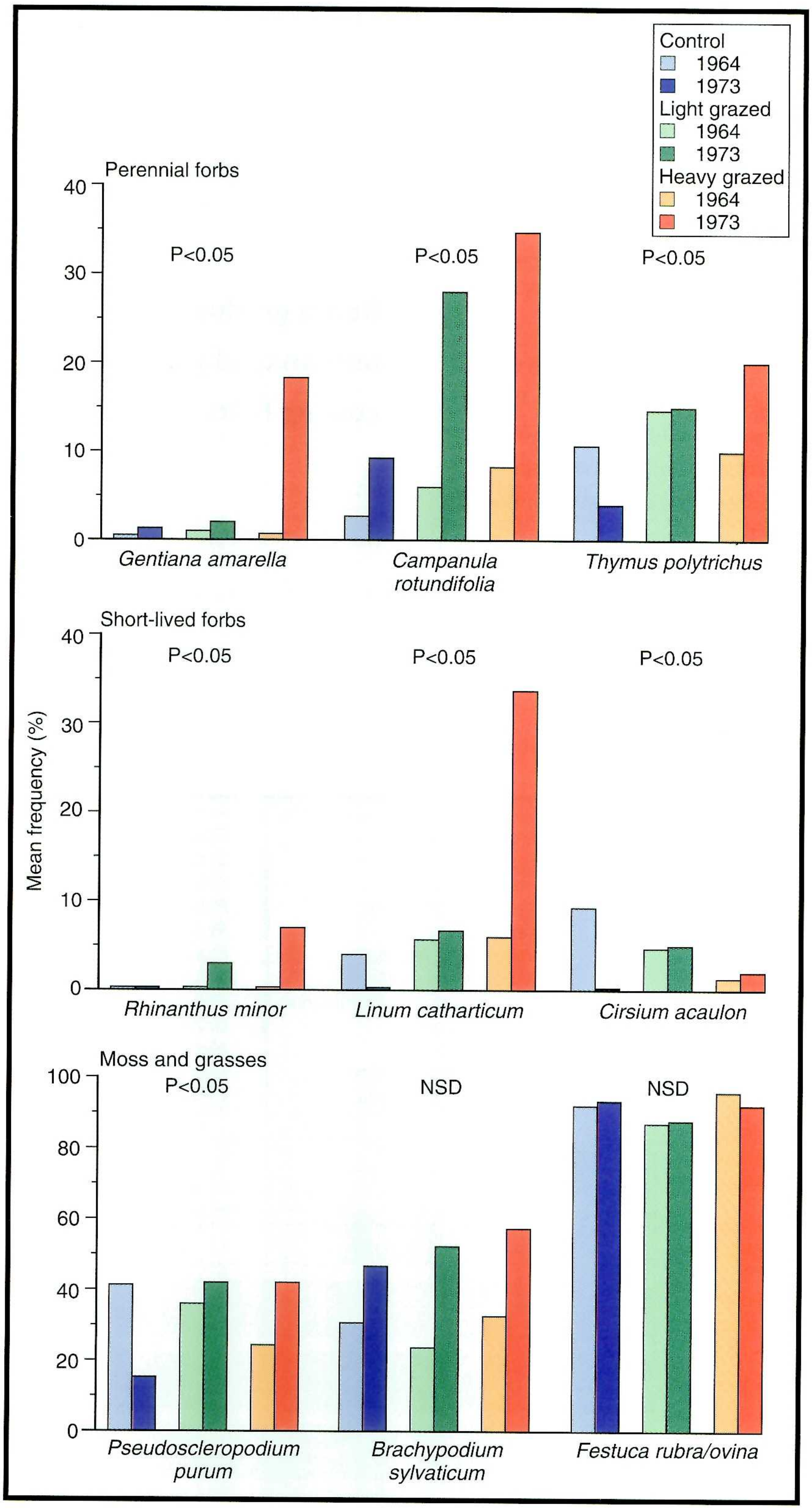

Figure 20. Changes in the frequencies of selected plant species over the first ten years of the experiment at Aston Rowant. Treatment effects on the differences between 1964 and 1973 were analysed by one-way ANOVA (NSD=no significant difference)

allowed many species, especially forbs, to establish and spread, and the higher stocking rate accelerated this process (see Bullock 1996). Although the treatments ceased, continued grazing at variable rates over the next 20 years maintained the forb-rich community, indicating the inherent stability of well-managed grassland. These results illustrate the importance of long-term monitoring to detect responses to grazing.

