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REPORT

Institute of Terrestrial Ecology

Natural Environment Research Council

Report of the Institute of Terrestrial Ecology 1989/1990

Natural Environment Research Council

Contents

Science Reports

Forest science

The Forest Science Programme is concerned with strategic research on tree biology and forest soils, and on the ecology of forests and woodlands, including tropical forests. A significant proportion of the work is now being focused on issues related to the 'greenhouse' effect. This focus is exemplified by the reports given below on carbon storage in forests and the emission of nitrous oxide from forest soils. No reports are presented this year on our tropical forestry programme, which has expanded to include work in Cameroon, Chile, Costa Rica, Kenya and the Sudan. Substantial studies have been completed this year on the management of forests in the UK for conservation, exemplified by the reports below on Scots pine and on a study of forest design at Kielder.

Carbon storage in forests

How much carbon can be stored by growing and harvesting trees? Concern about the 'greenhouse' effect has provoked considerable interest in the possibility of collecting and storing carbon (CO_2) in the form of living trees and their wood products, in order to slow down the present increase in atmospheric carbon dioxide (Marland 1988; Thompson & Matthews 1989). A growing forest acts as a net sink of CO_2, whereas a mature forest is essentially in CO_2 equilibrium with the atmosphere. If trees are harvested periodically and the wood is used for building material, then carbon storage is enhanced in two ways: by increased CO_2 fixation during the regrowth of the forest, and by long-term storage as timber.

A carbon storage model

At ITE's Edinburgh Research Station, a model of carbon storage has been developed (Dewar 1990a, b) which describes the storage of carbon in vegetation (especially forests), in the products removed from vegetation (timber, grain, etc), and in the detritus that is added to the pool of soil organic matter. The analytical nature of the model facilitates a general understanding of the ways in which the various carbon pools interact, and complements the numerical approach of computer models designed to study specific forest stands. The model can be used to examine the effects of different land uses, especially afforestation, and of changes in management and climate on the storage of carbon in the UK and elsewhere.

Figure 1 illustrates the main components of the model for a forest which is periodically harvested and replanted. There are three carbon stores.

1. The FOREST box represents carbon stored in the living parts of trees (ie roots, stems, branches, foliage), and is a sink for CO_2 while the forest is growing. Carbon uptake by trees is modelled using a logistic growth curve, describing the approach to maximum biomass (and CO_2 equilibrium with the atmosphere) as the forest matures, and is interrupted by harvesting after a specified rotation period.
2. The PRODUCTS box represents carbon stored in various wood products after harvesting (eg paper, fibreboard, building timber), which have not yet decayed back into CO_2. The decay of products is modelled by a set of carbon retention curves, in terms of which decay times can be defined for an average wood product.
3. During the life of the stand, the LITTER box continuously receives carbon from the forest in the form of dead roots, branches and foliage, which decompose in the process of soil formation. Litter input rates are related to the growth curve of the forest. The model also includes the

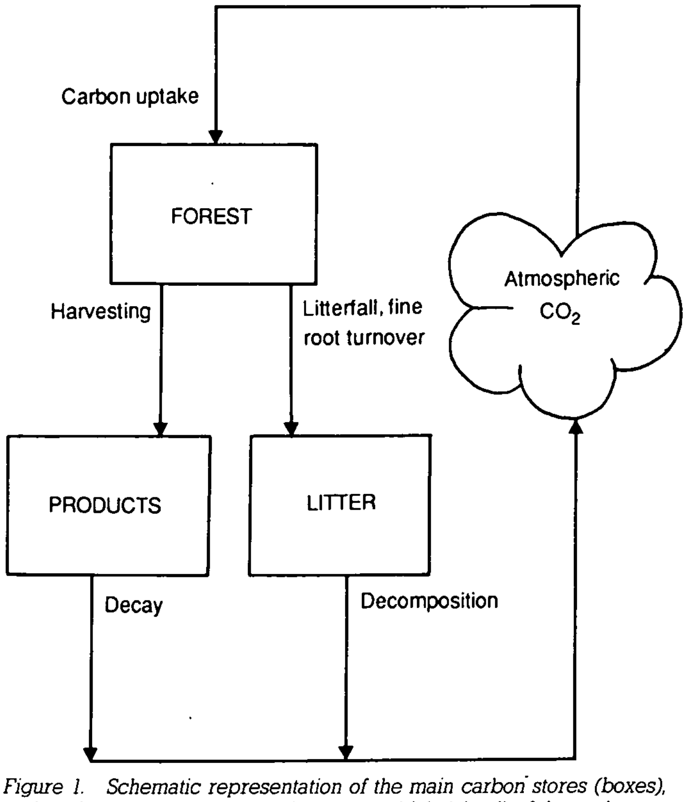

Figure 1. Schematic representation of the main carbon stores (boxes), carbon fluxes (arrows) and carbon source/sink (cloud) of the carbon storage model

decomposition of forest debris left on site at the end of each rotation, the amount of which will depend on harvesting intensity.

Carbon storage in living trees and wood products

The resulting pattern of carbon storage in trees and their products is shown in Figure 2. The amount of carbon in trees follows the repeated pattern of felling and regrowth in successive rotations. If the decay curve of wood products from a given harvest extends beyond the time of the next harvest, then carbon builds up in the form of wood products. Ultimately, an equilibrium is reached where, over the life of the stand, as much wood decays as is produced.

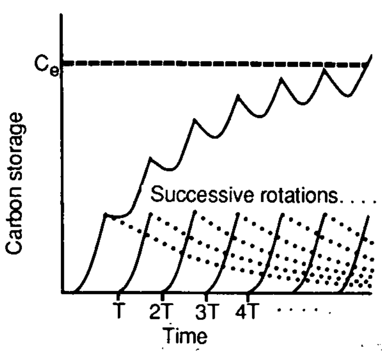

Figure 2. (Top curve) The behaviour of carbon storage (t C ha^{-1}) in trees and their wood products as a function of time (years) since initial planting. C_e is the equilibrium level of carbon storage. The lower sequence of curves shows the contributions from the growing forest (solid curves) and decaying products (dashed curves) in successive rotations of length T (years)

The factors which affect the equilibrium level of carbon storage (C_e) in trees and their wood products are the tree growth rate, the rotation period (T), and the decay time of wood products (D_w). The general result can be expressed by the following equation:

$$C_e = C_f(T) + D_w \times \text{mai}(T) \quad (1)$$

$C_f(T)$ is the carbon content of trees, averaged over a rotation period of T years. The second term, representing the contribution from wood products, involves mai(T) (the mean annual increment), which is equal to the carbon content of trees at harvest divided by the rotation period, and is therefore a measure of the carbon productivity of the forest.

The optimum rotation period

If there is no risk of windthrow, it is normal forestry practice to choose the commercial rotation period (T*), such that the mean annual increment, and hence productivity, is maximised. In general, such a choice does not maximise carbon storage. Figure 3 plots the result in equation (1) for equilibrium carbon storage as a function of rotation period (T) and wood product decay time (D_w). For a given tree growth curve (inset), the rotation period for maximum carbon storage depends on the size of the decay time relative to the commercial rotation period (T*). Two cases arise:

1. Decay time of wood products (D_w) less than the commercial rotation period (T*)

   This case applies to the lowest curve in Figure 3, which is typical of a forest harvested for short-lived products such as paper, whose general shape is dominated by the storage of carbon in trees. Maximum carbon storage occurs when the forest is left as long as possible to mature before harvesting. In fact, the maximum level of carbon storage is equal to the carbon content of mature trees. For this case, therefore, most carbon is stored when the forest is not harvested at all.

2. Decay time of wood products (D_w) greater than the commercial rotation period (T*)

   This case applies to the curves with peaks in Figure 3, which are typical of forests harvested for long-lived products, such as building timber. If D_w is much larger than T*, then most of the carbon is stored in wood products, and maximising productivity will also maximise carbon storage, and the horizontal position of the peak will coincide with the commercial rotation period (T*). Because the size of each peak is greater than the carbon content of mature trees, it follows that, in this case, managed forests and their products together store more carbon than unmanaged forests alone.

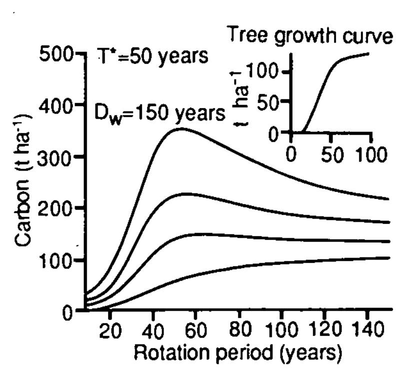

Figure 3. The relation between equilibrium carbon storage in trees and their wood products (C_e in Figure 2) and the rotation period of harvesting, T, for a forest (growth curve inset) with a commercial rotation period, T, of 50 years which is converted to different wood products with half-lives, D_w, of 10, 50, 90 and 150 years respectively*

The same two cases arise when carbon storage is examined as a function of tree growth rate and rotation period, for a given set of wood products. Figure 4 compares species which mature to the same carbon content but at different rates (see inset). In this Figure, the faster-growing species accumulate more carbon in wood products because they are harvested more frequently. In general, therefore, it is the ratio D_w/T^* (decay time of wood products/ commercial rotation period) which determines whether or not carbon storage is enhanced by harvesting trees.

The model also indicates the general result that, for commercially harvested forests, the proportion of carbon stored in trees and wood products is in the ratio $1:2.5D_w/T^*$. This result underlines the relative importance of the pool of carbon in wood products when short-rotation species are harvested for long-lived products.

Carbon storage in forest soils

The largest pool of carbon in most temperate forest stands resides in dead organic matter on the forest floor and in the underlying soil layers. It is, therefore, important to quantify the effects of harvesting on the storage of carbon in forest soils. While the complexity of soil systems presents major difficulties in this respect, one generally expects forest

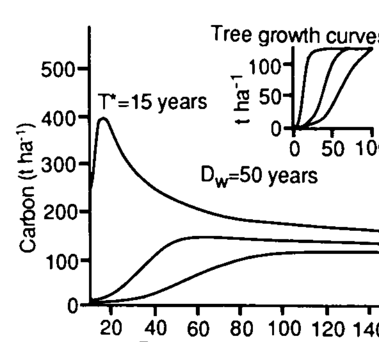

Figure 4. The relation between equilibrium carbon storage in trees and their wood products (C_e in Figure 2) and the rotation period of harvesting, T, for three different forests (growth curves inset) with commercial rotation periods, T, of 15, 50 and 80 years, respectively, converted to the same set of wood products with a half-life, D_w, of 50 years*

floor organic matter to undergo an initial period of decline after harvesting, followed by a period of recovery towards pre-harvest levels.

This response is the result of a lag in the recovery of litter production by the new crop, perhaps coupled with enhanced soil decomposition rates following disturbance at harvesting. In the model, such responses have been obtained analytically in terms of the litter input parameters and decay times.

Successive harvesting, therefore, leads to a reduction in the storage of carbon in soil organic matter, relative to that of an undisturbed stand. Analytical calculations from the model show that, for a given species, the size of the leaf litter pool depends negatively on the ratio t_c/T (canopy closure time/rotation period); this ratio governs the extent of the early period after harvesting – during which the litter pool is responding to a decline in input – relative to the lifetime of the stand.

For commercially harvested forests, one expects little variation in the ratio t_c/T^* from one species to another. In this case, the model shows that the size of the equilibrium leaf litter pool is determined mainly by the level of litter production following canopy closure. Field data indicate a positive linear relation between leaf litter production and species growth rate (Miller 1984). If similar relations hold for branch and root litter production, the model suggests that the conversion of slow-growing, long-rotation forest to fast-growing, short-rotation forest could enhance the soil carbon pool through an increase in litter production.

Further analysis indicates that the proportion of carbon stored in living trees and in the leaf litter added by afforestation is in the ratio $1:0.5D_l/T^*$, where D_l is the decay time of leaf litter and T^* is the commercial rotation period. Generally, leaf litter represents a relatively small contribution to carbon storage, in comparison with living trees, wood products, and root and branch litter.

Future developments

The model is being extended to include a fuller description of the soil and detritus components. In this regard, some insight can be gained from numerical results of the computer model FORTNITE (Aber & Melillo 1983), which contains a forest floor decomposition module and which is currently being applied to UK forests by ITE. In particular, because litter production and decomposition respond to temperature and moisture variations, the extended model will include these responses in order to examine the effects of climatic change on carbon storage.

R C Dewar

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Forest soils and the 'greenhouse' gas nitrous oxide

The gaseous loss of nitrogen (N) *via* denitrification is the least understood aspect of the nitrogen cycle in forest ecosystems. This lack of data relates both to the difficulties associated with making such measurements and to the assumption that nitrification rates, and hence also denitrification rates, are insignificant in acid environments. It is now accepted, however, that nitrification, whether autotrophic or heterotrophic, may be important in forest soils.

Additionally, a number of studies have shown that nitrification and nitrate leaching increase following clearfelling of forest sites (eg Adamson *et al.* 1987). This increase in nitrate concentrations coincides with increases in the water content of the soil as a result of the cessation of transpiration by the trees, and with increases in the supply of organic matter in the soil by the decomposition of roots and slash left on the site. It is these three factors – nitrate availability, energy supply, and state of aeration of the soil – which control the rates of denitrification in soils. Thus, it would appear that, if denitrification is an important mechanism for the loss of N from forest sites, it is in the years following felling that losses may be greatest. The measurement of such losses has recently assumed increased importance as attempts are made to quantify the various inputs of 'greenhouse' gases to the atmosphere, of which nitrous oxide (N_2O) is one. Nitrous oxide is one of the principal products of denitrification, under certain conditions.

Although there are obvious links with human population increase and the rising atmospheric concentrations of carbon dioxide, we are still fairly ignorant of the sources and sinks for nitrous oxide in the environment. Nitrous oxide absorbs infrared radiation much more strongly than carbon dioxide, and is therefore a more potent 'greenhouse' gas. The concentration of the gas in the atmosphere is currently very low, but it is rising at an annual rate of 0.25%, and no-one is quite sure why.

Nitrous oxide has an average lifetime in the atmosphere of around 170 years, and is mainly produced as a result of microbial activity in the soil. The increased utilisation of nitrogen fertilisers goes some way to explaining the rise in atmospheric concentrations, but only about 10% of all the N_2O released is attributable to the use of fertiliser. Soils produce both di-nitrogen (N_2) and nitrous oxide in the process of denitrification, and N_2O release is thought to dominate in acid soils. The purpose of the work described here was to determine whether forest soils lose appreciable quantities of nitrogen through denitrification, particularly after felling, and the extent to which N_2O is produced.

Rates of nitrogen loss through denitrification were monitored for a standing Sitka spruce (*Picea sitchensis*) plantation, and for an adjacent clearfelled area located on a peaty gley soil at Kershope Forest in the north of England, in two year-long studies. The site is described in detail by Adamson *et al.* (1987), and has been used for a parallel study on the release of nutrients into freshwaters following felling (Plate 1). The rates of denitrification were determined using soil cores brought back to the laboratory and incubated at 15°C in the presence of acetylene.

In the first study, sampling was performed once every two weeks over the course of a year, with six cores being taken per sampling and plot. In the second year of study, twice as many cores were taken, and half were incubated without acetylene (C_2H_2) to assess the relative emissions of N_2 and N_2O.

Acetylene specifically inhibits the conversion of N_2O to N_2, and enables total denitrification to be assessed simply by quantifying N_2O accumulation in the presence of acetylene. An equation relating denitrification to temperature was derived from laboratory studies and applied to the sampling data to provide an estimate for the monthly loss of nitrogen *via* denitrification from the sites.

A gaseous loss of 1–3 kg N ha^{-1} yr^{-1} was estimated for the standing forest, while losses from the clearfelled sites were estimated at 10–40 kg N ha^{-1} yr^{-1} during the first two years after felling. This loss returned to pre-felling levels four years after felling. The differences in denitrification rates between the two plots during the first period of study can be seen in Figure 5. These differences disappeared by July of the second year, after which time the two plots behaved in very similar ways. Cores taken from the clearfelled plot evolved N_2O at a consistently greater rate than those from the standing forest, and cores incubated in the presence of C_2H_2 evolved N_2O at a greater rate than those incubated without. Only data derived from incubations with C_2H_2 are presented, representing the total losses of N through denitrification, including losses that would have occurred as N_2 in the absence of the block. Parallel studies which attempted to explain denitrification rates in terms of soil moisture content, nitrate levels or available carbon failed to show any clear explanation for the sporadic nature of the denitrification process, which is clearly seen in Figure 5ii.

The annual loss of nitrogen from the standing forest in the current study lies within the range of estimates obtained from similar studies in the USA. Such losses are not large in terms of the N cycle for the site, and are more than compensated for by the wet deposition of N (estimated as 6.7 kg ha^{-1} during 1984, Adamson *et al.* 1987). The data from the felled sites suggest that denitrification increased in the first two years after felling, and represented a loss from the site of 10–40 kg N ha^{-1} yr^{-1}. The lack of any marked difference in denitrification between the plots in the second year of study indicates that such increases are not maintained over many years. The increase, and subsequent decline, in denitrification following felling at Kershope corresponds well with the measured changes in nitrate concentrations in the drainage waters from the plots (Adamson *et al.* 1987). The gaseous loss of N is not large enough to suggest that the site is being impoverished by this process, but it is of the same order of magnitude as leaching losses (Adamson *et al.* 1987).

Plate 1. Kershope Forest, Cumbria, showing standing and clearfelled forest in the experimental plot

The losses of N measured here are not considered to be important in terms of a nutrient depletion from the site. The fact that the majority of the N produced in the

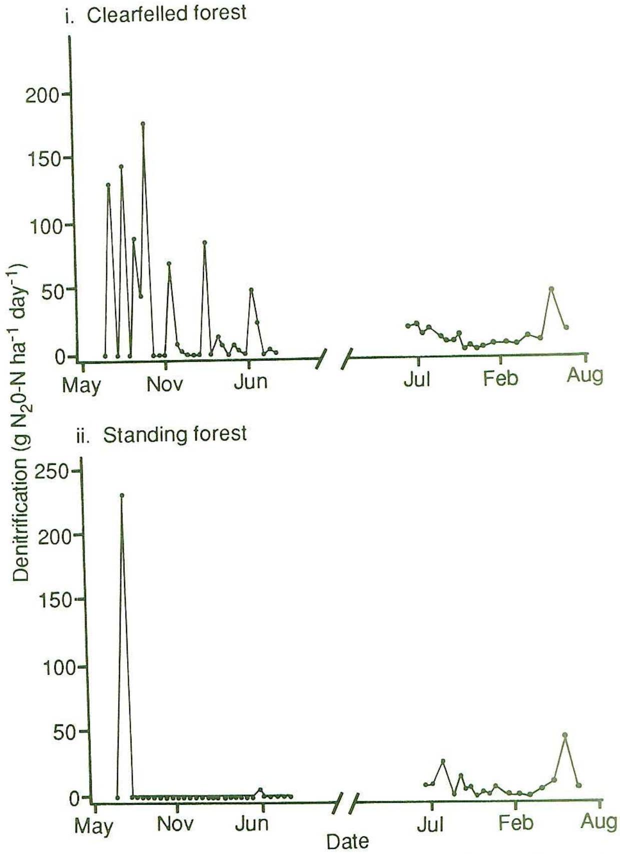

Figure 5. Denitrification losses from the clearfelled plot and from the standing forest, after correction of the data for field temperature

1987–88 study was in the form of N_2O (2.6 kg of the total 3.2 kg measured) may be significant, given both the increasing concern over inputs of 'greenhouse' gases to the atmosphere and the involvement of N_2O in the destruction of the ozone layer.

The figures from the 1987–88 study of the standing forest fall within the typical range for forest ecosystems, and it is possible to make a provisional estimate of the order of magnitude of denitrification losses from forestry in the UK. Such extrapolation is subject to many errors, because different soil types, management regimes and climate will have overriding effects, yet a comparison with the losses from agriculture in the UK is useful.

The total area of woodland in the UK is approximately 2.21×10^6 ha, including conifers, hardwoods and scrub. When multiplied by the 3.2 kg N ha^{-1} yr^{-1} derived from the current study, an estimated annual denitrification loss of 7.1×10^6 kg N from these ecosystems is derived. Approximately 5.7×10^6 kg N would be in the form of N_2O, assuming the N_2/N_2O ratios observed in the current study. In comparison, UK agricultural systems including grassland cover approximately 18×10^6 ha, and the annual gaseous loss of N *via* denitrification of applied fertiliser N has been estimated as 2.1×10^8 kg. Approximately 6% of this loss is in the form of N_2O, giving a total annual production of N_2O from fertiliser applications to agriculture in the UK of 12.6×10^6 kg, approximately double that estimated above for woodland and afforested areas. This figure is related to the high N_2/N_2O ratio observed for denitrification in acid forest soils, rather than to a high rate of total denitrification.

Such estimates are extremely approximate, and more studies are necessary to increase their precision. However, in terms of N_2O inputs to the atmosphere, they do indicate that forest ecosystems may approach the importance of intensive agricultural systems in the UK. Data relating to forests on other soil types and with other land uses are needed, if UK emissions of nitrous oxide are to be estimated accurately.

P Ineson

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Colonisation of a raised bog by Scots pine

Scots pine (*Pinus sylvestris*) occurs in both semi-natural and plantation woodlands in Britain and can tolerate a wide range of conditions. As well as growing on light and freely drained soils and on heaths, it is often found on lowland peats and even on some waterlogged peats. Scots pine is an aggressive coloniser in many parts of northern Europe, as was suggested in last year's Annual Report, where it was shown to be the most abundant of 15 tree species regenerating on open upland in Deeside and Donside. It is able to survive in bogs, even where water tables are close to the surface for large parts of the year, so long as conditions in the rooting zone are not reducing. Bogs may be expected to become more susceptible to colonisation where their slow, natural drainage has been enhanced by artificial drainage, either internally to facilitate peat extraction, or peripherally to improve drainage of surrounding agricultural land.

An example of Scots pine colonisation is at Kirkconnell Flow National Nature Reserve, Kirkcudbrightshire, where the demography of both pine and birch (*Betula* spp.), another coloniser, has been studied since 1972. The site is an estuarine raised bog, about 9 m above sea level; it occupies a rectangular area of 155 ha, and has an annual rainfall of approximately 100 cm. Following a survey of vegetation in 1972, and of trees in 1974, the trees were remeasured in 1979 and 1988, so that it is now possible to assess the rates of colonisation and growth in different parts of the bog.

The original vegetation survey, on 159 systematically distributed sample plots arranged on a grid of 100 m, produced data which were classified into eight groups of quadrats identified by indicator species. The two major groups represented, on the one hand (Groups 1–4), vegetation of the central wet bog or that associated with peat-cutting activities immediately surrounding the central area, characterised by species such as cotton-grass (*Eriophorum* spp.) and marsh rosemary (*Andromeda polifolia*), and, on the other hand (Groups 5–8), that of the peripheral and drier area, parts of which have a developing woodland flora with abundant ferns. The subsequent surveys of trees, which included measurements of diameter and height, positions of individual trees, and numbers of saplings and seedlings, were restricted to 40 plots, chosen so as to sample stands in different regions of the site and using the eight vegetation groups as sample strata.

The 1974 tree survey showed marked contrasts between vegetation groups, first in the relative importance of numbers and basal area of Scots pine and birch, and second between the numbers of pine trees, saplings and seedlings in different groups.

Scots pine

The most dynamic parts of the system (Figure 6) are Groups 1 and 2, the youngest stands of Scots pine. Here, the rapidly increasing density of pine trees is fed by recruitment from the sapling class, and little mortality occurs. Basal area increased rapidly over both periods at an annual compound rate of between 4% and 7%, but, because of the increasing number of trees, mean basal area per tree only increased slightly from 0.012 m^2 to 0.014 m^2. Tree numbers in Groups 3, 4 and 5 remained stable in terms of numbers throughout the whole period, with only slight recruitment or mortality. Basal area continued to increase but the annual compound rate of change was lower than in the younger stands, slowing from 5% to 2% over the two periods in Group 3 because of some mortality, and remaining at about 5% in Group 4. The plots with largest pine trees, in Group 5, increased in basal area by a consistent 2% over the whole period, during which mean basal area per tree increased from 0.078 m^2 to 0.112 m^2.

Whilst numbers of pine trees in Groups 1 and 2 increased in both periods, those of saplings (<5 cm diameter at 1.3 m) and seedlings (<1.3 m high) decreased considerably. Sapling numbers can change as a result of promotion into the tree category, recruitment from the seedling category, or by mortality. Promotion reduced sapling numbers to an extent which was approximately balanced by recruitment, but there was significantly higher mortality, especially in the second period. This finding conforms with experience elsewhere: the number of stems in a sapling stand decreases as stem diameter increases, according to a negative exponential probability distribution. Pine sapling numbers in plots of Groups 3 and 4 were little changed. Pine seedlings, which, like the saplings, had been marked with numbered tags so that their fate as individuals could be followed, failed to show a consistent numerical increase in any part of the bog over the whole period; indeed, only in Group 2 plots was an increase shown in either period.

Even allowing for promotions to the sapling category, it is clear that seedling numbers declined markedly. What are the reasons for this decline? First, there has been little recruitment of seedlings

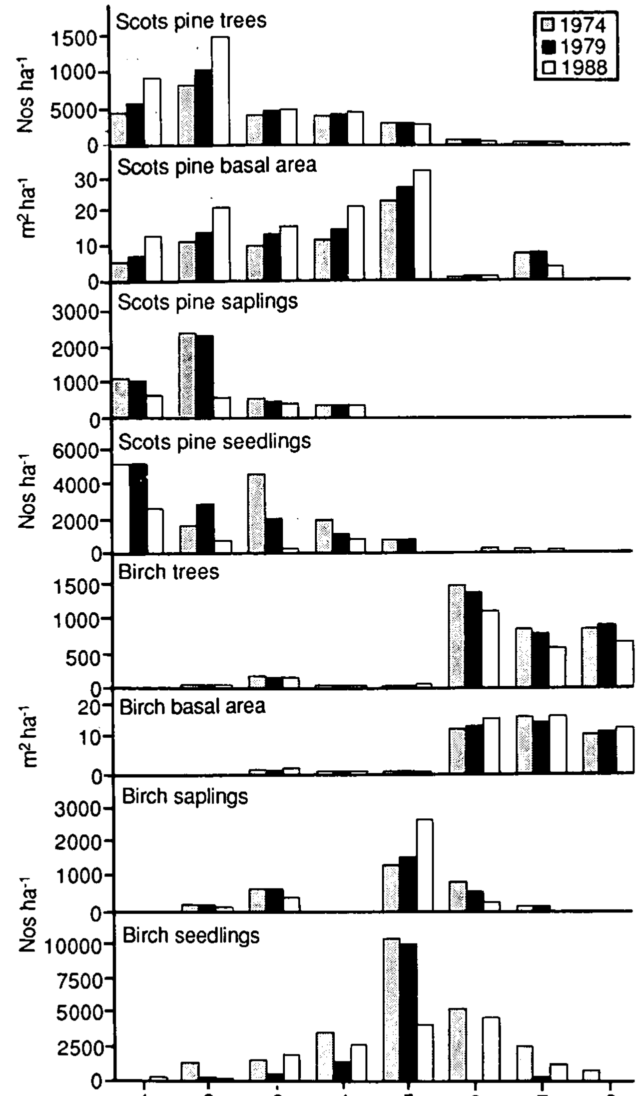

Figure 6. Characteristics of Scots pine and birch stands in different types (Groups) of vegetation at Kirkconnell Flow in 1974, 1979 and 1988

into the population; the vast majority of seedlings recorded in Groups 1, 3 and 4 in 1979 were survivors, and this was true of all groups in the second period. However, there was some recruitment in Group 2 plots during the first period, suggesting that there was no site-wide dearth of pine seeds. Second, it is possible that increased numbers of roe deer (*Capreolus capreolus*) contributed to the decline in seedling numbers, but a more likely cause is the drying out of the surface layers of peat in dry summers, as in 1976 and 1984.

Measurements carried out at dip-wells between 1979 and 1981 showed that, even in the wettest parts of the bog, water levels fell to 90 cm below the ground surface during the summer. Summer water levels for Group 2 plots were the highest, being above 20 cm in 35% of the fortnightly samples. This fact could account for the better survival of existing seedlings and for additional recruitment in some parts of the bog. Similar declines in pine seedling numbers have been observed in another raised bog, Rusland Moss, in south Cumbria. Pine seedling numbers appear to follow a cyclic pattern at these sites, reaching maxima following particularly good seed years, but gradually declining over long periods, in spite of occasional recruitment.

Birch

The interest in birch, another light-demanding colonist, centres on its ability to make inroads on the wet bog and to retain its dominance in the dry, peripheral areas where it might be expected to be overtaken by pine. Scots pine and birch have similar site tolerance but, in direct competition, pine is often more successful.

There is little evidence of birch invading the wetter parts of the central bog, represented by Groups 1 and 2, or in Groups 3 and 4 which immediately surround it, although numbers of birch seedlings were much the same at the end of the period as at the start in Groups 3 and 4. Group 5 plots are characterised by very large pine trees with an understorey of birch saplings, whose number increased by recruitment from the seedling category during both sample periods. These saplings are expected to take advantage of the break up of the pine stand during the next two decades. Elsewhere, the birch stands of Groups 6–8 showed reduced numbers of stems and only very small changes in basal area, with maximum annual compound rates of change of 2%. Numbers of saplings decreased and, although seedling numbers showed inconsistent trends in the two periods, the general trend over the whole period was downwards. There was, however, no influx of pine seedlings into these areas, many of which have dense vegetation dominated by ferns. Thus, although the birch stands may be starting to decline, present conditions are unsuitable for pine colonisation.

These results from repeated surveys show that rates of tree growth and patterns of development of wooded bog are quite varied; moreover, there is some evidence that colonisation may occur in cycles or waves rather than in a continuous fashion. They also demonstrate that, whilst repeated surveys can show trends in development and can be used to generate hypotheses relating cause and effect, they are themselves unable to clarify these relationships without additional research.

J M Sykes

Nature conservation in upland conifer forests

(This project was funded by the Forestry Commission and the Nature Conservancy Council)

The objectives of this study were to determine the effects of forest design, structure and management, during the forest cycle, on wildlife conservation in upland conifer forests, and to make recommendations for improving the nature conservation values of such forests.

Most of the work was done in Kielder Forest (Figure 7, Plate 2), which is the

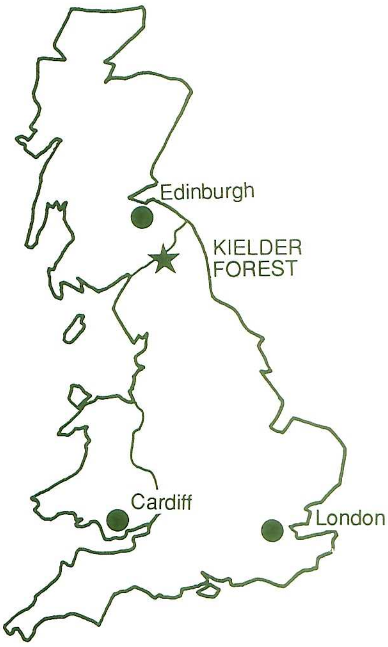

Figure 7. Map of Britain showing the location of Kielder Forest

largest man-made forest in Europe. As in other forests in exposed situations on predominantly peaty gley soils, the trees at Kielder are prone to windthrow. Therefore, as thinned stands are more likely to blow down, most of the crop, over 75% of which is Sitka spruce (*Picea sitchensis*), is unthinned. To pre-empt windthrow, susceptible crops are felled much younger than they would otherwise be, at 35–40 years rather than at 50–55 years. This practice has resulted in fragmentation of the large blocks of forest of even age, and in the development of a much more diverse forest structure.

The main investigation was based on a sample vegetation survey of planted and unplanted areas throughout Kielder Forest. The revegetation of clearfelled areas was investigated in more detail, and a comparison was made of vegetation succession beneath thinned and unthinned stands of a range of species. In addition to the vegetation surveys, a study was made of selected invertebrate groups (moths, spiders, carabid and staphylinid beetles), relating their diversity and abundance to vegetation type.

A physiographic stratification technique was used for the main vegetation survey. Fifty-four 1 km squares were chosen, representing a range of altitude, soil and geographical drainage classes, and a structured system was used to select sites within them for sampling the vegetation. The plant communities in the sampled areas were classified using multivariate analysis procedures, and were matched, where possible, with communities of the Nature Conservancy Council's *National vegetation classification* (NVC).

The vegetation in the sample squares was mapped on aerial photographs, each unit of vegetation being assigned to an NVC community. A computerised cartographic technique was used next to determine the areas of the units, and to calculate the total lengths of linear features and the areas of other unplanted land occupied by each NVC community in each sample square. Estimated areas for the whole Forest were then derived on the basis of the original stratification. Using Lunn's map of the vegetation of Northumberland as a guide, and comparing the areas of plant communities on his map with those determined for similar physiographic units, a map was produced showing the probable distribution of NVC communities within unplanted areas in the Forest. (This map is too detailed to reproduce at a small scale, so is not included in this Report.)

A dichotomous key was devised for the NVC communities likely to be found in upland conifer forests, and, because it was intended for use by people with little knowledge of upland flora, it was based on easily recognisable dominant plant species.

A map of proposed broad management units was produced for Kielder (Figure 8), using the occurrence of NVC communities in relation to physiographic zonation. To assist the interpretation of this map, a series of block diagrams was drawn showing the distributions of particular NVC communities in 1 km squares representative of particular management units (Figure 9). With a little experience, the map of management units can be used, together with the management prescriptions for individual NVC communities, to determine appropriate conservation management for the range of vegetation types.

The effects of clearfell location (altitude, soils), size, and isolation on revegetation were investigated by standard vegetation survey techniques. The influence of microhabitats (brash, ditches, tree stumps) was also included. The effects of thinning were studied using information provided by the Forestry Commission on thinning treatments as a basis for selecting stands for field visits and subsequent interpretation of the vegetation survey. The effects of different intensities of thinning were not examined.