Further analyses of the long-term studies are providing information on the important aspects of grazing (livestock type, grazing season and stocking rate) and cutting management, and monitoring is continuing to assess the long-term effects on calcareous grasslands.

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A wetland GIS: an ecologist's tool for wet grassland management

(This work was funded by the Ministry of Agriculture, Fisheries and Food, and undertaken in collaboration with the Agricultural Development and Advisory Service (ADAS) and Silsoe College of the University of Cranfield. Data for West Sedgemoor were kindly provided by the Royal Society for the Protection of Birds)

Many of the wetland communities of north-western Europe have evolved as an integral part of the farmed landscape. Under the traditional farming systems of England and Wales, these communities have developed a high wildlife value, which has been reduced through land drainage and the associated intensification of farming practice. Opportunities are now available through agri-environment schemes (such as Environmentally Sensitive Areas) to reverse this loss of ecological value. ITE has developed techniques for predicting the benefits of different water management actions on both agricultural and ecological interests within defined test catchments and procedures for spatial analysis.

Making full use of the particular advantages of geographical information systems (GIS) for bringing together and manipulating spatial datasets, the project has sought to integrate hydrological, soil, topographic and land use data with information on the distribution of plants, birds and selected invertebrates. Test 'catchments' were identified in three Environmentally Sensitive Areas (ESAs), namely the Upper Thames Tributaries, the Broads, and the Somerset Levels and Moors. The selected sites were chosen for their wide geographical spread, and hence their ability to demonstrate the applicability of the GIS modelling approach to the range of soil and hydrological conditions encountered in wetland habitats.

Two examples are given of the use of GIS as a strategic planning tool:

- identifying those areas of a catchment which might be selected as the most appropriate for successful reinstatement of wet grasslands on arable land;
- identifying which fields are used consistently by two chosen bird species.

The Upper Thames tributaries ESA – the River Ray

Is it possible to identify arable fields of potential value for reversion to desirable grassland communities? Three stages were required to answer this question:

i. identification of fields with existing target plant communities, as defined by the National Vegetation Classification (NVC), to act as sources of colonisation;
ii. identification of arable fields close to those fields;
iii. ranking of arable fields in terms of proximity to those 'source' fields.

Fields containing good examples of selected target communities were defined as 'source' fields where field quadrat data had a goodness-of-fit value of more than 60% to the specified NVC community.

Many wetland communities of NW Europe have evolved as an integral part of the farmed landscape.

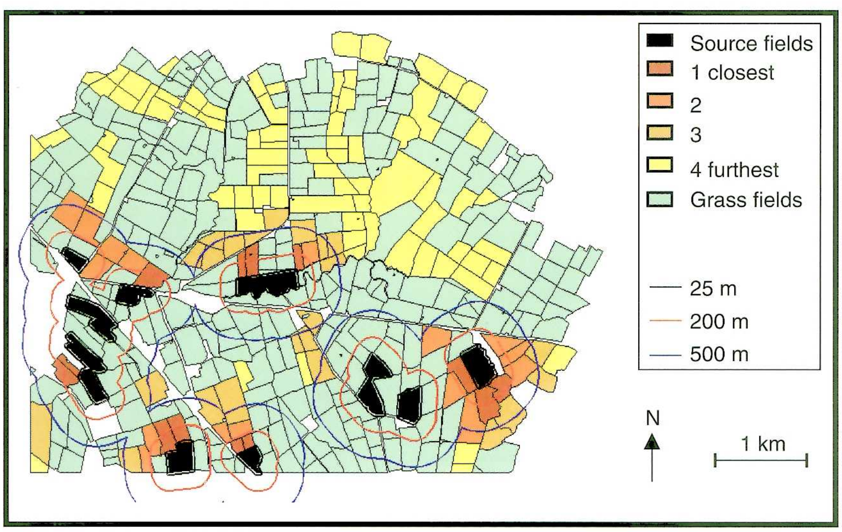

Figure 21. Identification of arable fields within 25 m, 200 m and 500 m of the MG8 'source' fields in the River Ray

Table 5 Total area of arable land within 25 m, 200 m and 500 m of a 'source' of each of the three target communities MG4, MG5 and MG8 (figures in ha)

Community	Rank 1 (25 m)	Rank 2 (200 m)	Rank 3 (500 m)
MG4*	18	43	112
MG5**	36	97	77
MG8***	64	107	149