Twenty-one locations, representing as wide a range as possible of the plant communities and habitats within the Forest, were selected for the survey of invertebrates. Pitfall traps and turf samples were used to determine

Plate 2. View of Kielder Forest showing the characteristic rolling terrain with afforestation at intermediate to high altitudes. The effects of restructuring the Forest can be seen clearly, with the development of structural diversity

Plate 3. The effects of browsing by roe deer on trees and ground vegetation. While the trees are damaged by the deer, the ground vegetation is inadequately grazed for the retention of floristic and associated faunal diversity

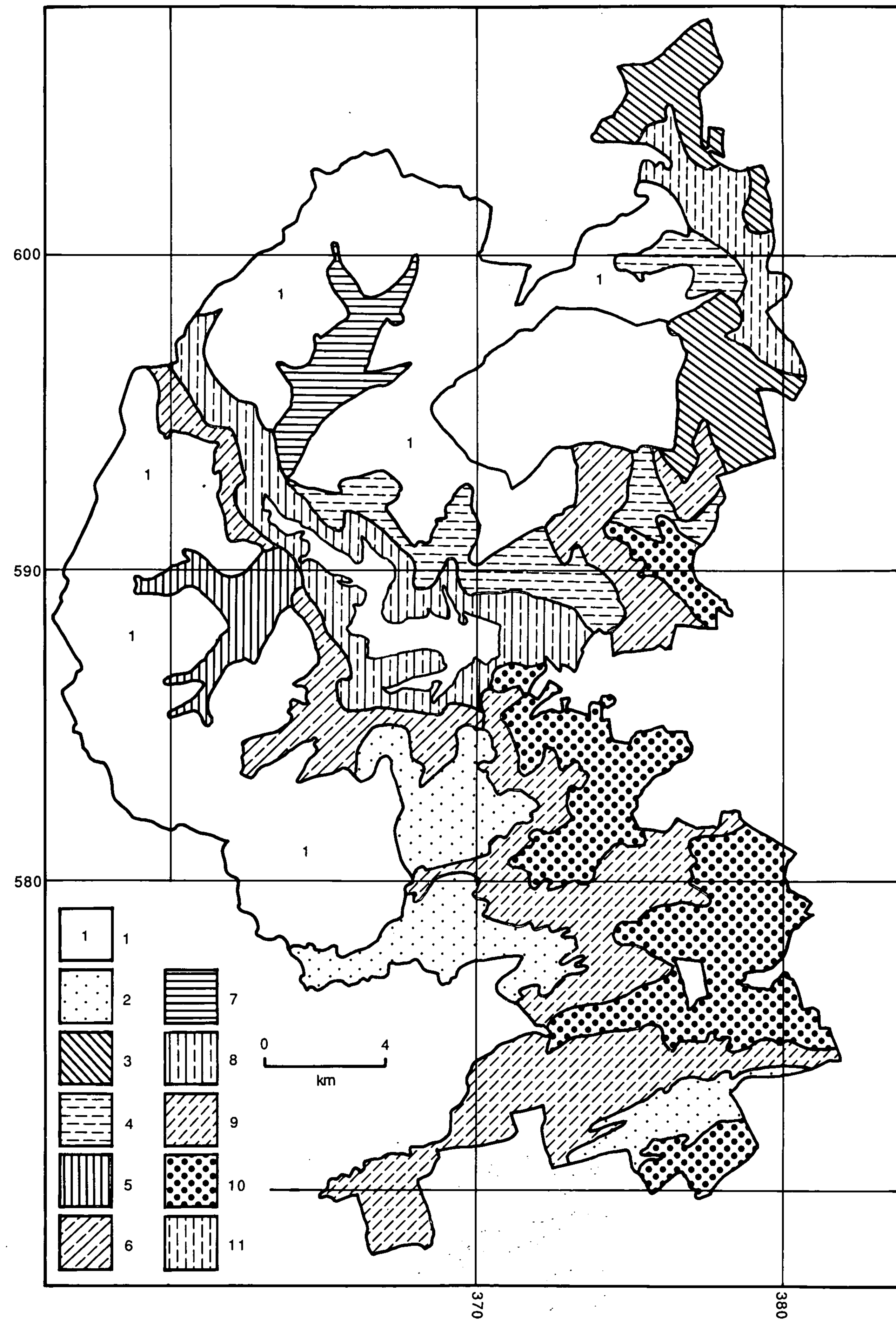

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Figure 8. (Opposite) Map of Kielder Forest showing proposed management units
Key

1. High-altitude (300–500 m) areas on deep peat with extensive rock outcrops. Vegetation dominated by heather (*Calluna vulgaris*)
2. High altitudes, though rarely reaching over 500 m. Predominantly peat, but with occasional boulder clay deposits. Usually dominated by heather, but with mire dominated by moor-grass at lower elevations
3. High altitude with boulder clay prevalent. Vegetation a mosaic of acid grasslands and dry heath
4. Moderately steep river valleys to the north of the reservoir. Broadleaved woodland frequent
5. Steep north-flowing river valleys in which limestone outcrops enhance the diversity of the vegetation
6. Low-altitude boulder clay forming gently sloping land to the south of the reservoir
7. Kielder and Scaup burns. Rocky terrain supporting a mix of dry heath and acid grassland
8. Lowland lakeside. Mainly mesotrophic grassland with some broadleaved woodland
9. Low-altitude boulder clay forming more or less flat land, almost completely afforested. Vegetation dominated by purple moor-grass or, on better-drained mineral soils, tufted hair-grass
10. Lowland boulder clay on the south-east part of the Forest. Moor-grass grassland or rush (*Juncus* spp.) pasture common over much of the area. Acid grassland remains where sheep grazing has been maintained
11. Low-altitude boulder clay, river valley. Still actively farmed and essentially outside the influence of afforestation

Table 1. Estimated proportions (%) of stands with little or no vegetation in first-rotation crops and restocked areas at different elevations in Kielder Forest when surveyed in 1987

	Proportion of stands with little or no vegetation		
Elevation class (m)	First-rotation stands	Restocks	All
<300	54.0	5.2	29.6
>300	73.0	14.3	43.6
All	63.5	9.7	36.6

Age class composition of sampled stands in each elevation class were as follows:

Age range (yr)	Elevation (m)	
0–20	<300	>300
21–40	15	7
>40	52	73
	33	20

abundance and diversity, and Heath portable light traps were used at ten of the sites to survey night-flying moths.

Sixty-three per cent of first-rotation forest blocks at Kielder either had no ground vegetation, or cover and species diversity were so low as to preclude recognition of even remnants of NVC communities (Table 1). The much lower proportion of bare ground in the restocked areas reflected recent establishment: in most cases, the trees had not yet closed canopy and suppressed the vegetation. The highest proportion of ground with little or no vegetation (73%) was in first-rotation stands above 300 m elevation. However, this result may have been influenced by the age composition of the crops: there were fewer pre-thicket crops but more closed canopy stands above 300 m than at the lower elevations. There is no doubt, however, that the effects of afforestation were most marked at the highest elevations, notably on deep peat and peaty gley soils above 425 m. Even though tree growth tended to be slower there than at lower elevations, and gaps in the canopy were more frequent, allowing survival of some ground vegetation, the original mire communities were generally much altered with loss of some of their most characteristic species which depend on waterlogged soil conditions. This is not surprising bearing in mind that trees cannot be grown on such sites without first draining them and fencing them to exclude domestic livestock, both processes which are

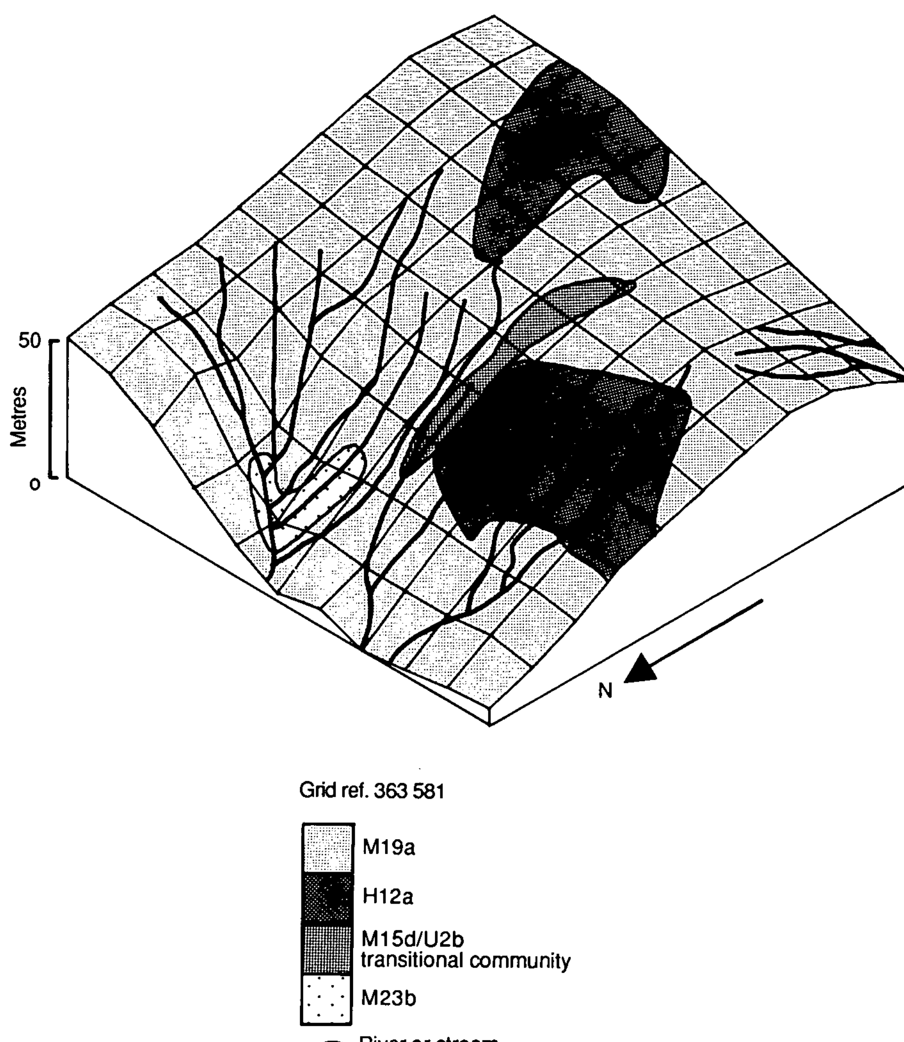

Figure 9. Example block diagram showing distribution of differing NVC communities in a high-altitude 1 km square on deep peat with extensive rock outcrops
Key

19a	Heather/cotton-grass (*Calluna vulgaris/Eriophorum vaginatum*) blanket bog; cross-leaved heath (*Erica tetralix*) sub-commmunity
H12a	Heather/bilberry (*Calluna vulgaris/ Vaccinium myrtillus*) heath; heather (*Calluna vulgaris*) sub-community
M15d/U2b	Transitional community between deer-grass/cross-leaved heath (*Trichophorum cespitosum/Erica tetralix*) wet heath – bilberry (*Vaccinium myrtillus*) sub-community) – and wavy hair-grass (*Deschampsia flexuosa*) grassland – bilberry (*Vaccinium myrtillus*) sub-community
M23b	Soft/sharp-flowered rush/lesser marsh bedstraw (*Juncus effusus/ acutiflorus/Galium palustre*) rush pasture

antagonistic to the health of mire communities. The problems are further exacerbated by the fact that thinning of the crop to increase light penetration, which would be helpful to the conservation of ground vegetation, is generally not possible at these high elevations because of windthrow hazard. Therefore, nothing can be done to improve the conservation of ground flora in these crops.

The estimated 35% of land at Kielder where ground vegetation can develop is nearly all on mineral soils at low altitude. The vegetation present before afforestation was changed even in thinned crops, the former grassland communities tending to be replaced by those dominated by woodland species. Thinned conifer stands, including Sitka spruce, had developed similar plant communities to thinned broadleaves on the same soils. The invertebrate survey suggested, albeit from information obtained from very few stands, that thinned mature spruce crops and unthinned mature larch (*Larix decidua*) may have more diverse and abundant invertebrate communities than unthinned spruce crops on similar sites (Table 2). In addition, the communities were not dissimilar to those beneath semi-natural alder (*Alnus glutinosa*) growing on a more fertile and freely drained site. There may, therefore, be good opportunities for conservation by thinning conifer crops at low altitudes on mineral soils.

Table 2. Mean numbers of individuals (and species) of selected invertebrate groups taken in pitfall traps in different tree stands at Kielder Forest in 1988

Invertebrate group	Tree crop: Unthinned spruce	Unthinned larch	Thinned spruce	Alder
Spiders	159(20)	351(27)	388(24)	575(34)
Staphylinid beetles	119(19)	260(30)	152(29)	106(23)
Carabid beetles	72(3)	22(7)	699(12)	201(16)
Diptera*	275	722	534	890
All (abundance)	625	1355	1773	1772

*Diptera not identified to species

The vegetation developing on clearfelled ground was determined primarily by the amount and type of vegetation surviving through the previous crop cycle (which was influenced primarily by whether or not the crop had been regularly thinned), the availability of buried seeds, and the presence of microhabitats in the clearfelled areas. It was influenced very little by the size of the clearfelled area, its isolation from sources of colonising plants, or the vegetation in adjacent areas. Therefore, diversifying forest structure by creating more, smaller, clearfelled areas scattered throughout the crop is unlikely to affect the conservation of plant communities. Clearfelled areas seem to develop diverse and abundant communities of some invertebrates, such as carabid beetles, soon after tree removal, whereas other invertebrates, such as spiders, seem to reinvade more slowly, probably because many species are less mobile and require well-developed vegetation to support their webs.

Unplanted areas comprise approximately 20% of the total forest area. They include rides, riversides, forest roads, quarries, rock outcrops, Sites of Special Scientific Interest (mostly raised mires), and unimproved farmland. Some of the undesignated areas, particularly riversides and unimproved agricultural land, retain characteristic plant and animal communities which are now scarce in Northumberland. In many instances, however, they are threatened by the removal of domestic grazing animals, without which species-rich grassland is replaced by vegetation dominated by a few species of common tussock grasses, notably purple moor-grass (*Molinia caerulea*) and tufted hair-grass (*Deschampsia cespitosa*). These changes are occurring even though roe deer (*Capreolus capreolus*) are present at densities which often preclude the regeneration of broadleaved trees and shrubs and cause severe damage to conifers (Plate 3). However, unlike sheep and cattle, roe deer are primarily browsers rather than grazers.

In order to retain or retrieve the conservation interest of these old field and riverside sites, it is necessary either to reinstate a grazing regime or, where possible, to replace grazing with mowing. A few representative sites conserved in this way could be used to gauge the effects of changing management elsewhere in the unplanted parts of the Forest. An alternative management approach where the existing evidence suggests that the former meadow was not especially species rich is to plant broadleaved trees with the long-term aim of developing permanent broadleaved woodland. This method is only likely to be successful within reasonably short time periods where there is broadleaved woodland nearby from which woodland flora and fauna may invade the new plantings.

Both the vegetation survey and the invertebrate study showed that man-made habitats within the Forest, notably roadsides, make a major contribution to the overall diversity of flora and fauna. Many plants and animals occur most commonly on roadside verges, while some, including species which are rare in Northumberland, are restricted to them. Much of this conservation interest is a result of the frequent disturbance associated with road maintenance and the variety of microhabitats commonly associated with roads, including the road surface, drainage ditch, bank, disturbed and undisturbed pre-existing vegetation. There are opportunities for diversifying roadside vegetation further, for example by mowing to create zones of differing vegetation height and by planting broadleaved shrubs adjacent to the conifer crop. Extra freshwater habitat, essential for many aquatic plants and animals, could easily be introduced by digging small roadside pools. If these pools had shallowly sloping sides, they would allow colonisation by marginal water plants and encourage their use as breeding sites by amphibians. Roadstone quarries, which occur throughout the Forest, provide opportunities for the creation of water bodies on a larger scale.

J E G Good, T G Williams and D Norris

Land use, agriculture and the environment

The contributions from this Research Programme demonstrate the importance of scale in relating ecology to the study of landscape and countryside. Although the first article rightly emphasises the flexibility and wide applications of remote sensing techniques, it also shows that the main achievement has been in identifying land use cover and change at a geographical scale. The incorporation of remotely sensed data into geographical information systems (GIS) is an important development of this work. A more specific use of remotely sensed data is given in the second account of airborne imaging spectrometry. The demonstration that amounts of fertiliser application, reflected in vegetation characteristics, can be detected by this means is valuable both practically and for scientific ecological investigation.

The ECOLUC project is central to the theme of relating land cover and land use to a geographical setting and emphasises the dynamics and results of change. The development of this theme to provide a rigorous conceptual framework for landscape ecology is seen as a major initiative. The fourth article on the siting of wind turbines effectively points up in detail the relationship between ecology, the physical environment, and 'institutional' (social, political and administrative) constraints in a relatively novel field. By providing information upon which sensible planning decisions can be made, it encapsulates the role of NERC in relation to public administration.

The fifth article describes a relatively straightforward example of problem-solving, which nevertheless combines ecological, agricultural and wider land use components and places them in a general economic context. It also demonstrates the growing ability of ITE to undertake useful ecological studies overseas, in countries faced with many of the most urgent environmental problems.

The history given in the final paper in this section charts the progress of the Biological Records Centre from its 'academic' origins, and records the development of products which are generally applicable to real problems, notably those of wildlife conservation. The wide relevance of the work of the Centre and the opportunities for imaginative applications (in such rapidly developing areas as climate change) are emphasised.

Remote sensing for agricultural applications

Remote sensing is used to map and measure land cover, land use, and various physical aspects of ecosystems, at local to global scales. It can be used to detect and measure landscape patterns, and the way in which such patterns change. It may highlight the effects, for example, of pollution, soil damage, or climate change. Remote sensing can be used to map topography, thermal effects, soil type and soil moisture. It can provide a direct measure of the composition and condition of natural and agricultural vegetation. It can be combined with other spatially referenced data sets within a geographic information system (GIS), as a means of investigating ecological relationships in the context of topography, substrata, climate, land use and management. Remote sensing enables us to look at past landscape patterns, to assess the present situation, and then to make predictions about the future. It is a powerful tool, with a wide range of applications.

ITE is concerned with the ecology of the natural, semi-natural, and man-made environment of Britain. Therefore, the Remote Sensing Unit at ITE's Environmental Information Centre (EIC) is frequently involved in studies of agricultural landscapes. There have been large-scale changes in agricultural land use over the last 50 years, and the trend is continuing, with schemes such as set-aside, the definition of water protection zones, moves towards farm forestry, and general extensification in both uplands and lowlands. Furthermore, if climate changes follow typical predictions, we may see quite different patterns of land use, not only because of changing land capabilities in Britain, but also because of the economic and political pressures which will naturally arise from any shortfalls in production at the European or world scale. The role of remote sensing in resource assessment, predicting changes, and assessing environmental impacts is at least as important as it ever was.

Air photographs have long been used by ITE for ecological purposes. A study of two parishes in Lincolnshire examined historical changes from semi-natural grasslands to arable farmland. Results provided test data for a model of nitrate changes in aquifers used for potable water supply. The study used the archive of aerial cover for Britain which extends back to the 1940s. The study of changing extent and quality of grasslands in lowland England and Wales combined field data collected in 1978 and 1984, derived from the sample-based ITE ecological surveys of Great Britain (Bunce & Heal 1984), with air photointerpretation of 1940s prints. The results highlighted the loss of 95% of Britain's unimproved lowland pastures. A general resurvey in 1990 is currently using air photographs to provide accurate base maps which will be supplemented with field data.

The rate and extent of reedswamp regression around the Norfolk Broads were assessed using a sequence of historical air photographs. The changes related closely to the numbers of feral coypu (*Myocastor coypus*), an introduced rodent pest of both wetlands and farmland. Observations of the damage caused by such animals to natural vegetation, crops and flood banks led the Ministry of Agriculture, Fisheries and Food (MAFF) to undertake a campaign to eradicate coypu from Britain. A more general study of semi-natural and agricultural land in Broadland used contemporary air photographs and digital cartography to generate a management data base for the Broads Authority. It emphasised the need for traditional management of the relatively small remaining area of semi-natural habitats.

Digital satellite imagery is increasingly being used to generate information on extensive areas of landscape. The EIC has used Landsat Thematic Mapper (TM) data to map patterns of major land cover types in Cambridgeshire, including three agricultural grassland types and five arable crops (Fuller *et al.* 1989). A combination of summer and autumn data provided more accurate results than studies using single-date imagery, with a typical 85–95% success, depending on the class and the exact definition of success (Fuller, Jones & Wyatt 1989). TM data have been combined with digital maps in a GIS for integrated land use planning and management in the Snowdonia National Park (Jones & Wyatt 1988). The feasibility and cost of expanding public access were assessed by measuring the extents of different land uses, within different altitudinal ranges, to estimate the likely compensation payments to farmers. Use of TM data is being extended to classify grasslands in Wales, as a data source for a model of water chemistry in relation to acid runoff.

The EIC is currently planning to map the land cover of the whole of Great Britain, using TM data. It will be the first full land cover survey of Britain since the early 1960s, the first to use Landsat imagery, and the first to provide complete, national, digital data which are fully GIS compatible. The resultant data base will be integrated with ITE's ground-based surveys of Britain, and with the European CORINE mapping exercise (COordination of INformation on the Environment) (CEC 1989). Digital maps of land cover, viewed on a European scale, together with sample field data and biological records, analysed in a GIS environment, will offer a wide range of uses in landscape monitoring, impact assessment, planning and management.

Remote sensing has worldwide potential for applications in agriculture and the environment. The EIC has been involved in an European Community programme to monitor rangeland productivity in West Africa. This programme aims to develop techniques to provide up-to-date information for forage management in drought regions. Landsat multispectral scanner (MSS) data were used to predict the impacts of dams on rivers feeding the brackish Lake Ichkeul, in Tunisia. The historical archive of data showed how vegetation cycles varied as a natural response to rainfall, and helped to predict impacts of changing lake hydrology, both on aquatic habitats and on the grazing marshes surrounding the lake. This valuable ability to obtain archival data for almost anywhere in the world, covering a period of nearly 20 years and, weather permitting, perhaps for several times in each year, is a unique feature of Landsat MSS.

Where finer spatial resolution (eg 1–10 m) is required, airborne sensors have been used, eg to record the liming of improved grasslands in catchments with acid soils, as part of a study of acid runoff. On the Swavesey Fens, one of Britain's last grant-aided drainage schemes for arable conversion, class maps from airborne imagery supplement field ecological surveys, while scientists from MAFF are measuring and modelling groundwater relations.

Methodological developments in the EIC are applicable to semi-natural and farmed landscapes, and, indeed, many examples have been tested in both. The Unit has collaborated with Cambridge University in the design and implementation of new algorithms for the geometric correction of airborne data. This process is vital if we are to make accurate spatial measurements from ATM, overlay the information with other GIS data, or use multitemporal imagery to refine analyses and highlight changes. Work with the NERC Unit for Thematic Information Systems (NUTIS) has involved topographic correction of differential illumination in hilly terrain to improve the accuracy of classifications in uplands. NUTIS collaboration has tested the mixture modelling approach, which estimates proportional cover within pixels, in order to classify fine landscape patterns with relatively coarse imagery. This procedure is particularly valuable for mapping and measuring in complex semi-natural vegetation and/or where field sizes are small, such as in horticultural areas or grazed uplands. Further work on classification has involved collaboration with statisticians in the Agriculture and Food Research Council (AFRC) to evaluate discrimination procedures.

Future generations of spacecraft will carry imaging spectrometers, which will provide the more precise spectral information needed for assessing plant health and for making reliable estimates of crop yields. The EIC has been a principal investigator in successive airborne campaigns, mounted by NERC and by the European Space Agency, using an imaging spectrometer under experimental conditions. This equipment has been flown over an experiment on the Somerset Levels, in which grassland swards are subjected to a range of fertiliser treatments (see pp 17–19).

Remote sensing based on visible and near-infrared radiation (VIR) will always be limited in northern temperate regions because of the problems of cloud cover. The future of remote sensing for regular applications in Britain will rely heavily on the availability of radar systems which can penetrate clouds, starting with ERS-1, ERS-2 and Radarsat in the early 1990s and, later, using the synthetic aperture radar (SAR) aboard the various Polar Platforms, due to be launched towards the end of the century. Radar essentially generates imagery which depicts surface roughness and the dielectric constant of the surface layers. It is important that models are established describing the relationships between surface conditions and radar backscatter. Work with Cambridge University, NUTIS, and the British National Space Centre is investigating the use of SAR in areas of forestry and arable farmland at Feltwell. An EIC-based NERC/AFRC Special Topic will test the integrated use of SAR imagery from ERS-1 with visible/infrared data in a GIS environment.

Remote sensing projects in EIC will continue to test new technology, to develop analytical methods, to transfer techniques to operation in ecology, and then to use operational techniques for the acquisition of data in applied ecological research. The close relationships between ecology and land use will ensure that the work is relevant to those with agricultural interests.

R M Fuller, A R Jones and B K Wyatt

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Airborne imaging spectrometry for vegetation studies

Imaging spectrometry

Imaging sensors used in remote sensing typically build up an image of a target from a mosaic of pixels; each pixel records one or more values (of radiance, surface temperature, radar backscatter, etc), averaged over the instantaneous field of view of the sensor. Multispectral sensors, such as the Landsat Thematic Mapper and the high resolution visible sensor aboard SPOT, detect radiation in a small number of broad spectral bands. Typically, the current generation of airborne and satellite radiometers sense in 3–11 spectral bands, with a band width of 50–100 nm.

In contrast, imaging spectrometers acquire images simultaneously in many narrow, contiguous spectral bands. Therefore, for each pixel in the image, it is possible to construct a detailed reflectance spectrum, covering the complete spectral range of the instrument (Figure 10). The interest in such imagery lies in its use for detecting specific chemical entities and processes from the presence of characteristic absorption bands in the reflected spectra and for mapping these features in space (Vane 1988).

This paper describes experiments designed to assess the potential use of data from airborne spectroradiometers for detecting the spectral response of differing nutritional levels in grassland. If successful, the technique could prove invaluable in mapping and monitoring fertiliser usage.

Spectral response of vegetation

Actively growing green vegetation exhibits a characteristic spectral response (Figure 11), with an absorption band at 400–700 nm caused by the presence of leaf pigments, such as chlorophyll, and a strong peak in the near-infrared from 750 to 1300 nm, due to reflection at cellular boundaries within the leaf structures.

In spectra of vegetation under stress, eg from a deficiency of nutrients or water, there is commonly a decrease in reflectance of the near-infrared (NrIR) plateau and a purported blue shift in the red edge of the chlorophyll absorption. This shift in the red edge is associated with changes in concentration of chlorophyll and carotenoids in the leaf structure because of the conditions of stress (Milton *et al.* 1983).

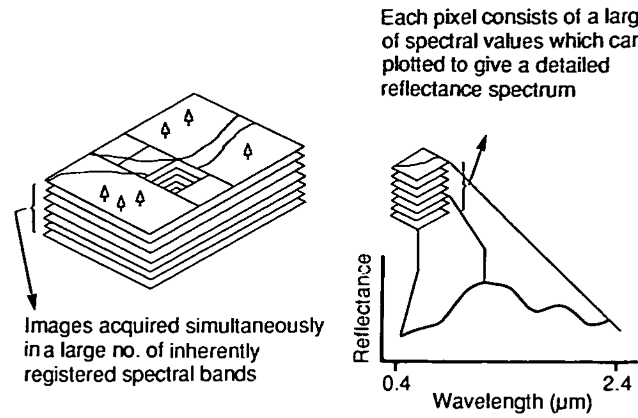

Figure 10. Imaging spectrometry

Experimental design

In grazed pasture, the bulk of nitrogen (N) is returned to the soil via plant litter and organic manure. In conditions where a high proportion of the vegetation is removed from the land, chemical fertilisers are used to bolster soil N levels. Excess use of N fertiliser on agricultural land should be avoided because of its expense, adverse ecological effects, and the risk of elevated levels in drinking water of nitrates leached from agricultural sources. To minimise the waste of fertilisers and their undesirable side-effects, methods are needed to monitor the condition of crops and grassland, in order to provide early warning of conditions of nutrient deficiency. This work was undertaken to demonstrate that imaging spectroradiometry can be used to detect and identify subtle diagnostic spectral features associated with stress in grassland canopies. Specifically, the spectra of grassland swards treated with varying levels of nitrogen were examined with a view to identifying spectral features which were diagnostic of the treatments used.

The project is being carried out in conjunction with a long-term experiment, run by the Institute of Grassland and Animal Production and ITE (Wyatt *et al.* 1989), and involves a series of experimental treatments, located on 20 ha of unimproved species-rich hay meadows in the Somerset Levels (Plate 4). The aim of the experiment is to identify a level of N application which can be used without reducing species diversity on the peat soils, and to quantify how much production farmers would lose as a result.

The experiment comprises three replicates of five treatments, in which biennial applications of nitrogen fertilisers range from 0 kg to 200 kg ha^{-1} (referred to as NO and N200 in the following text).

Imaging spectrometry and data collection

A series of aircraft overflights of the study area were made as part of an experimental airborne campaign, funded by NERC. The aircraft carried a high spectral resolution imaging spectrometer, known as the Programmable Multispectral Imager (PMI), manufactured by Moniteq Ltd of Canada. The PMI acquired data in 288 contiguous bands between 430 nm and 800 nm, with a

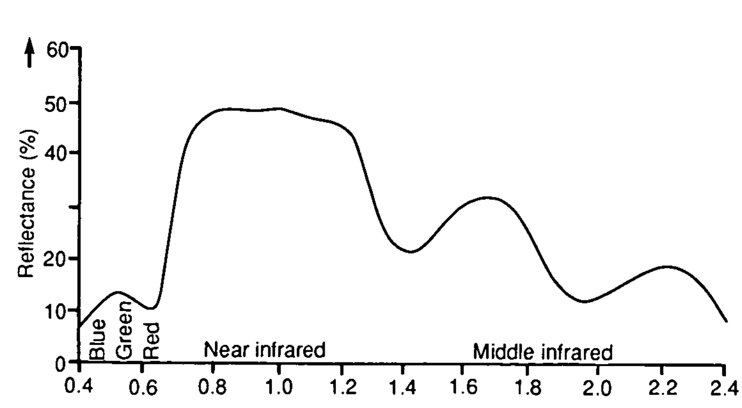

Figure 11. Typical spectral response of green vegetation

Plate 5. *A false colour infrared 'spatial mode' image of the study area. Note differences between the cut fields (blue), grassed fields (red) and the peat extractions (green)*

Plate 4. *Oblique aerial photograph of the Tadham Moor experimental plots. Darker fields resulting from increased fertiliser levels are clearly visible*

band width of 2.6 nm. The PMI was also operated in 'spatial mode', giving eight narrow band passes (10 nm) covering the red edge, at higher spatial resolution (Plate 5).

Ground conditions at the time of the flight were recorded. The field measurements included observations of sward height, composition and biomass, soil moisture, and the levels of nitrogen in both soil and vegetation. In addition, *in situ* spectral reflectance measurements were made in the range 400–2500 nm, using a GER Mk IV IRIS spectroradiometer so that spectral reflectance could be related to the specific conditions at each sampling point.

Analysis

The image data were acquired as digital counts. The PMI spatial mode imagery was calibrated to radiance, using information supplied with the data. It was possible to identify clearly individual treatments in the imagery, and averaged radiance values were computed for each treatment. The eight mean radiance values for each treatment were plotted against wavelength (Figure 12). A spectral response typical of green-leaved vegetation was obtained; differences between treatments could be discerned around 600 nm and, more distinctly, within the red/NrIR plateau between 750 and 1300 nm. Within the NrIR plateau, highest radiance values were displayed by the N200 treatment, with lowest values from the N0 treatment, this trend being the reverse of the observations for the shorter wavelengths. Other treatments showed intermediate responses in both spectral regions. Similar trends were apparent in the data collected in 'full spectral mode' (Figure 13).

Statistical assessment of the significance of these differences requires quantification of the key parameters of the red edge. The algorithm chosen uses an inverted gaussian curve to characterise the geometry of the red

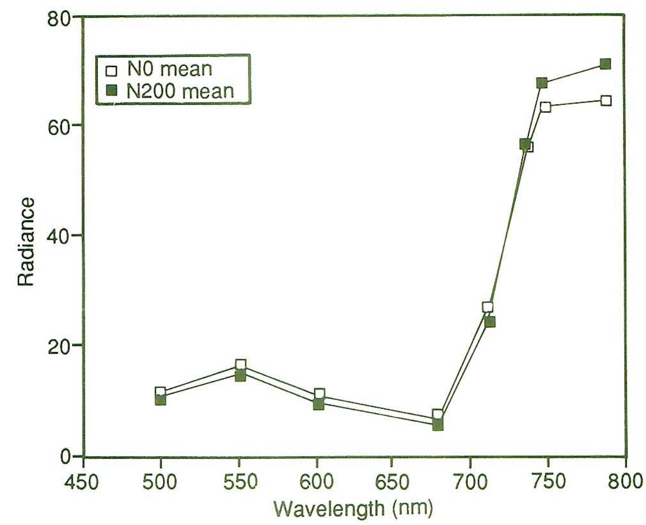

Figure 12. *Example of PMI spatial mode data*

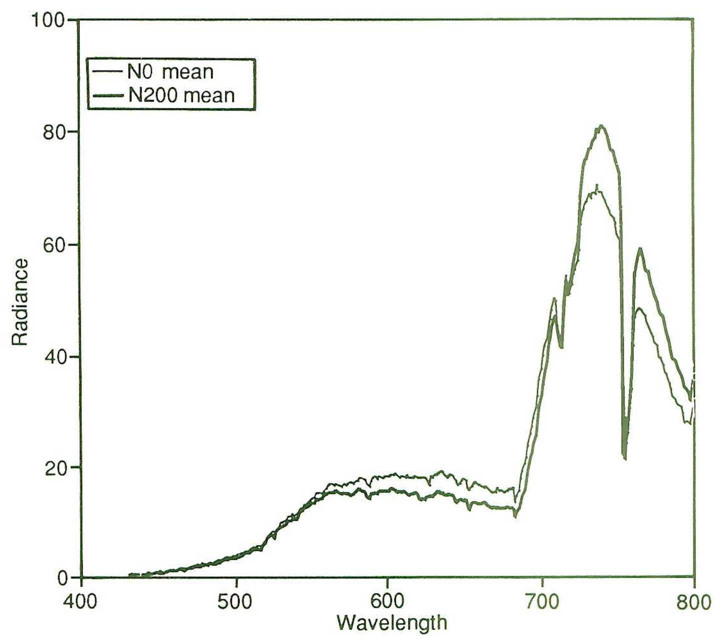

Figure 13. *Example of PMI spectral mode data*

Table 3. Results of inverted gaussian modelling

	Plot 0	Plot 50	Plot 200
Shoulder reflectance	65.94	69.32	70.74
Reflectance minimum	4.39	2.80	3.03
Wavelength minimum	686.66	687.31	687.48
Sigma	26.18	26.79	27.16
Inflection wavelength	712.84	714.11	714.64

edge with a minimum of parameters (Bonham-Carter 1988). The results of processing PMI spatial mode data, after radiometric calibration, are presented in Table 3 and Figure 14.