* Meadow foxtail/great burnet (*Alopecurus pratensis/Sanguisorba officinalis*) grassland
** Crested dog's-tail/common knapweed (*Cynosurus cristatus/ Centaurea nigra*) grassland
*** Crested dog's-tail/marsh marigold (*Cynosurus cristatus/Caltha palustris*) grassland

Table 6 Invertebrate characteristics of two contrasting fields in the Ray favoured by two different bird species snipe and lapwing

	Typical snipe field	Typical lapwing field
Soil penetrability (kg F)	4 7	7 3
Soil wetness	4 2	1 5
Worm count (gm)	13 4	2 0
Other invertebrates (gm)	20 4	3 6

Within the GIS, buffers were constructed as a means of identifying arable fields within 25 m, 200 m or 500 m of the 'source' fields The arable fields identified as being closest to the 'source' fields were assumed to have the greatest potential for colonisation by target species Each of the arable fields found within the buffers were then ranked according to location (Table 5)

The findings for NVC Community MG8 are shown in Figure 21 On the basis of geographical location alone, 64 ha were found to be suitable for restoration to MG8, 36 ha to MG5, and 18 ha to MG4 However, suitability of arable land for restoring target wetland plant communities will also be influenced by site wetness

A further question might then be posed 'which of these selected arable fields are hydrologically similar to the "source" fields' The stages involved included

i finding the typical hydrological regime for the 'source' fields of each target community,
ii identifying all other fields in the catchment with the same regime,
iii locating arable fields in the buffer strips which shared this hydrological regime

For each field ADAS provided modelled hydrological data for every ten-day period throughout the year The average values for the MG8 source fields were derived from this dataset Of the original selection of 64 ha, the model predicted that 21 ha shared a similar hydrological regime

Bird data – comparisons within and between three sites

Two bird species of particular interest are the snipe (*Capella gallinago*) and lapwing (*Vanellus vanellus*) Because their foraging ecology differs, the two species require slightly different habitats for breeding success In answering the question, 'which fields are used consistently by these birds within the study area', two stages were required

i field data for each site were queried to find those fields used consistently by snipe and lapwing,
ii species distribution maps were displayed and analysed

Fields were classed as being 'consistently' used where birds were present in two or more winters of the three study years Although both species favoured the riverside fields, their distributions were mutually exclusive (Figure 22)

The wetness of the sites is of critical importance to the number of wading bird species, both within and between sites A preliminary analysis of the habitat preferences of these two birds in the River Ray suggested that snipe preferred wet fields rich in invertebrates whereas lapwings preferred dryer fields with a low abundance of invertebrates (Treweek *et al* 1994) To examine these patterns further the invertebrate information contained within the GIS was queried on a field-by-field basis (Table 6)

The snipe field is relatively wet (where 0 is dry and 5 is 25% flooded) but contained a high biomass of worms and invertebrates In contrast, fields favoured by the lapwing tended to be drier (1 5), with harder soil (in this case 7 3 kg of force was required to penetrate the surface) and comparatively poor food sources Easy soil penetrability is probably not as important for lapwing as it is, by virtue of its bill morphology, a near-surface feeder, whereas the snipe probes deeply into the soil to feed

Figure 22. Fields used in two or more winters by lapwing and snipe in the River Ray catchment

These single-site, species-specific analyses found broad agreement with the findings available for the Southlake Moor ESA and the West Sedgemoor ESA (managed by the Royal Society for the Protection of Birds), where the distribution of breeding waders could be related to management of the sites for wetness. Those under raised water management held higher densities of waders in spring than those where it was absent (Caldow & Pearson 1996).

The wetlands GIS

The wetlands GIS can readily produce detailed summary statistics on a wide range of attributes, enabling the environmental manager or planner to estimate the size and distribution of each resource. For example, rapid tabulations of water regimes, land use, plant species distributions, and bird numbers can be obtained. Together with hydrological and ecological field survey and experimentation, the wetlands GIS confirms that the water regime has a strong influence on the distribution of biota throughout the 'test' catchments. From the GIS, numerical estimates can be made of the regimes, and the appropriateness of particular 'tier' prescriptions in securing the communities and species desired for the different parts of the ESAs can be assessed. Closer guidance can be given about the optimal management of the water regime, both for agriculture and conservation.

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Summary statistics from the wetlands GIS enables the environmental manager to estimate the size and distribution of a resource.

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