The model demonstrates conclusively the effect of increasing levels of nitrogen on NrIR reflectance. The height of the NrIR plateau (shoulder reflectance) increases progressively with increasing nitrogen. The inflection wavelength, which marks the position of the red edge, shows a slight increase in wavelength with increased application of N. There was no significant shift in the position of the chlorophyll absorption maximum.

display internal variability, especially early in the season when growth is at its most vigorous. Fertiliser is applied in early April, and there is a time lag before the vegetation shows evidence of nutrient uptake. Because of operational circumstances, the campaign was completed before the end of April. It is possible that this timing was too soon after the application of N for the effects to be fully apparent, and that the differences detected by analysis of the PMI data may represent conservative estimates of what might be achieved, given optimal conditions.

B K Wyatt and A R Jones

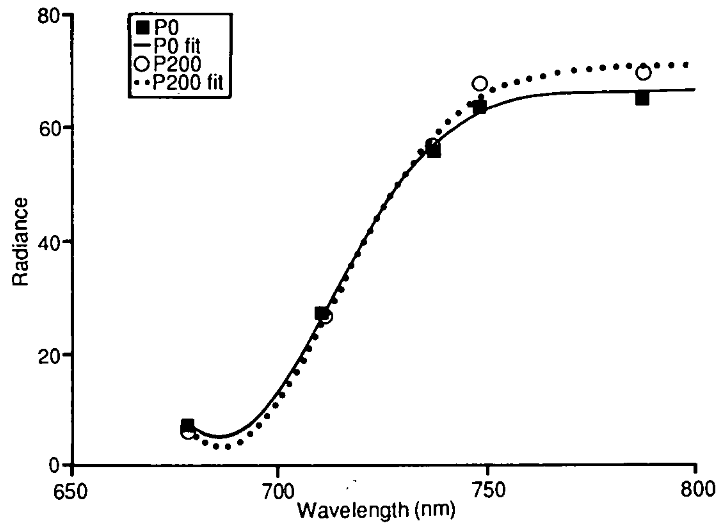

Figure 14. Inverted gaussian curve fitting for PMI spatial mode data

Discussion

Analyses of PMI data in both spatial and spectral mode data reveal similar trends. In either case, individual treatments can be differentiated both in the green spectral region and within the red/NrIR plateau. Modelling the red edge suggests a slight blue shift of the N0 response with respect to that of the N200 of approximately 2 nm. Results of similar experiments on vegetation, in particular coniferous forests, indicate that a 5 nm shift is significant for determining physiological stress. A comparable wavelength shift for the red edge had been expected in this study. Although the experiment has been running for several years, individual treatments still

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Ecological consequences of land use change (ECOLUC)

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

The composition of the lowlands and uplands of Britain has changed dramatically since the war, in response to economic, social and environmental pressures. The distinction must be made between land cover and the use to which the land is put. Land cover defines the type of vegetation, including the crop and the associated habitats which result from management practices within a land use, and harbours the variety of plant and animal species which constitute the visual landscape. Land use defines the main type of management, eg arable or forest. When land use changes, there is a very obvious change in land cover, but land cover can be significantly modified by small changes in management, eg decreased fertiliser use, grazing intensity, or time of cropping. Such small changes are not represented in land use statistics. For land use change, agricultural statistics reveal complicated shifts in the balance of areas of land under different crops. Forestry statistics show an expansion of conifers in the uplands and the conversion of broadleaved woods in the lowlands. Neither set of data contain the ecological information necessary to identify and quantify the consequences for wildlife of such changes in land use. It was for this reason that the Department of Environment (DOE) established the ECOLUC project.

ECOLUC has been a wide-ranging and exploratory research programme, designed to identify recent and likely future trends in land use, and to quantify the ecological changes that would result from alterations in land management. Much of the information available was fragmented, based on local studies, or, as with national coverage, it related to individual habitats or species. ITE was required to encourage communication and collaboration between various disciplines and research groups, and to recommend techniques for improving the measurement and assessment of change, including both traditional ground survey methods and remote sensing.

At the outset it was recognised that the ITE land classification system and its associated national ecological data bases at Merlewood would form a central element of the programme. However, the wide remit set by DOE was designed to ensure the involvement of appropriate expertise, not only from within NERC – from ITE, the Institute of Freshwater Ecology, and the Unit of Comparative Plant Ecology (UCPE) – but also from many Universities and organisations. The breadth of the involvement is reflected in the 13 major subcontracts of ECOLUC, in addition to the separate DOE contract placed directly with the National Remote Sensing Centre which made a key contribution to the programme.

Change in land use and cover

From the 1940s through the 1960s, the major trend in agricultural land use was the extension of arable farming, at the expense of grassland and moorland (Plate 6). Concurrent with the change in crop/vegetation cover was the loss of hedges in the lowlands and the increase of fences in the uplands. The balance between arable and grassland was consistent over the late 1970s and early 1980s, although the areas of oilseed rape and wheat increased significantly, while that of barley decreased. The major change in the uplands has been caused by afforestation: the forest cover of 8.6% of the land area of GB in 1977 expanded by about 22 000 ha per year between 1975 and 1985.

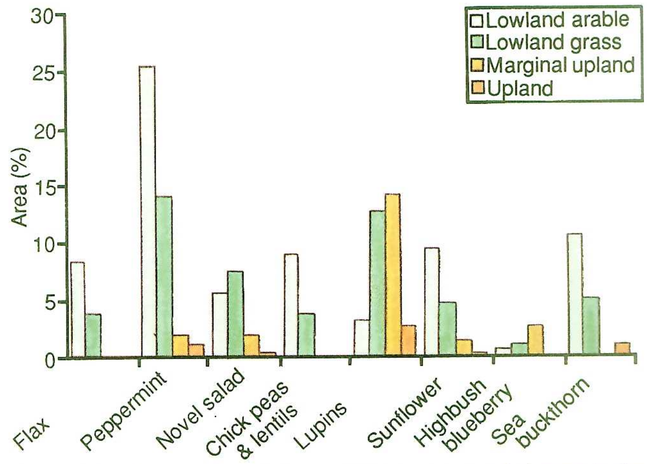

Figure 15. A comparison between four scenarios of change in the countryside, carried out by Lawrence Gould (Consultants). The analysis was caried out on eight 1 km squares from each of the 32 land classes, grouped according to the following sequence:
Land classes dominated by arable land in the lowlands (2,3,4,9,11,12,14,25,26)
Land classes dominated by lowland grasslands (1,5,6,7,8,10,13,15,16,27)
Land classes in marginal areas (17,18,19,20,28,31)
Land classes in the uplands (21,22,23,24,29,30,32)

Plate 6. Abandoned farm machinery at Diabeg, Highland Region. National trends can mask regional patterns. Within ECOLUC, the national trend is for agricultural intensification leading to the loss of native vegetation. However, locally, as in this photograph in NW Scotland, a decline in the traditional management of hay meadows can lead to colonisation by bracken (Pteridium aquilinum) and shrub species, such as willow (Salix spp.)

The basic statistics on land use are provided by the agricultural and forestry agencies. The information has been supplemented by more extensive data on land cover collected in sample surveys during the *Monitoring landscape change* (MLC) project which was sponsored by the Countryside Commission and DOE. The project used air photography, whilst ITE concentrated on field survey and provided detailed information on the species composition of land cover.

Each data set differs in certain respects: the detail provided, the categories surveyed, and the methods used. Despite the differences, the general distribution and type of change in land use are detected by all the surveys. However, only the ITE survey provides a general classification to which all land use and cover types can be related, as well as details of the ecology. For this reason, the ITE ecological data base formed the core of the ECOLUC project; it consists of data collected during surveys in 1978 and 1984 throughout Great Britain, using standardised procedures. The surveys were based on field sampling of 1 km squares, randomly selected within each of the 32 land classes defined using geological, climatic and topographic characteristics. The field survey information provides quantitative data on land cover, vegetation type, and plant species composition. This data base includes details of over 3000 quadrats and linear plots, and can provide information on the distribution of plant species in open land, at its margins and in linear features, such as roadsides, either with their spatial relationships or as summaries by 1 km square or land class.

Future change in land use may differ from those in the past. To assess likely future trends, a number of studies were undertaken by specialists who examined the options for new agricultural and forestry crops and the probable responses to fiscal policy. Lawrence Gould (Consultants) predicted that the greatest change in land use is likely to occur in the lowlands: up to 35% of the land may be subject to reduced intensity of agriculture, but, because of the quality of the land, a range of alternative options are open (Figure 15). This prediction contrasts with that for the uplands, where the range of options is severely limited and where current trends are likely to continue. The scenario was expanded by the Centre for Agricultural Strategy (CAS), who identified alternative crops which are economically viable on different land types. The results (Figure 16) indicate that a range of 'novel' crops may follow the development of oilseed rape on arable and, to a lesser extent, grassland, with lupins the only significant option for marginal land.

As quantified by both Gould and CAS, the upland options considered are mainly limited to forestry, although other recreational scenarios could eventually be considered. A separate analysis of the land availability has shown that up to 15% of the uplands could be used for wood energy plantations, the remaining area being either unsuitable, constrained by designation, or economically viable under agriculture (Figure 17). Although the lowlands have greater growth potential, less expansion of forest for energy is predicted because of the strength of agriculture.

The extent to which options are exploited is strongly influenced by financial forces, eg through the Common Agricultural Policy, and particularly by the economic assumptions made at the outset. In conjunction with the University of Newcastle and ITE, CAS analysed the

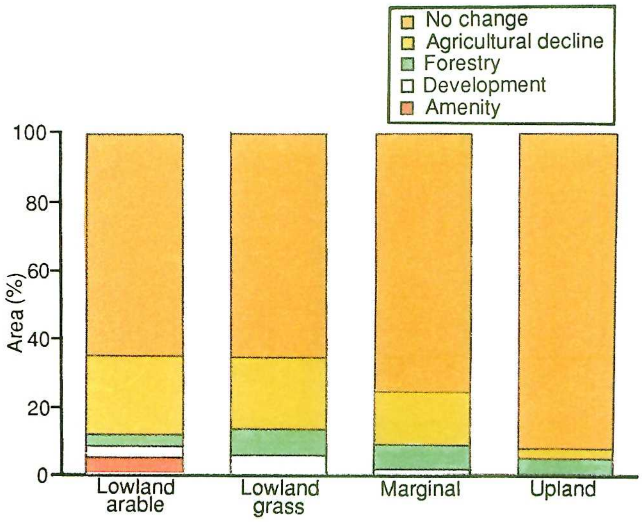

Figure 16. A comparison between estimates of the potential area that could be occupied by novel crops, assuming that all suitable land was included. The analysis was carried out on data from eight 1 km squares from each of the 32 land classes, grouped in the same categories as in Figure 15

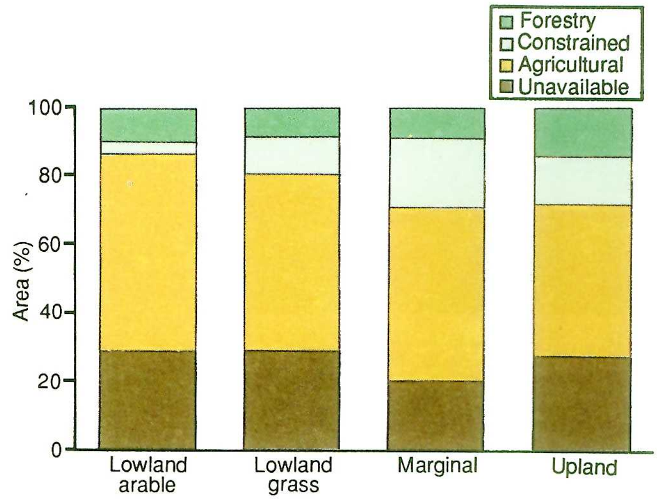

Figure 17. A comparison between estimates of the potential area that could be occupied by wood energy plantations, excluding land which was more economic under agriculture, assuming a 5% discount rate, and land identified as being under defined planning constraints. The analysis was carried out on data from eight 1 km squares from each of the 32 land classes, grouped in the same categories as in Figure 15

likely impact of four policy options in England and Wales. The results emphasised that change in land use is most likely to occur where a particular land use is economically marginal. Thus, core areas of arable or intensive grassland are likely to remain, and even to intensify; the change will occur at the interface between these uses. Geographically, the probability of change between arable and grass is greatest in the Midlands and south-west of England. Marginal uplands are likely to continue to be changeable, as they are at the margins of a number of land uses. The specific mechanisms controlling change in land use may be financial incentives, such as set-aside or farm woodland schemes, designations such as Environmentally Sensitive Areas, or other forms of regulation. The result will be a change either in land use or, through modified management regimes, in land cover and its composition.

Thus, the change may be quantitative, in terms of area of land under a particular use, or qualitative, in terms of the composition of the vegetation and diversity of species.

Ecological consequences of land use change – flora

Whilst census statistics are available for land use, ecological interpretation requires information on species composition. The ITE data base provides comprehensive information on the plant species composition of the major types of land cover, over the range of environmental and land use conditions in Britain. Within ECOLUC, the data base was used to quantify the type and diversity of species and communities in each type of land cover, as a measure of how plant assemblages would be affected by any alteration of land use or management.

Analysis of the data indicates that improving permanent pasture either to short-term ley or to arable would tend to reduce the number of vascular plant species. However, this picture is incomplete. The diversity of vegetation types in the open countryside is lower in the fertile, intensively managed lowlands than in the marginal uplands, where there is often a combination of both lowland and upland habitats, as shown in Figure 18. By contrast, an important feature in the distribution of diversity is that, in the intensively managed lowlands, linear features such as hedges, stream banks and roadside verges (Plates 7 & 8), which constitute only 5–10% of the land area, contain 60–80% of the species present, and about 20–30% of species are found only in the linear features, being absent from the open fields (Figure 19).

In the more extensively managed uplands, linear features are less distinctive in their contribution to the ecology of the landscape. Within a given 1 km square, there are generally more species in the lowlands than in the uplands, whereas the species in the latter form part of the vegetation cover rather than being present in relict patches as

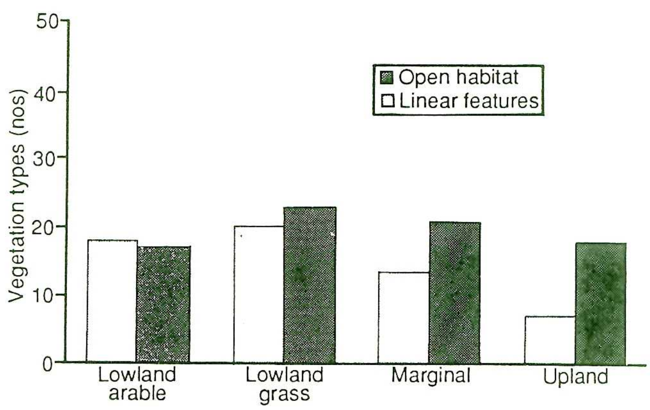

Figure 18. A comparison between the number of vegetation types in open habitats and linear features (hedges, roadside verges and streamsides). Records of all vascular plants and a limited list of bryophytes were collected in 1978 from quadrats in eight 1 km squares in each of the 32 land classes. The data were analysed by TWINSPAN and grouped in the same categories as in Figure 15

*Plate 7. Many plant species are important as food sources for animals. The wild rose (*Rosa canina*) is common in the hedgerows, but is also able to establish along walls and fences. It provides cover for birds, a food source for insects, and the hips in autumn attract resident and migrating birds*

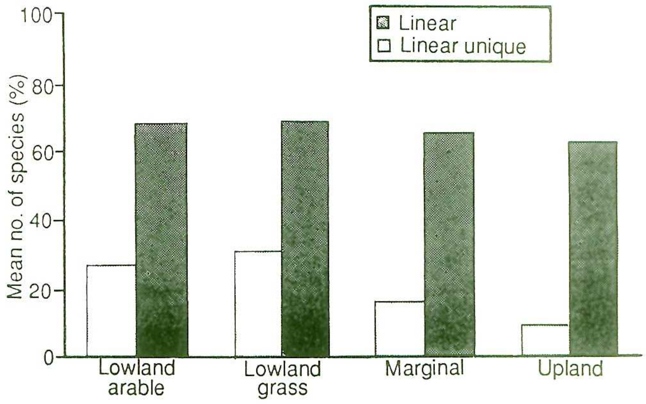

Figure 19. A comparison between the number of species recorded in 1988 from open land and those in linear features, as mean proportions of the total species number and those that were only found in the linear features. All species of vascular plants were recorded from two 1 km squares in each of the 32 land classes, and were grouped in the same categories as in Figure 15

fragmented populations. The implication of such distribution patterns for rural policy is that maximum gain in terms of future maintenance of diversity can be obtained by protecting, expanding or diversifying linear features in the lowlands, whereas in the uplands the whole landscape is involved.

An independent analysis of the data base by UCPE at the University of Sheffield provides a theoretical approach to assessing the likely response of species to an alteration in management. Based on the growth strategy of individual species, the theoretical framework shows the plants' response to environmental stress (eg soil infertility), disturbance (eg trampling or ploughing) and competition (eg in fertile undisturbed habitats) (Figure 20). The analysis defines the composition of the vegetation in different habitats in terms of functional groups.

Thus, arable areas show a high proportion (49%) of ruderal species which are successful in fertile but highly disturbed habitats. In contrast, moorland habitats are dominated by species which are stress-tolerant, reflecting their ability to survive in nutrient-poor, acid soils. Such generalisations are well known, but here they are expressed in quantitative terms which allow interpretation and prediction. For example, in grasslands, an increase in fertiliser use would tend to

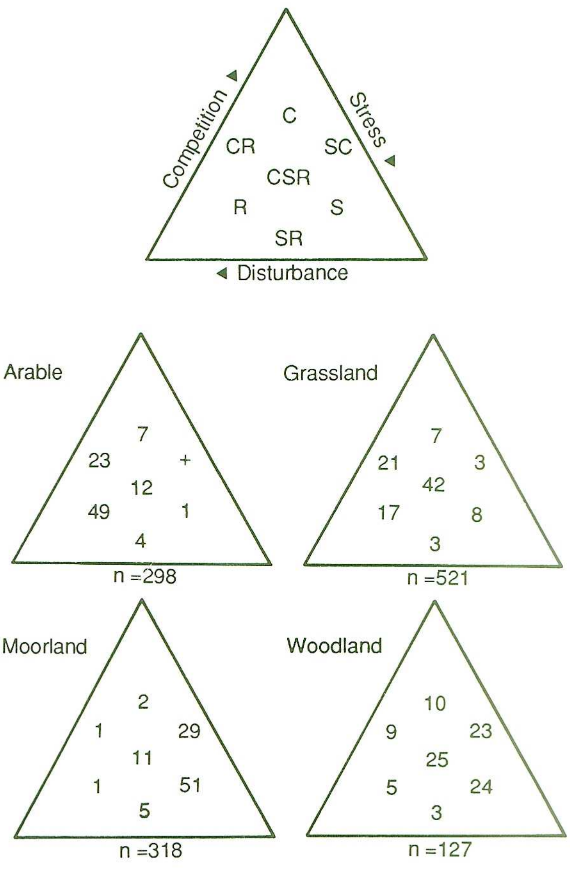

Figure 20. The mean percentage distribution of strategies for four major land use categories, as defined by UCPE. The data were taken from open habitats, as in Figure 18

*Plate 8. Species-rich roadside verge, Earlston, Lothian Region. The studies in ECOLUC have shown the importance of linear features in maintaining species which have disappeared from the open landscape. Management within such features is important, and within ECOLUC it has been demonstrated that, with the decline in roadside cutting, verges will be overtaken by coarse species, such as nettles (*Urtica dioica*)*

increase the proportion of competitive ruderal species from the present 21%, whereas, in moorlands, eutrophication, possibly from pollution sources or agricultural improvement, would tend to reduce the stress-tolerant component of the vegetation from its current dominance (51%). The latter component has been identified by UCPE as the most vulnerable grouping in the UK flora; the resurvey in 1990 of the vegetation sampled in the national survey of 1978 should allow tests of predicted change, as well as interpretation of observed differences.

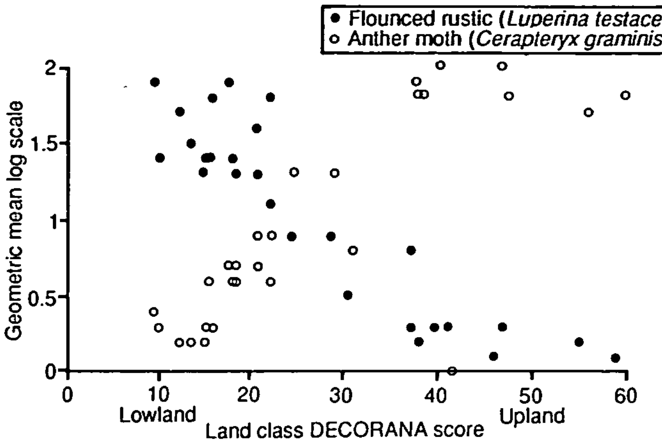

Figure 21. The relationship between two moth species recorded within the Rothamsted Lepidoptera Survey. The data were collected from 313 sites throughout GB, which were subsequently assigned to the 32 land classes. Geometric mean annual catches per land class were converted to a log scale, and correlated with the mean first axis ordination score (DECORANA) for the 32 land classes defined by the analysis of the original environmental attributes of the land classification

Ecological consequences of land use change – fauna

Unlike vegetation, there is no comprehensive information on fauna, although there are many excellent national or local data on individual species or groups, eg those of the British Trust for Ornithology. The challenge in ECOLUC was, therefore, to assess the potential of bringing together different sets of faunal information and relating them to data on land use and land cover. The common base or framework considered was the 32 ITE land classes, strengthened by the field information on land cover. The latter is particularly important because it is the mosaic of land cover to which animal populations respond, as well as the presence or absence of a particular habitat.

Three approaches to the integration of zoological information into the land classification were explored:

1. sampling by land classes,
2. retrospective classification of study sites,
3. assessment of population density based on land class and cover information.

An example of the first approach is in the sampling of 2000 1 km squares of known land class in Britain by Dr S Harris (University of Bristol) to assess badger (*Meles meles*) population size. The survey showed that high densities of badgers (0.5–1.0 main sets km^{-2}) were concentrated in five of the 32 land classes with lowland grass cover dominant. In these classes, management is unlikely to intensify significantly towards the lowland arable cover type in which badger main sets had much lower frequency (0.05–0.3 km^{-2}). These data were then used, in conjunction with the scenarios from the CAS study, to assess the most likely effects of land use change on badger populations.

Retrospective classification of areas for which extant faunal data are available can enable these data to be related to independent information of land use or cover. The Rothamsted Lepidoptera Survey is an example of the second approach. It collected data from 313 sites over 25 years, and the analysis by Dr I Woiwod has shown a series of distinctive relationships between individual species and land class characteristics (Figure 21). These relationships provide a mechanism for predicting species composition in areas which have not been sampled.

The third approach uses the habitat information available from the sample of 256 1 km squares to assess population density of particular species. This technique has been explored by the British Trust for Ornithology for birds, by Dr D Macdonald (University of Oxford) for foxes (*Vulpes vulpes*), and by the Game Conservancy for pheasant (*Phasianus colchicus*), grey partridge (*Perdix perdix*) and brown hare (*Lepus capensis*). In the first two cases, expert opinion is used to identify the number of animals likely to occur in particular or general types of landscape. By contrast, the Game Conservancy used formal regression to quantify bird numbers in relation to land cover and, in the case of the grey partridge, to assess the effects of changes in cover and management.

With a few exceptions, information on the distribution and abundance of fauna lacks a comprehensive base from which to assess the consequences of land use change. Most of the data are from localised studies or do not have associated detail of habitat characteristics. Through a variety of invertebrate and vertebrate case studies, ECOLUC has provided a method by which partial or fragmented information can be related to a common framework, within which the effects of land use change can be assessed. The approach has highlighted the need for research to define relationships between abundance of animals and measurable attributes of the landscape, ie the pattern or mosaic of habitats. In a number of cases, eg foxes, game and other birds, abundance could be related to the generalised composition of the landscape, but not to quantified spatial relationships such as heterogeneity or connectivity.

Although the ecological relationships between landscape pattern and ecology are poorly developed, the ability to define pattern and to detect change in pattern by remote sensing has developed rapidly. As part of a joint study with the National Remote Sensing Centre in the use of remote sensing to detect change in land cover, an automatic system was established which defines the size and nearest neighbour of identified cover types or habitats, and calculates a measure of heterogeneity, or 'graininess', of the landscape. The system can be used rapidly to identify areas where the general pattern is changing in repeated images over time, eg in the occurrence of woodlands of different sizes. Such size frequency distributions are potentially useful when information is available about the minimum habitat size requirements of a particular species.

A major element of the remote sensing programme has been to link satellite imagery with ground data. Using a combination of single-date and multi-season imagery, the broad land cover types in Britain can be mapped. A variety of techniques for classifying the image data was compared, including visual interpretation, supervised and unsupervised classification. In practice, the optimal solution is to combine the statistical classification of spectrally separable cover types with visual interpretation of the residual. Change maps were also produced showing the increase or decrease in the area of a particular cover type. The study emphasised that field survey and satellite imagery are complementary techniques, and demonstrated how future surveys can utilise the strengths of both approaches.

Knowledge-based information system

The communication of large amounts of data and the expertise of specialists to those who are concerned with policy decisions is a real problem. The advent of various forms of expert- or knowledge-based systems has provided a powerful set of techniques. In ECOLUC, an exploratory study has produced a knowledge-based information system, built on the framework of the land classification. It holds information on the characteristics of the land classes and the associated land use and land cover features for which census data are available, together with predictions of other features in the ITE data base. The system is compatible with various models predicting potential changes and their consequences. The data are all held by 1 km square, and the system allows the user to select any block of squares for interrogation.

Conclusions

ECOLUC has been a technically far-ranging and exploratory study which has involved many people in the research community. Although concentrating on the terrestrial environment, it extended into freshwater ecology and combined remote sensing with detailed information on plant and animal ecology, both theoretical and practical.

In particular, ECOLUC has demonstrated the following points.

1. Land use statistics and ecological information from different sources can be related to a common baseline of the ITE land classes.
2. Major changes in land use result in clearly quantified effects on biological diversity. Adjustments in the type and intensity of management which are not recorded in land use statistics have ecological effects which are of the same order of magnitude.
3. A high proportion of the biological diversity, especially in the lowlands, is concentrated at the margins of fields and in other linear features which comprise less than 10% of the land area.
4. Remote sensing can provide systematic and extensive detection of the major characteristics and change in land cover. Integration with field survey provides detailed ecological interpretation as well as ground truth. Remote sensing with field survey provides a strong combination for detecting change at three inter-related scales of resolution:
   i. major land cover features,
   ii. land cover or habitat characteristics,
   iii. species distribution and abundance.

These conclusions have implications for management policy and for the provision of national statistics. The efforts of many individuals and organisations involved in ECOLUC are fully acknowledged. The next stage is to build on the experience gained to implement the 1990 Countryside Survey.

R G H Bunce and O W Heal

Siting of wind turbines in Britain

(This work was funded by the Department of Energy, Energy Technology Support Unit)

Wind power is currently one of the most promising of the renewable energy technologies for generating electricity in the United Kingdom. If predicted costs can be achieved, it is possible that wind power could be supplying at least 10%, and perhaps as much as 20%, of national requirements by the year 2025. Although the UK appears to be endowed with sufficient wind, is there enough land on which the turbines could be sited?

Much of our land is unsuitable for technical reasons; for example, built-up areas or forest blocks distort wind flow. Such areas are considered to be 'physically constrained'. Other areas are protected by statute, such as the National Nature Reserves and Areas of Outstanding Natural Beauty. Planning controls in these and other specially designated areas may prohibit the construction of wind turbines. Such areas are 'institutionally constrained'.

ITE was commissioned to provide a quantitative estimate of the area of Britain which could not be used for wind energy generation because of physical and institutional constraints.

The areas with physical constraints were obtained from published cartographic sources, and information for this study was supplied, in electronic form, by a company involved in the production and publication of maps. The institutional data were more difficult to access in suitable published form, and were acquired by digitising maps obtained from the agencies that designate protected areas, such as the Nature Conservancy Council and the Countryside Commissions of England and Wales and of Scotland. Initially, the data were stored as Ordnance Survey grid referenced co-ordinates for each designated area. These boundaries were used to allocate the grid referenced 1 km squares fully, or partially, to appropriate designations.

Plate 9 shows the distribution of 1 km squares which are unconstrained by both

Plate 9. The distribution of 1 km squares in Britain unconstrained by either physical or institutional constraint. This represents 12.5% of the total land area of Britain

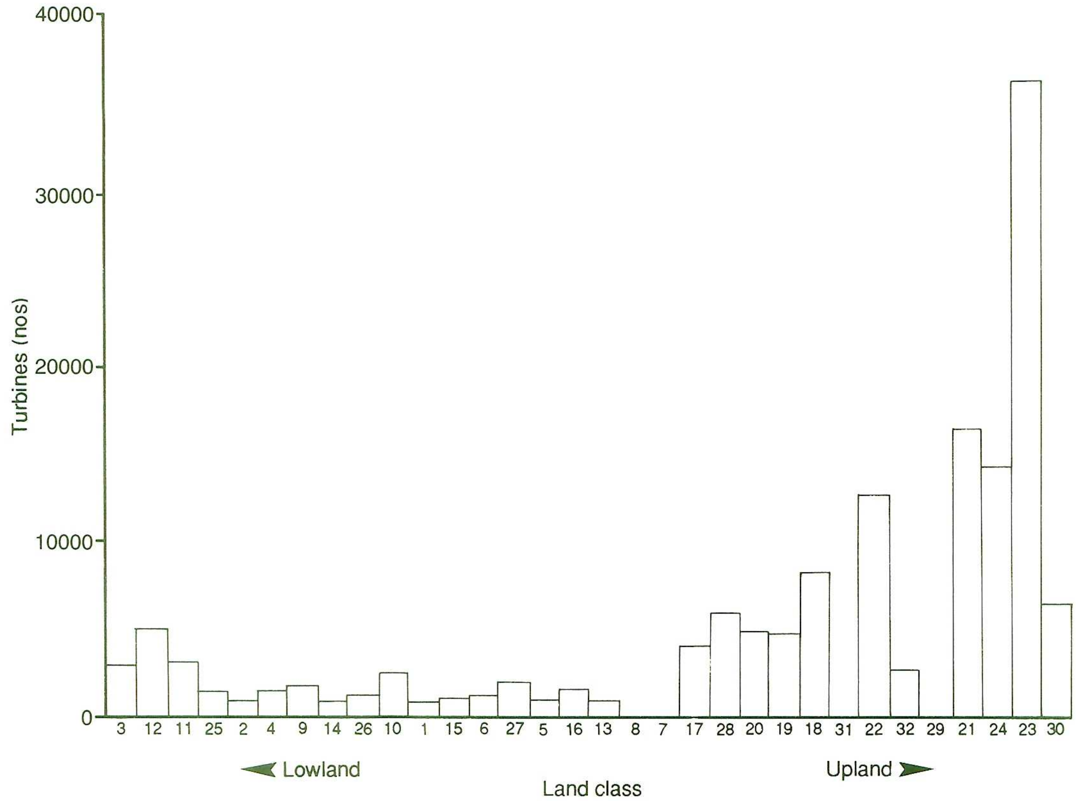

Figure 22. The distribution by ITE land class of unconstrained 1 km squares in Britain (ranked lowland-upland)

physical and institutional factors (shown in red). For the purposes of this study, the presence of a physical feature or institutional designation within a 1 km square made it unsuitable for turbine siting. Clearly, there are occasions where only a small area within a 1 km square is so constrained, so that some of the land within the square would, in fact, be available. It is also possible that planning controls for some of the institutional designations do not prohibit turbine siting. The 12.5% of land in Britain shown as unconstrained in Plate 9 is, therefore, a conservative estimate of that which may be available. Physical elements constrain 79% of Britain, while 47% is covered by institutional constraints (approximately 38% of the land is constrained by both physical and institutional factors). Most unconstrained land occurs in northern England and upland Scotland, and represents mainly open mountainous landscapes.

Each unconstrained 1 km square was classified according to the ITE land classification (Bunce & Heal 1984), and Figure 22 shows the distribution of squares by land class. Classification of the unconstrained land not only enables it to be allocated to particular land classes, the characteristic features of which are known, but also provides a framework for predicting the number of

Figure 23. Map of a 1 km square of ITE land class 17 (predominantly marginal upland in Wales, SW and N England). This Figure illustrates that three wind turbines could be sited in the 1 km square (at the centre of each of the green circles). The green circles represent a zone which ensures that turbines are not situated within ten turbine blade diameters (330 m) of each other or forest. The grey circles represent exclusion zones around settlements within which turbines should not be placed

Table 4. The number of unconstrained squares in each ITE land class and their potential for siting wind turbines. The number of turbines per 1 km square represents a mean for 12 squares drawn at random from each land class

	Land class	Unconstrained 1 km squares	Turbines per 1 km square	Number of turbines in thousands
^ Lowland	3	928	3.0	2.8
	12	1348	3.6	4.8
	11	790	3.8	3.0
	25	561	2.2	1.2
	2	344	2.2	0.7
	4	384	3.3	1.2
	9	591	2.5	1.5
	14	271	2.5	0.7
	26	551	1.8	1.0
	10	899	2.5	2.2
	1	297	2.4	0.7
	15	414	2.1	0.9
	6	430	2.3	1.0
	27	529	3.4	1.8
	5	430	1.7	0.7
	16	640	2.1	1.3
	13	348	2.0	0.7
	8	9	1.8	0.0
	7	2	2.3	0.0
	17	880	4.5	4.0
	28	1568	3.7	5.7
	20	1168	4.1	4.8
	19	819	5.8	4.7
	18	1236	6.7	8.3
	31	7	3.2	0.0
	22	2634	4.8	12.7
	32	818	3.3	2.7
	29	0	3.6	0.0
	21	2670	6.3	16.7
	24	2485	5.8	14.3
	23	4108	8.8	36.3
	30	1155	5.6	6.5
Upland v		29314		142.9

wind turbines which may be sited in each unconstrained 1 km square. The mean number of turbines which can be sited on a 1 km square in each land class can be predicted by examining small-scale (1:10 000) maps of a sample of 1 km squares from each class. Turbines sited close together or near afforested land do not perform efficiently because of turbulence effects. Also, for reasons of safety and environmental impact, eg noise, they should not be placed close to settlements. Scaled templates of the consequent aerial restriction around a turbine were placed over each map, with no overlap between the restrictions around turbines, turbines and houses, or turbines and roads (Figure 23). A turbine cannot be built closer than ten blade diameters to another turbine or to a settlement. Assuming a 33 m diameter blade (a medium-sized turbine), there is a minimum distance between turbine centres (and turbines and houses) of 330 m. Turbines were allowed to be placed with a centre not less than 165 m from a forest, and 100 m from roads, power and telephone lines, and rivers.

Table 4 shows the mean number of turbines which can be sited in a 1 km square in each land class. The Table also presents the number of unconstrained squares and the total number of turbines that could be erected. Figure 24 shows the predicted distribution of turbines by land class. Land class 23 has the highest

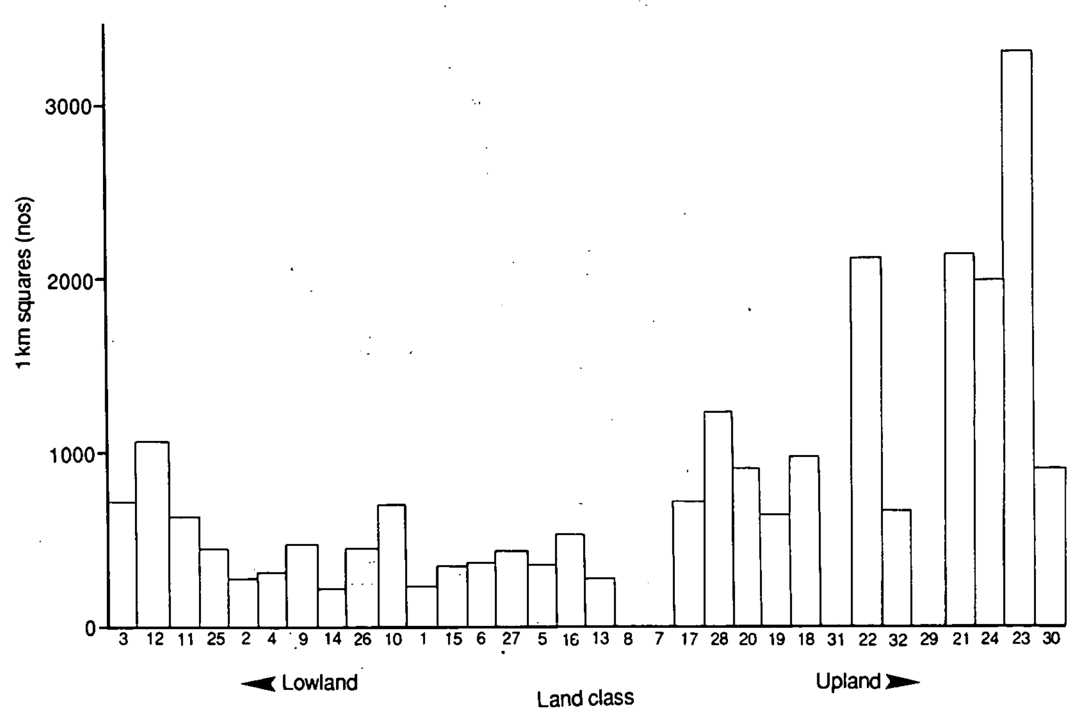

Figure 24. The predicted number of wind turbines which could be sited in the unconstrained squares in each ITE land class (ranked lowland-upland)

number of turbines; however, it contained more rugged terrain than most other land classes. The mean number of turbines per 1 km square in land class 23 is nearly nine (the maximum), but this figure reflects the isolation and remoteness of the squares. Such factors were not included in the analysis of these squares, and are likely to reduce the predicted number of turbines. If, for example, half the upland sites in land classes 21, 23, 24 and 30 were too isolated or remote to consider for siting turbines, the total predicted number of turbines would be reduced by 27%.

However, the most important variable in determining the suitability of the unconstrained land for wind turbines is the mean wind speed. The Department of Energy, Energy Technology Support Unit (ETSU) has developed a model which provides a wind speed value for each 1 km square in Britain, and overlaying these data on to the constraint-free land will indicate the best sites and determine the full potential for deriving energy from wind power in Britain. ETSU has applied the ITE constraint data to a pilot area in north-west England covered by the NORWEB electricity board, using modelled wind data, and has concluded that 'a significant amount of wind energy (1–2 terawatt hours per year) is available within the area at an attractive cost (0.3–0.5 kilowatt hour)'. The NORWEB area provides a good pilot study as it includes several large institutional areas (eg the Lake District National Park), large conurbations (eg Manchester), and both lowland and upland landscapes.

There is every reason to believe that, nationally, there is sufficient unconstrained land to provide the basis for a wind energy programme that can provide the estimated 10–20% of our national energy needs by the year 2025.

Decisions on the siting of wind turbines in wind farms, each with approximately 25 medium-sized turbines, will clearly have to take into account environmental features which constitute local constraints. Those causing most concern are visual impact, impact on birds, and noise. Much can be learnt in this respect from other countries which are already developing their wind energy programmes, in particular Denmark and the Netherlands.

B G Bell

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Rehabilitation of degraded agricultural soils in the Sudan

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

The dark, cracking clay soils in much of the Sudan savanna zone are inherently poor in nitrogen, phosphorus, and organic matter. In the past, soil fertility has been maintained by the traditional system of rotational cropping of sorghum (*Sorghum bicolor*) and millet (*Pennisetum americanum*), with *Acacia* fallows. The trees restore soil fertility over the 10–20 years of the fallow period, probably through increased soil organic matter and nitrogen (N) fixation by the *Rhizobium* root nodules. The trees also provide the benefits of fuelwood, and *Acacia senegal* yields a valuable 'hard currency' crop of gum arabic after about eight years.

Since the 1950s, the Mechanised Farming Corporation (MFC) has cleared between two and three million hectares of *Acacia* forest, and has established continuous crops of rain-fed sorghum, millet and sesame (*Sesamum indicum*). Initially, this policy was very successful. However, in many areas, yields have decreased progressively as soils have become 'exhausted', and, when the land has been abandoned, it has often reverted to desert.

In the Dali region of the Blue Nile province, annual yields of over 2 tonnes ha^{-1} of grain have decreased to less than 0.2 tonnes ha^{-1} over a period of 5–15 years. In 1970, the MFC abandoned 13 400 ha of land in the Dali region, and handed it over to the Central Forests Administration (CFA). The CFA seeded about 4000 ha with *Acacia senegal* in 1971–72, and seeded the remaining area at intervals up to 1982.

Today, the Sudanese Government places great emphasis on the need to conserve and restore soil fertility in areas of rain-fed agriculture (Sudan, Ministry of Finance and Economic Planning 1986). It suggests that the traditional practice of rotational cropping with *Acacia* fallows should be restored, in conjunction with the development of sustainable tree/crop mixtures. There is little or no published information in the Sudan on the rates of increase of N and organic matter in soils under *Acacia*, or on their rates of depletion under sorghum and millet. Information on these rates and on the nutrient balances is essential, before advice can be given about the optimum fallow period. In addition, little is known about factors that control or limit the rates of soil improvement or degradation.

Identification of a time series of plots and site conditions

In order to investigate the process ofrestoring soil fertility by the growth of trees, and the subsequent reduction of fertility by crops, a chronosequence (time series) of land management was established in February 1987 for eleven sites. A joint field trip by ITE and the Institute of Environmental Studies at the University of Khartoum located these sites with the help of the local staff from CFA. Five sorghum sites from early (1 year) to late (>20 years) rotation, four *Acacia* stands from early (4 years) to late (16–17 years) rotation, and two older natural stands of *Acacia* were identified. One year later, in February 1988, seven soil samples were taken from each site.

Plate 10 illustrates five stages in the traditional land use cycle. An initial chemical analysis of the soil sampled from each of the eleven sites showed some interesting trends in the levels of nitrogen over a 40-year period (Figure 25). There is a gradual loss of nitrogen over 20 years of continuous cropping; the decline then appears to be reversed after a prolonged period of fallow. More detailed analysis of further soil samples collected in November 1988 and 1989 is required to check these trends.

Nitrogen budget of *Acacia* fallow system

One of the long-term aims of this project is to determine the nitrogen budget of the *Acacia* fallows and, in particular, the rate of N_2 fixation. Estimates of N^2 fixation are being made by examining the natural abundance of ^{15}N, using a mass spectrometer at ITE Merlewood. Trees, understorey vegetation, and crops were sampled in November 1888, and are being processed to determine the total standing crop of N, phosphorus (P) and the biomass. Precise data are required to develop a model using the framework shown in Figure 26.

Factors influencing rate of increase and decrease in soil fertility

One of the factors thought to control the rate of increase in soil fertility under *Acacia* is the level of *Rhizobium* supply. No nodulation has been observed in the field during four field trips. A site that had been continuously cropped for 15

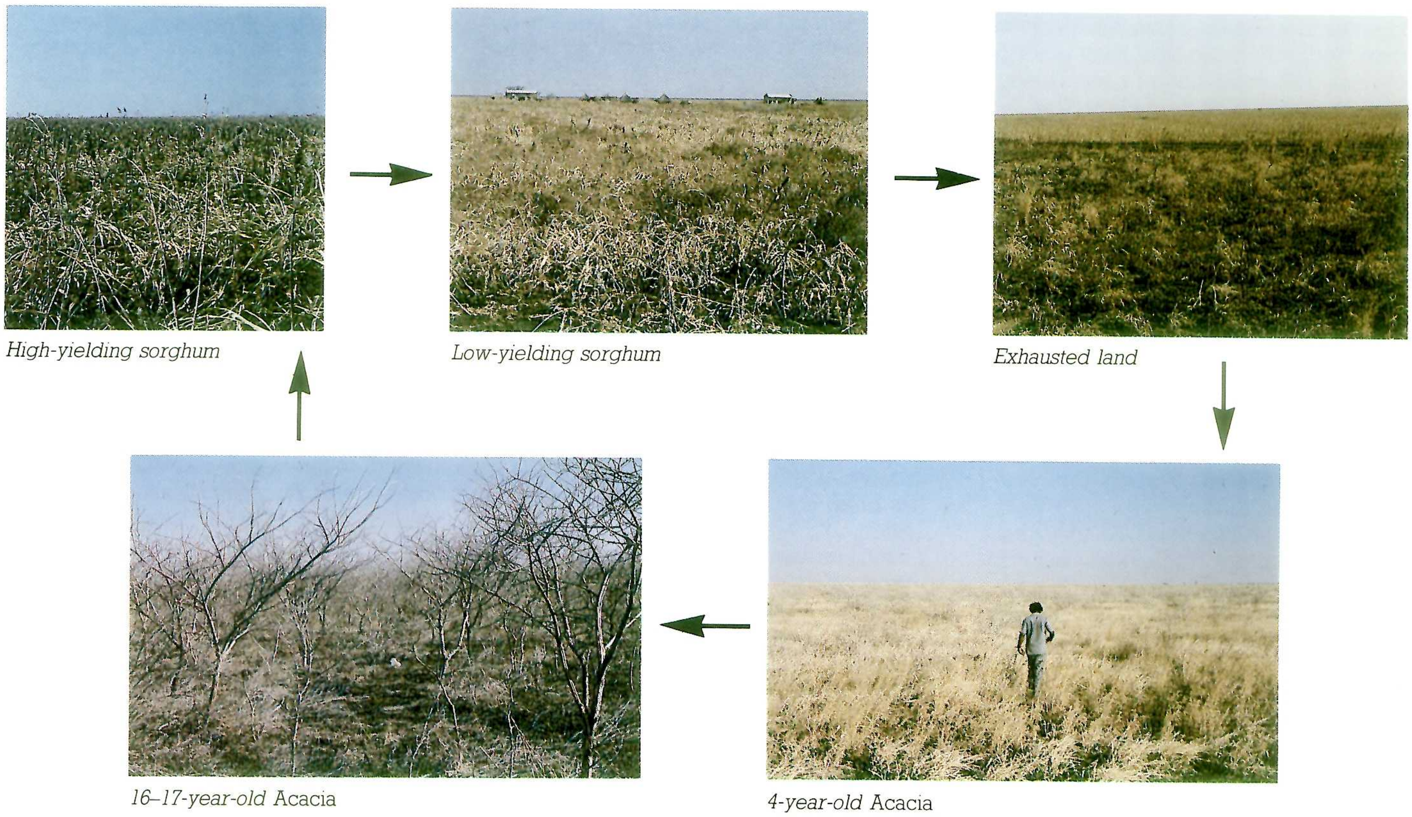

Plate 10. Five of the sites already located in the Dali region of the Blue Nile province, showing the progression through exhausted land to productive Acacia *woodland*

years, and then seeded with sorghum and *A. senegal* in August 1989, was visited the following November. Good rates of germination were observed but no evidence of nodulation was found down to 50 cm. Hogberg (1986) suggested that it can take between five minutes and five days to find evidence of nodules in savanna woodland trees in Tanzania.

In an attempt to understand the process of nodulation in more detail, experimental work was started to determine whether nodules would develop under standard nursery conditions at the CFA's forest

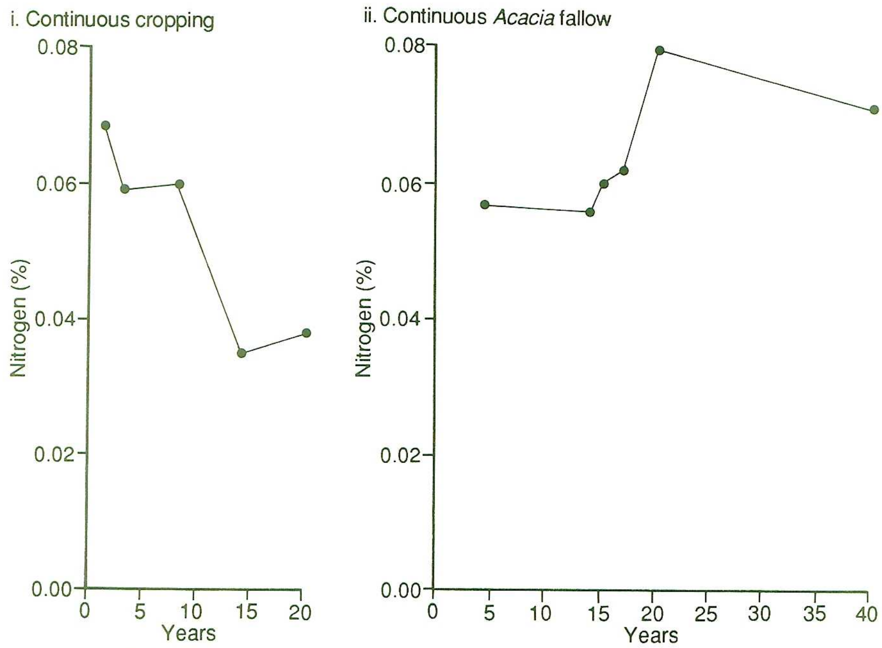

Figure 25. Fall and rise of nitrogen levels in cropping an Acacia *fallow site in the Dali region of the Blue Nile province in the Sudan*

nursery at Soba in Khartoum. Three species of *Acacia* were grown, namely *A. mellifera*, *A. senegal* and *A. seyal*, under two separate methods. The traditional Sudanese way used a 2:1 mixture of silt and sand, and sowing was done in polythene tubes. The new Finnish method used a 3:1 mixture of peat and silt, with sowing in plastic Enso-pot trays. After 75 days, the Finnish method was very much more successful at producing nodules, as shown in Figure 27. In a separate experiment, *A. mellifera* was germinated on soil collected at site 5 to see whether the soil collected at 20 cm intervals down the profile, to a depth of 1 m, had any influence on nodulation. No detectable pattern emerged with depth, although many nodules were produced, ranging from 0 to 50 per seedling. The seedlings produced from the first experiment will be planted out under field conditions, and the fate of the nodules will be traced over a season.

Two other factors considered to be important in determining the pattern of the rise and fall in soil fertility were the distribution and amounts of roots at both the *Acacia* and sorghum sites. This problem was examined during the last field trip in November 1989. Three root systems of 40-year-old *Acacia mellifera* and two of 5-year-old *A. senegal* were excavated with hand tools to a depth of about 1 m. The root systems were mapped in three dimensions to show the distribution of the main structural elements in the root systems of both species. A series of cores were taken so that the weight and distribution of the fine roots could also be determined. At two of the agricultural sites with crops of *Sorghum vulgare*, five cores were extracted to a depth of 0.6 m and two to a depth of 1 m. The samples were

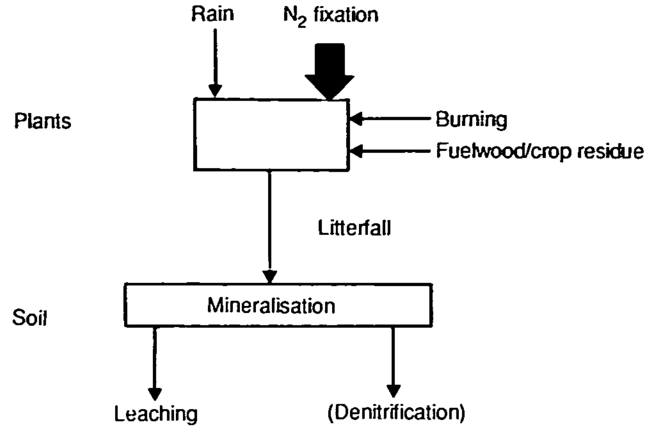

Figure 26. Simplified model of the nitrogen budget of the Acacia *fallow system*

transported back to the University of Khartoum, where the fine roots were washed out of the cores and their weights determined.

It was estimated that 45% of the root system of the 5-year-old *Acacia senegal* and 11% of the root system of *Acacia mellifera* exploited soil layers deeper than 0.5 m. An analysis of the weights of the fine roots under both tree species showed that they were significantly more concentrated near the soil surface than at greater depth (see Table 5).

These preliminary root results suggest that the redistribution of nutrients from depth via root turnover could be one of the most significant factors affecting productivity during the cropping cycle. Some initial calculations based on the turnover of each season's fine root production suggest that nitrogen inputs from this source could account for production suggest that nitrogen inputs from this source could account for 50–100% of the measured increase in soil N during the late stages of the *Acacia* cycle.

Table 5. Distribution of fine roots (c 1 mm diameter) in the surface 1 m of soil in stands of 40-year-old Acacia mellifera *and 5-year-old* Acacia senegal *growing in the clay plains of eastern Sudan*

Depth in soil (cm)	Root dry weight (g m^{-2}) *A. mellifera*	*A. senegal*
0–20	138.2	2.76
20–40	37.2	3.71
40–60	28.3	2.02
60–80	5.8	1.54
80–100	3.1	0.50
Total	213.1	10.53

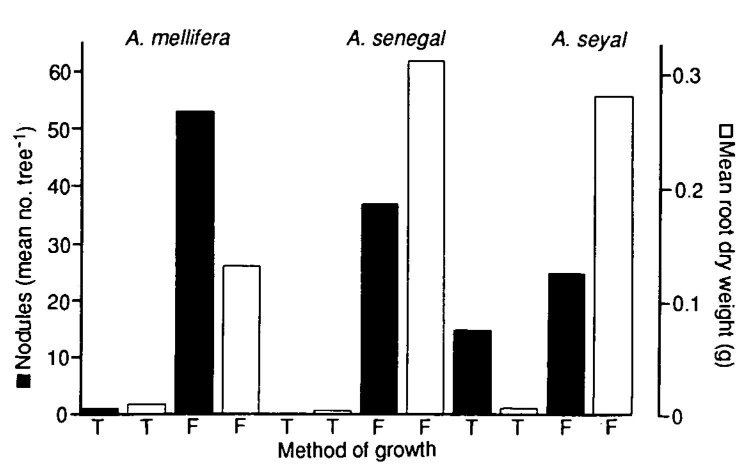

Figure 27. Production of root nodules on Acacia *seedlings grown by traditional (T) and by Finnish (F) methods*

Conclusions

Some promising results have already emerged from this project. Once the analytical chemistry and ^{15}N results are complete, the results will be incorporated into a simple model of the nitrogen budget. Although there are technical problems in measuring N_2 fixation using ^{15}N and it is difficult to interpret the results, we hope to achieve a reasonable value of N_2 fixation that will tie in with N accretion rates in the soil and trees. The information from this project is intended to provide useful, practical guidance for sustaining soil fertility and crop yields, by using *Acacia* tree fallow systems at the optimum level, thus maximising food production and preventing further desertification.

The project has progressed because of the very close co-operation between ITE and several institutions in the Sudan. Important contributions to the project have been made by Professor H O Abdel Nour and staff (Forests National Corporation of Sudan), Dr O M Ali (Institute of Environmental Studies, University of Khartoum), Dr T V Callaghan, G J Lawson and J D Deans.

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Biological Records Centre – 25th anniversary

The year in which the Biological Records Centre (BRC) became part of ITE's new Environmental Information Centre (EIC) also marked the 25th anniversary of the founding of BRC at the Monks Wood Experimental Station. How did it come to be established? What are its present aims, and its ambitions for the years ahead?

The past

The establishment of the Nature Conservancy in 1949 brought unprecedented opportunities for the study and conservation of plant and animal species, and their communities. The Botanical Society of the British Isles (BSBI) chose for the theme of its 1950 conference the recording of the distribution of British vascular plants. The absence of a national overview of the occurrence of every plant species was seen as a serious deficiency.

The BSBI conference gave unanimous support to a mapping scheme, based on the 10 km squares of the National Grid.

Under the aegis of the BSBI, and financed by the Nature Conservancy and the Nuffield Foundation, the mapping project began in April 1954. Nearly 1.5 million field record cards were contributed by about 1500 professional and amateur volunteer workers. In 1962, the *Atlas of the British flora* was published, showing the distribution of 1700 species. Never before had such detailed information been available on a uniform basis. The project had pioneered the use of data processing machinery for handling records at all stages, from the point of receipt to their appearing as symbols on a map.

Long before the survey was finished, recorders had begun to use field record cards for plotting other organisms. A meeting in November 1962, convened by the Nature Conservancy and attended by representatives of the main biological societies, supported the proposal to capitalise on the expertise and experience gained by establishing a permanent mapping unit as part of 'the scientific equipment of the country'. In April 1964, the Director of the BSBI survey, Dr F H Perring, and his staff moved to Monks Wood, where they became a fully integrated part of the Conservancy in 1967. By that time, the Conservancy itself had been absorbed into a larger research council, the Natural Environment Research Council.

Right from the start, the BRC was keen to initiate its own surveys. For some groups, and most notably insects, there was no suitable society to undertake mapping schemes. A project to map the distribution of British Macrolepidoptera got off to 'a very encouraging start', following the appointment of J Heath to the BRC in January 1967. The first part of the *Provisional atlas of the insects of the British Isles* was published in late 1970. Soon, the BRC was closely involved in ventures to map both the flora and invertebrate life of Europe. The benefits to be gained from a computer-based system were quickly recognised. With a basic record in computer store, updating could take place continually. It would become possible to map associations of two or more species, or to list those occurring in a single square or group of squares.

Meanwhile, major changes were taking place in the organisation of research and conservation. In 1973, the BRC became part of the new NERC Institute of Terrestrial Ecology, following the abolition of the Nature Conservancy. Whilst the Centre continued, under contract, to meet the species mapping needs of the new Nature Conservancy Council, a major rethink was required.

The BRC has developed to become much more a repository for detailed, site-relatable data, covering a wider field of ecological survey and research, including information for environmental assessment. The challenge has been met both centrally and through the establishment of a network of independent local record centres.

The present

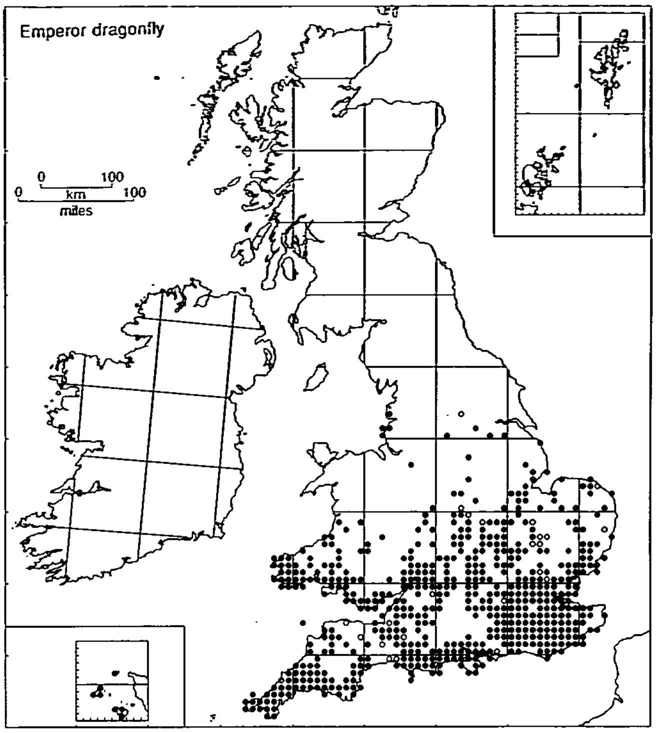
The BRC data base has grown markedly since the early 1980s. There are now over 60 schemes, covering some 16 000 taxa. Data continue to be collected by many individuals and groups, usually at a scale of detail greater than the 10 km square. Perhaps the term 'malleable' might be used to describe how the specialist volunteers have responded to requests for more detailed records and for assistance in project-oriented surveys and monitoring assignments.

Distribution maps (Figure 28) have been produced for over 7000 species, and published in a variety of books, journals, reports and, above all, atlases, together with text on the ecology and habitats of the species described. Through the use of time series maps, it is possible to trace the spread or decline of species in response to man-induced or more natural influences. BRC data are now held in an accessible relational data base, using ORACLE, and full opportunity is taken of access, as part of ITE's Environmental Information Centre, to other environmental data sets and spatial data handling technologies.

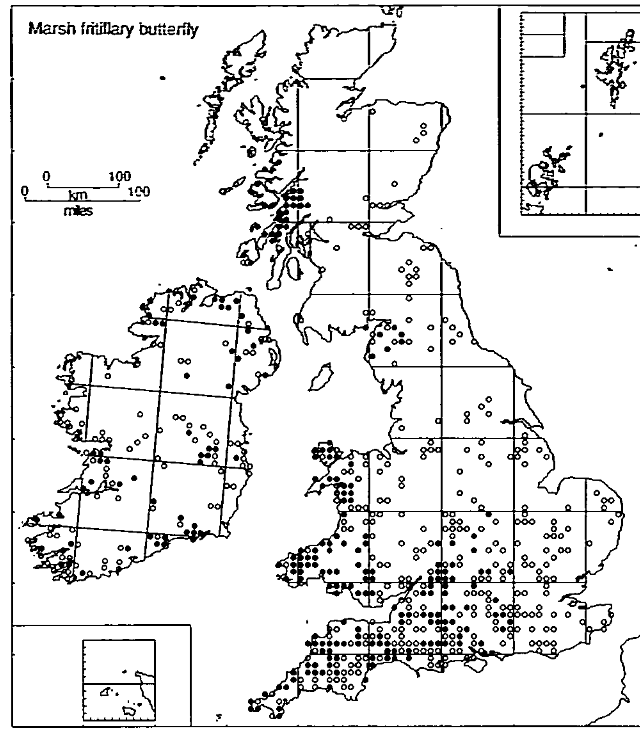
The BRC has always stressed that the accumulation of data is only a means to an end, namely the resolution of relevant questions in the life sciences and the more general understanding of the natural environment. The results have been crucial in establishing conservation priorities, especially in relation to threatened species and the selection of sites for wildlife protection. The data have also been of value in identifying what further analyses were needed. For example, many of the 100 000 records collected by the Odonata Recording Scheme are precisely dated, and therefore have formed a basis for determining patterns in the flight periods of individual species. The Butterfly Monitoring Scheme has provided a headstart for one particular group in assessing the effects of different weather patterns, and their relevance to any longer-term change in climate.

The BRC has continued to collaborate on major initiatives. A BSBI Monitoring Scheme was mounted in 1987–88 with two objectives in mind. First, the findings of the partial resurvey could be compared with those of the 1950s survey, in order to discover whether changes had taken place in the distribution of flowering plant species. Second, a baseline was established for future monitoring. In collaboration with the BRC, the University of Newcastle is carrying out multivariate analyses of data already available to the Centre, as a basis for site evaluations, and for making assessments of habitat assemblages and the preferences of species for different habitats.

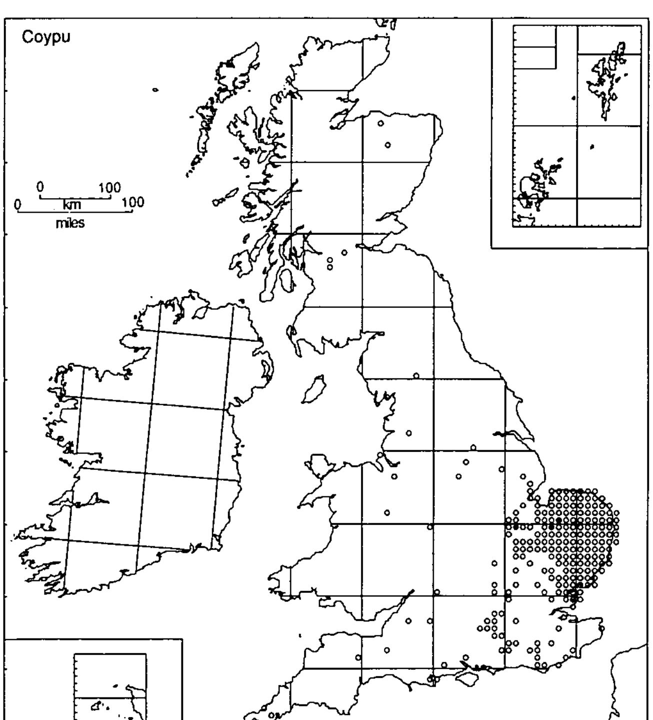
Figure 28. Examples of distribution maps compiled by the Biological Records Centre from the national data base. Maps show the recorded distribution of species in the 10 km squares of the British and Irish National Grids. Open symbols indicate early records, solid dots indicate recent records



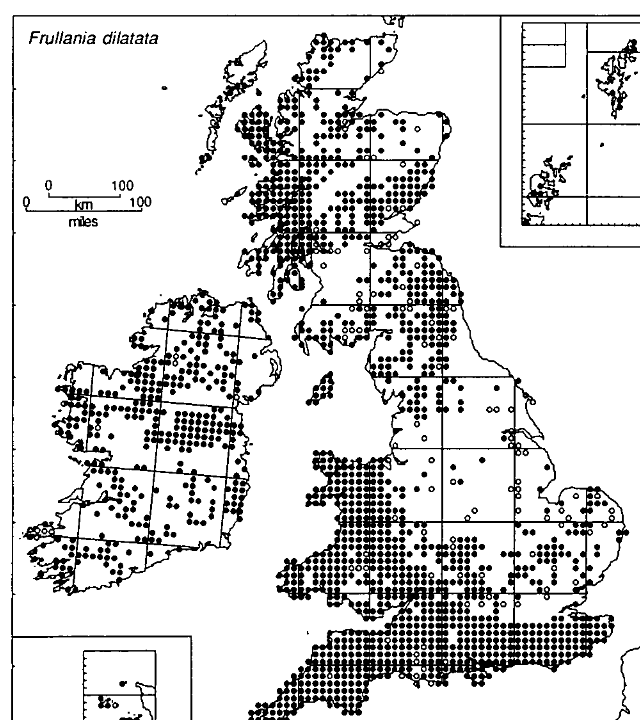
i. *Emperor dragonfly (*Anax imperator*), with an area shaded to show where the species has expanded its range during the period since 1970*
O pre-1970, ● post-1970



ii. *Marsh fritillary butterfly (*Euphydryas aurinia*) is an internationally threatened species which is still fairly widespread in parts of the British Isles. It is, however, still declining because of the loss of suitably managed grasslands in which it breeds*
O pre-1970, ● post-1970



iii. *Coypu (*Myocastor coypus*). This large, semi-aquatic rodent was introduced to Britain on fur farms, and it established wild populations. Effective control measures had, by 1988, reduced this pest species to a few solitary males, and the species may now have been exterminated in Britain*
O pre-1988, ● post-1988



iv. *The liverwort* Frullania dilatata *grows commonly on trees and also on rocks. It is sensitive to atmospheric pollution, particularly* SO_2*, and is therefore absent from areas of highest pollution in northern, midland and southern England, and in south Wales*
O pre-1950, ● post-1950

The future

The emphasis of this contribution, marking the Centre's Silver Jubilee, has been on the past and present. The history of BRC may be characterised as the development of data gathering techniques, the collection of data through the co-ordinated efforts of large numbers of volunteers, and the synthesis and interpretation of the information that has been collected. Clearly, all three aspects are inter-related; the Centre must continue to pioneer the application of techniques, and to ensure that the data base remains up-to-date and becomes even more comprehensive. The current emphasis is, however, unmistakably on the deployment of information in answering the questions posed by the increasing range of bodies seeking authoritative and comprehensive information about wildlife and the natural environment.

The BRC will continue to acquire most of its data from volunteer specialists, and thereby play a vital role in bringing together the kind of high-quality information required to build up a picture of what is happening at a national scale.

With over 5 million records, of which 3 million are now in site-relatable form, the BRC represents a unique national resource.

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